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AUSTRALIAN–AMERICAN FULBRIGHT COMMISSION

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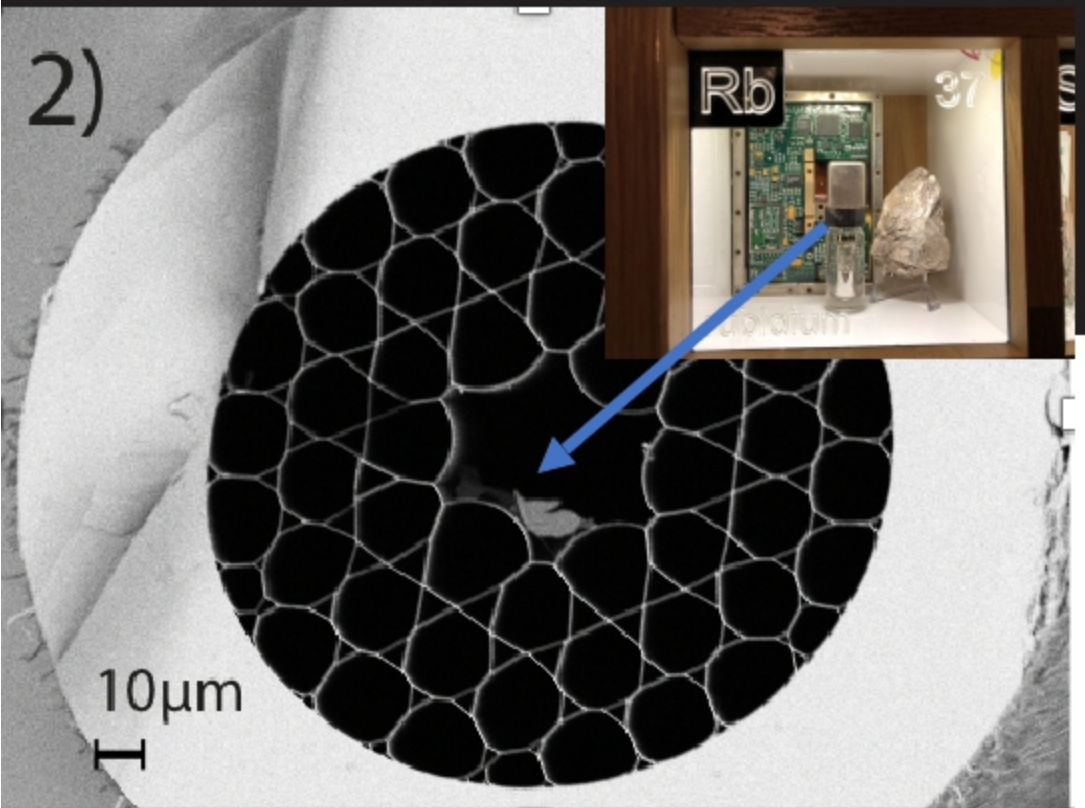
Institute for Photonics and Advanced Sensing



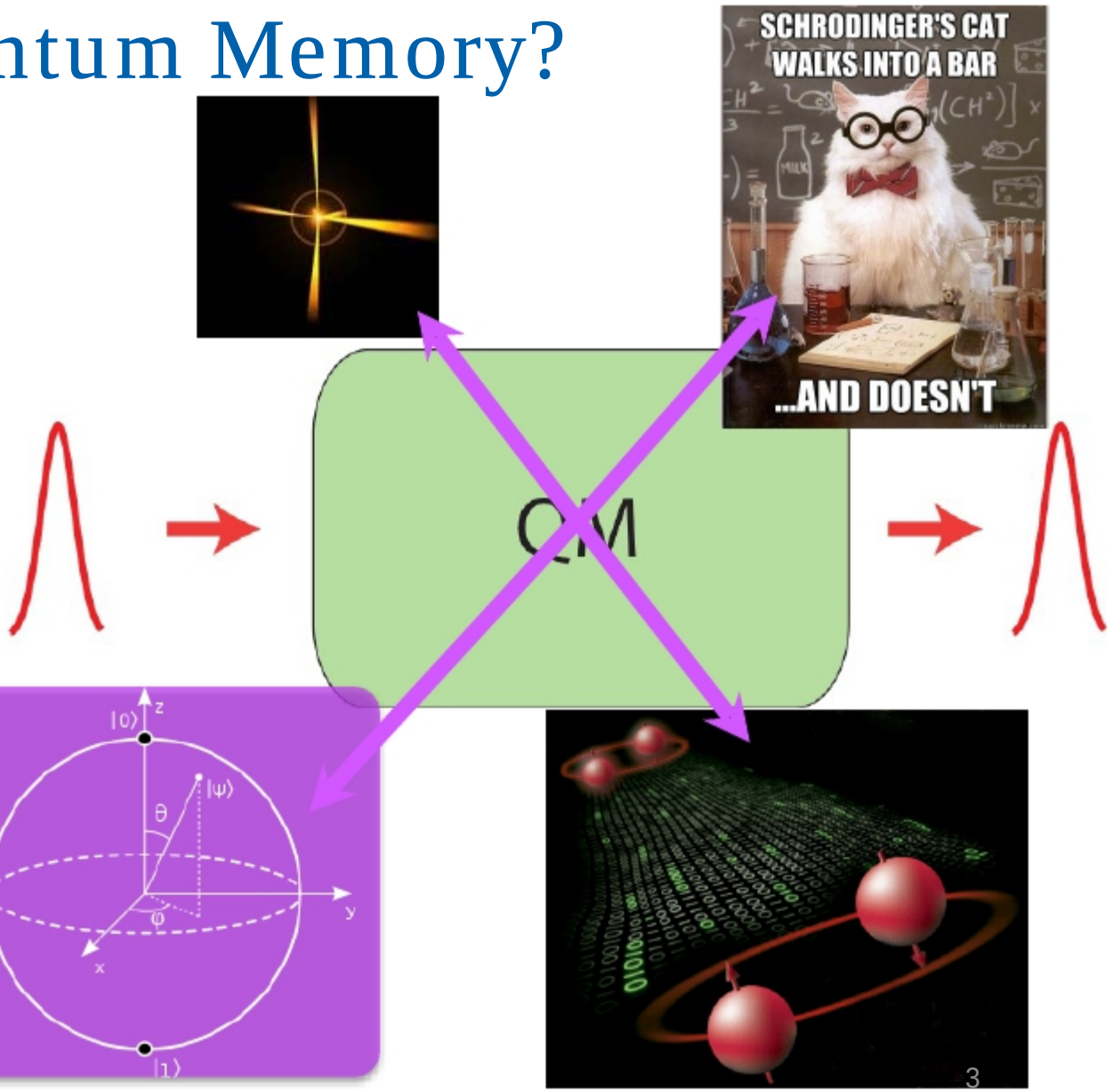
Towards Optical Quantum Information Processing in Atom-Filled Hollow-Core Photonic Crystal Fibres

B. M. Sparkes, J. Rowland, C. Perrella, J. P. Hedger, A. P. Hilton, P. S. Light, and A. N. Luiten

Outline

- Quantum Memory 101 – *What? Why? Where do I get one?*
- High-Bandwidth Memory – *Hot stuff with warm atoms in fibre*
- Long Lifetime Memories in Fibres – *Cool Experiments with cold atoms in fibre*

What is a Quantum Memory?

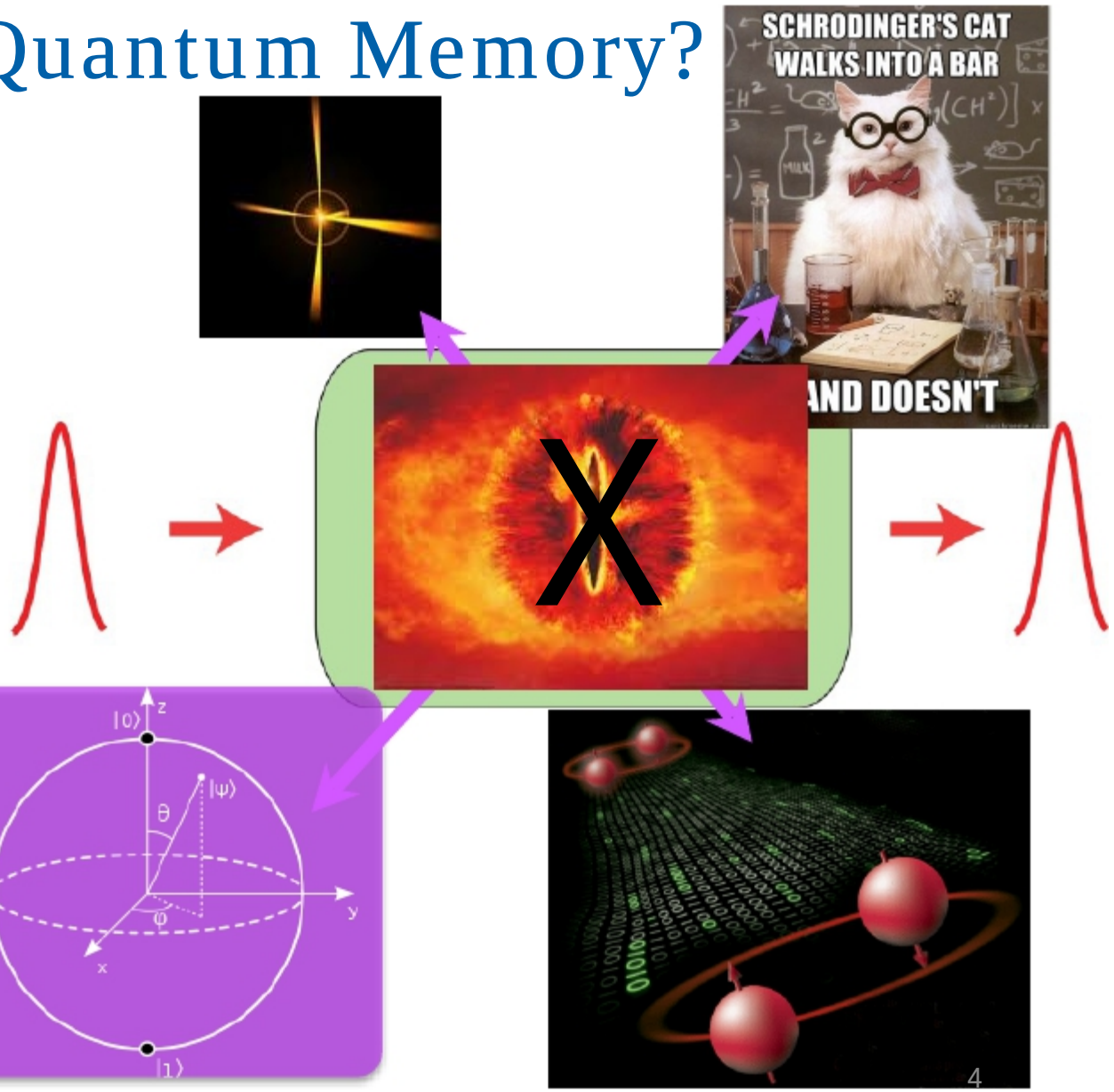


What is a GOOD Quantum Memory?

- Efficient
- Noiseless

} High Fidelity

- “Useful” Storage Time



Why Do We Want One?

*"[O]ne could characterise **quantum information processing** as the science of turning quantum conundrums into potentially useful applications"* Gisin *et al*,Rev Mod Phys **74**,145,(2002)

- Quantum Key Distribution

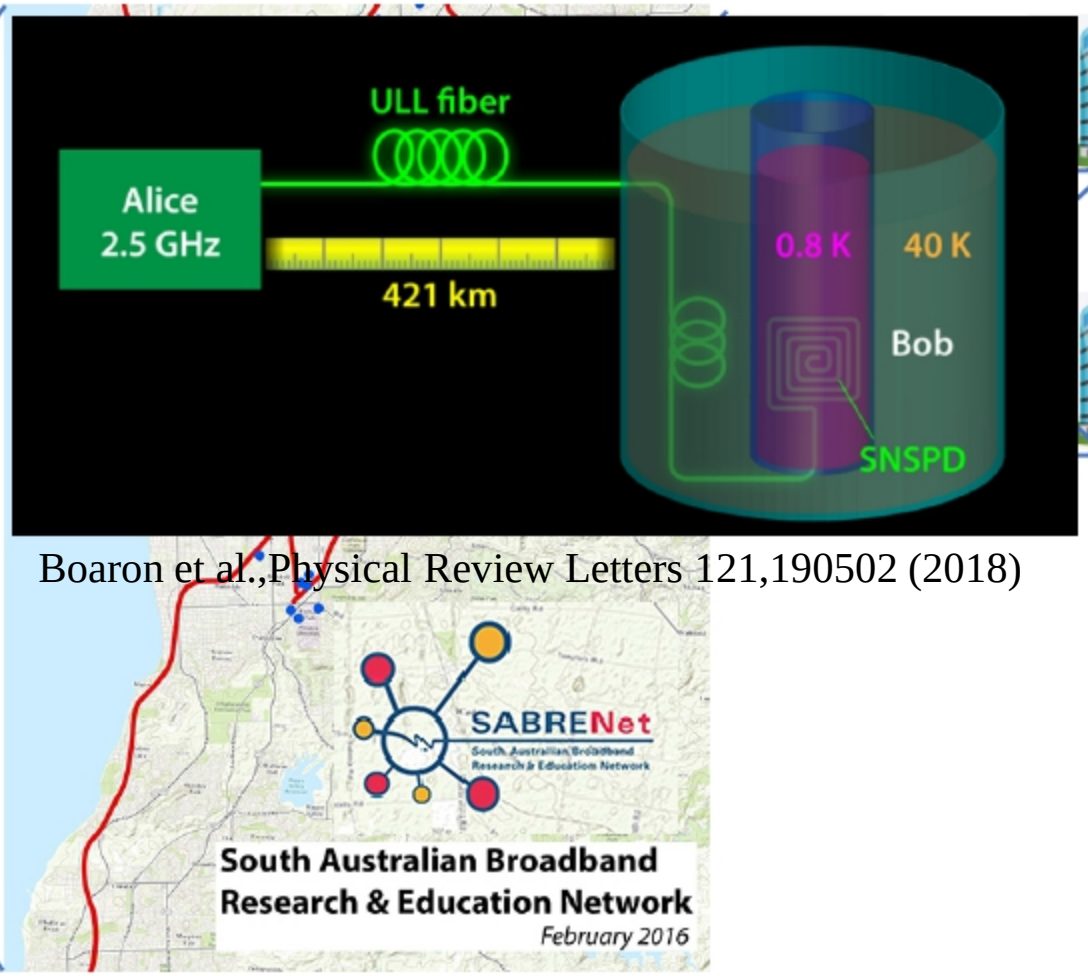
- Quantum Computing

Quantum Networks – Many Shapes and Sizes

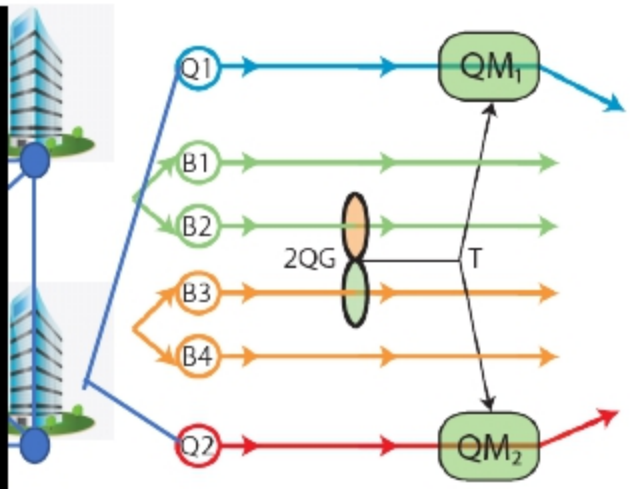
National / International Network

City-Wide Network

Local Network



Boaron et al.,Physical Review Letters 121,190502 (2018)



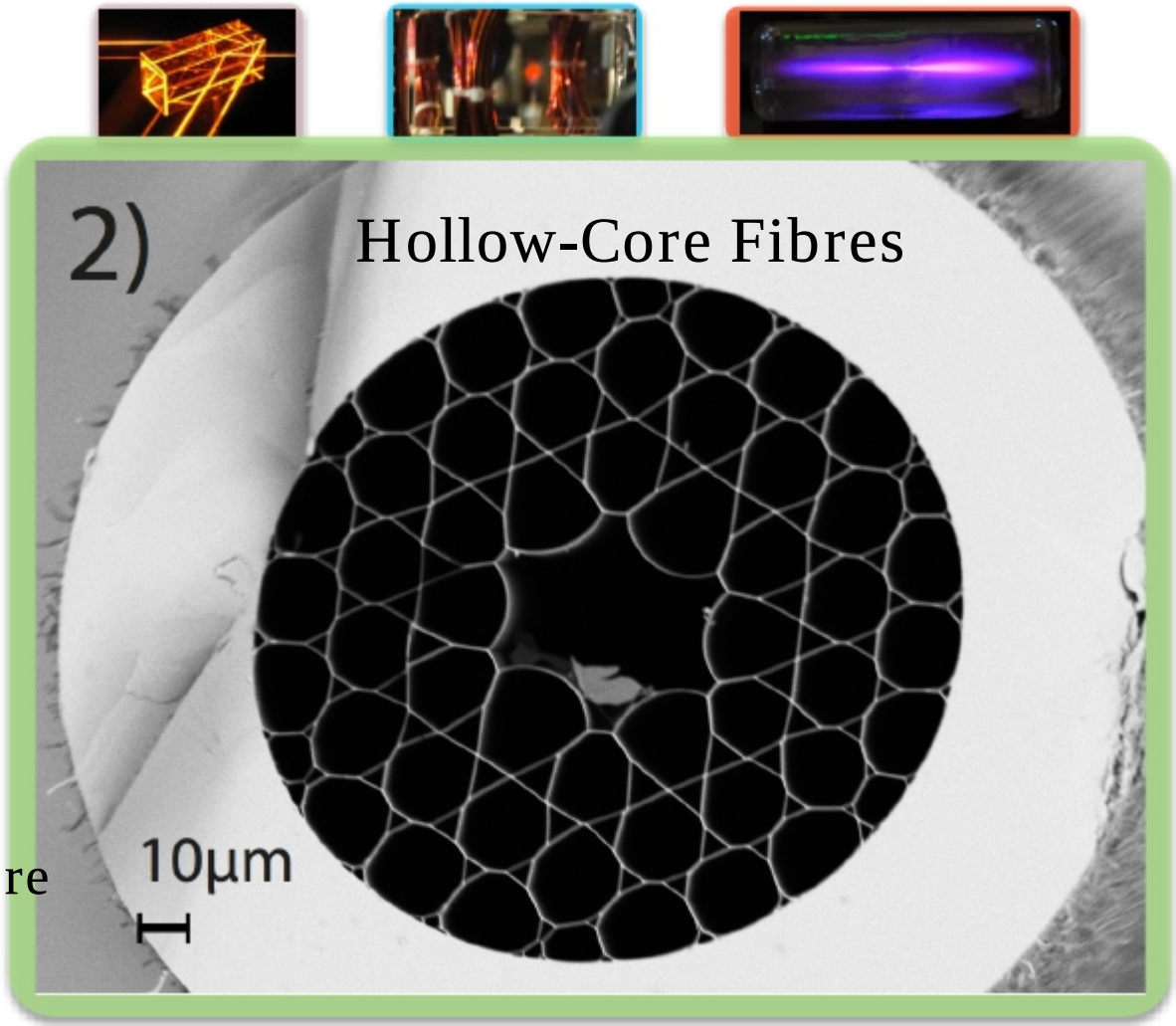
Quantum Repeater:
- Entanglement swapping
- Entanglement generation between nodes
- Timing: ms ⟶ s

Quantum Computer:
- State Preparation
- Quantum Gates
- Timing: ns ⟶ ∝s

The Ideal Storage Medium?

Criteria:

- Large Absorption
- Stationary Absorbers
- Tight Transverse Confinement
- Robust
- Integrable with current infrastructure

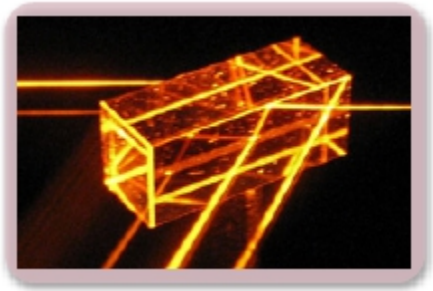


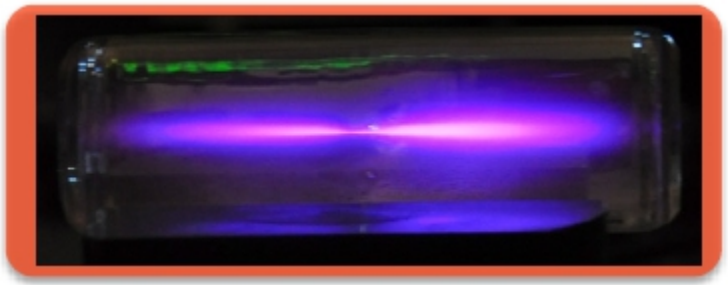
How Are We Doing?

Method:

- EIT
  - Eff =92%
  - ts > 2.3 s
- Atomic Frequency Comb
  - Eff =35%
  - TBP = 1060 pulses / B'width = 5 GHz
- Raman Storage
  - Eff=30%
  - TBP ~ 2500/B'width ~ 1.5 GHz
- Gradient Echo Memory
  - Eff=73,87,87%
  - TBP ~ 20/B'width ~ 1 MHz
  - ts > 1 ms

Medium:





Hsiao *et al*,Phys Rev Lett **120**,183602 (2018).
Longdell *et al*,Phys Rev Lett **95**,062601 (2005).

Amari *et al*,J Lumin.**130**,1579 (2010),
Usmani *et al*,Nature Commun **1**,1 (2010),
Bonarota *et al*,N J Phys **13**,013013 (2011).

Reim *et al*,Phys Rev Lett **107**,053603 (2011),
Reim *et al*,Nature Photon **4**,218 (2010).

Hedges *et al*,Nature **465**,1052 (2010),
Hosseini *et al*,Nature Commun **2**,174 (2011),
Cho *et al*,Optica **3**,100 (2016).

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- Quantum Memory 101 – *What? Why? Where do I get one?*
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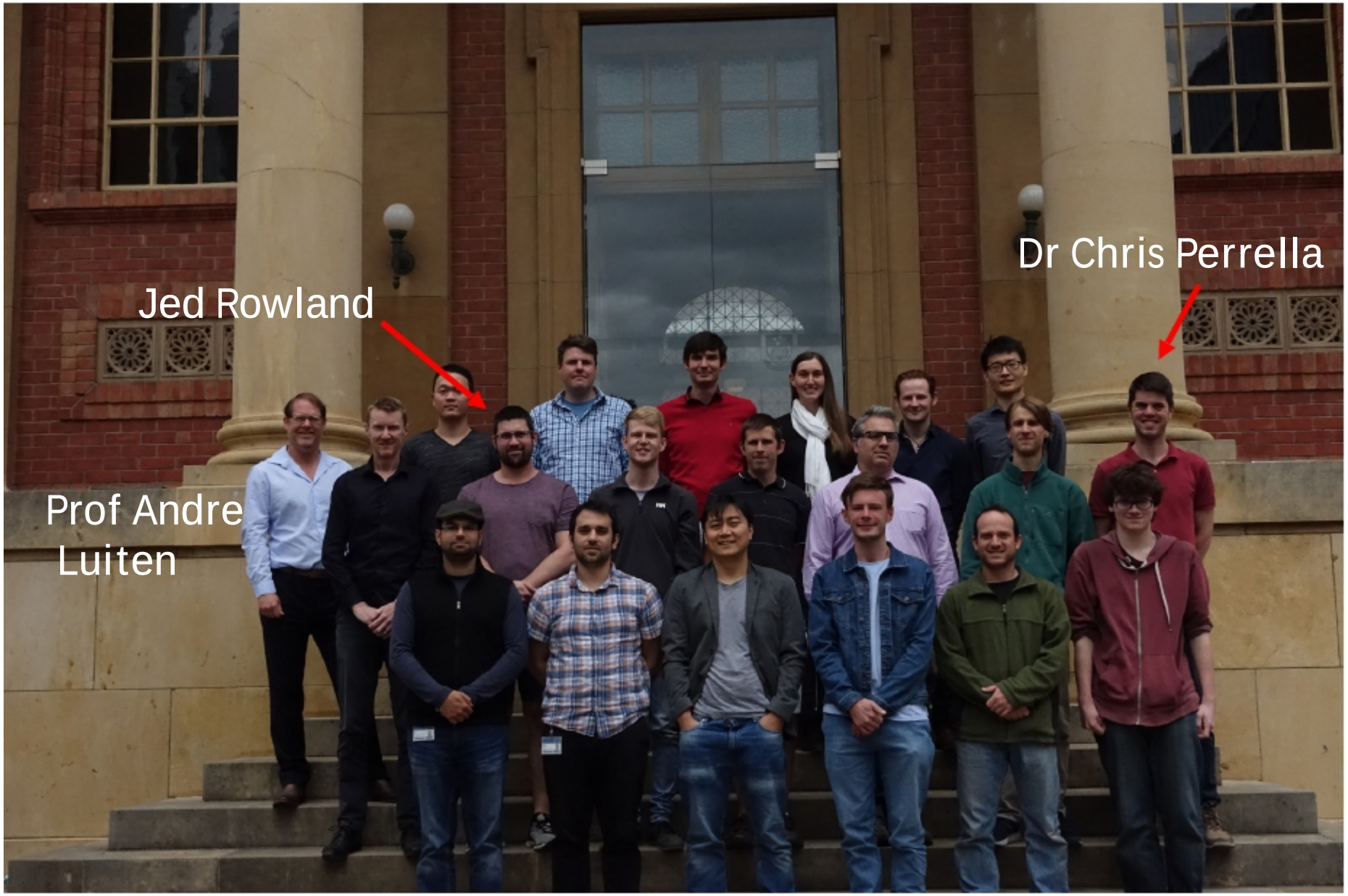
The Precision Measurement Group



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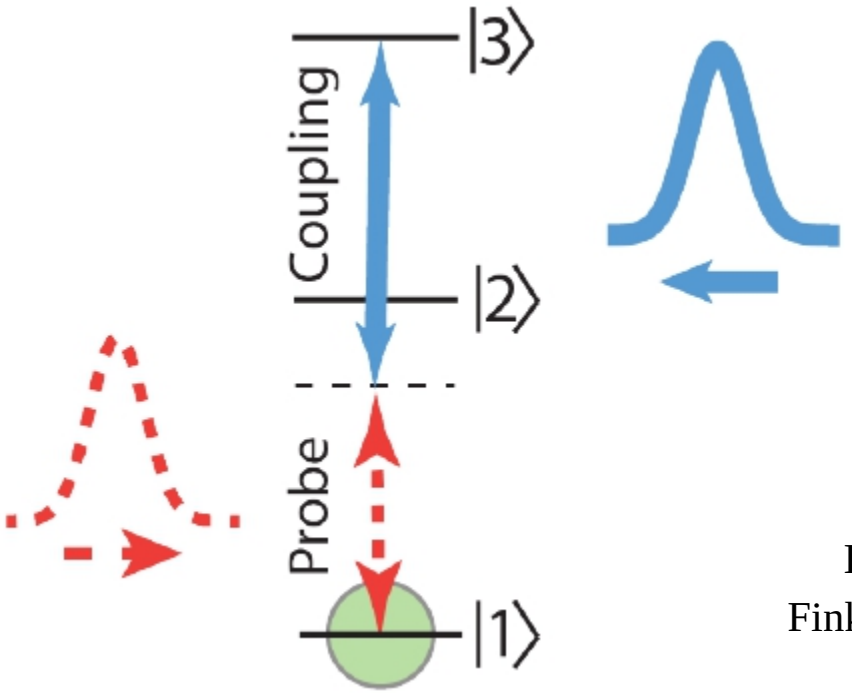
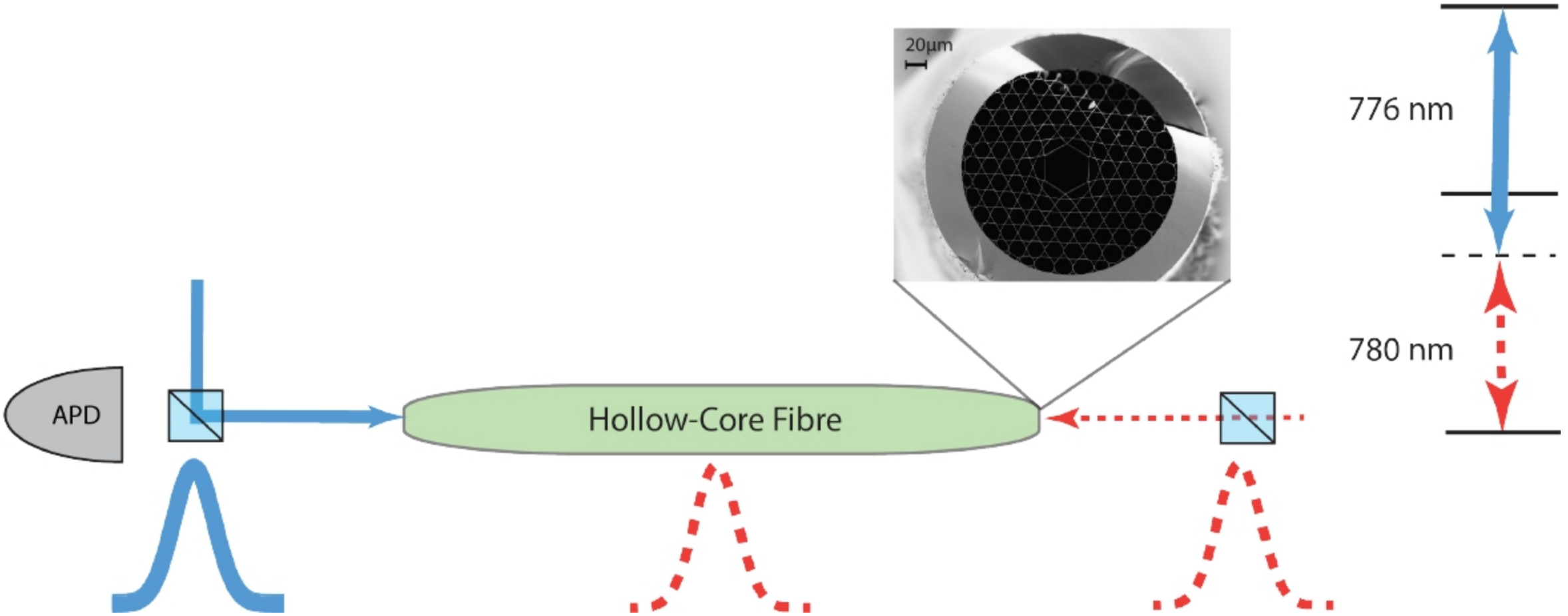
Off-Resonance Cascade Absorption (ORCA)

- High Bandwidth (>10 GHz)
- No Noise
- Short Storage Times
  - 5 ns in Cs (15% efficient)
  - 100 ns in Rb (25% efficient)

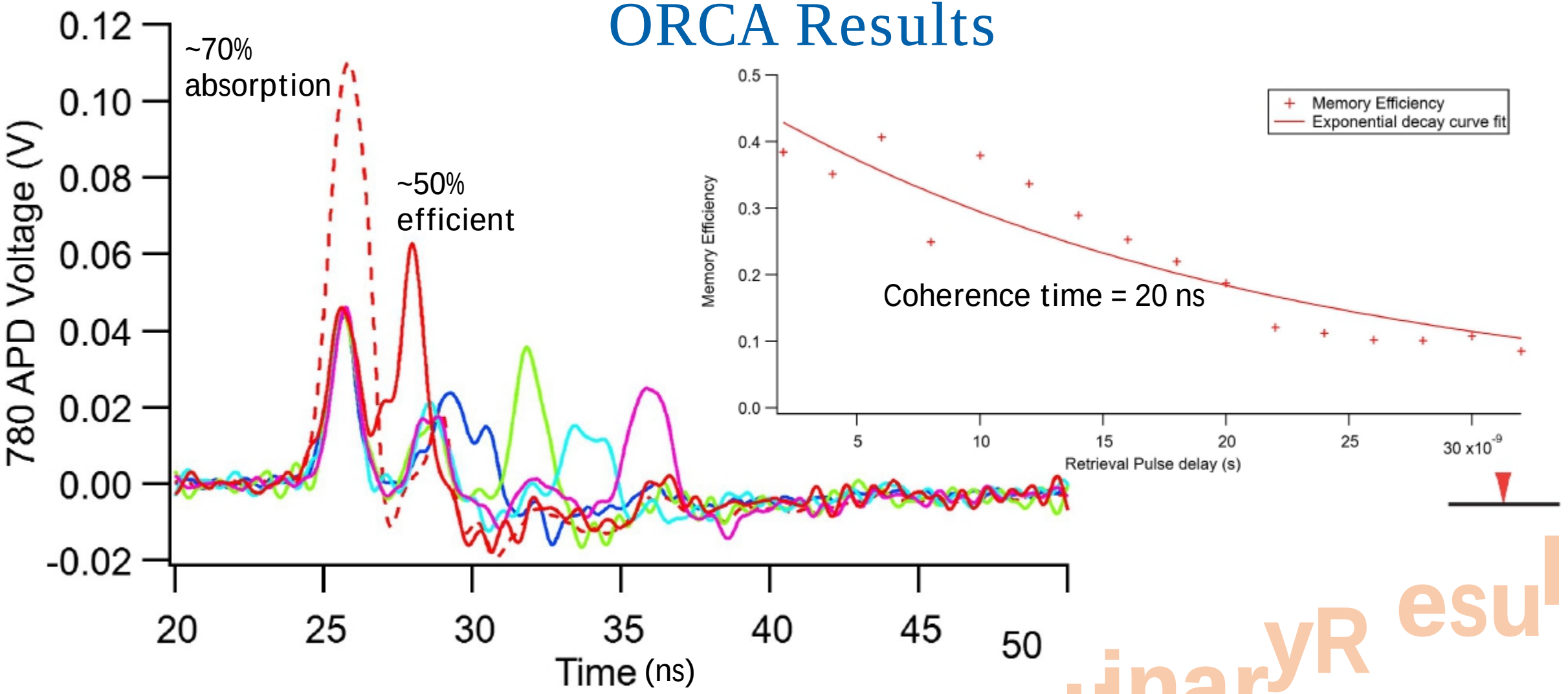


Kaczmarek *et al*,PRA 97,042318 (2018)
Finkelstein *et al*,Sci Adv 4,eaap8598 (2018)

ORCA Set-Up

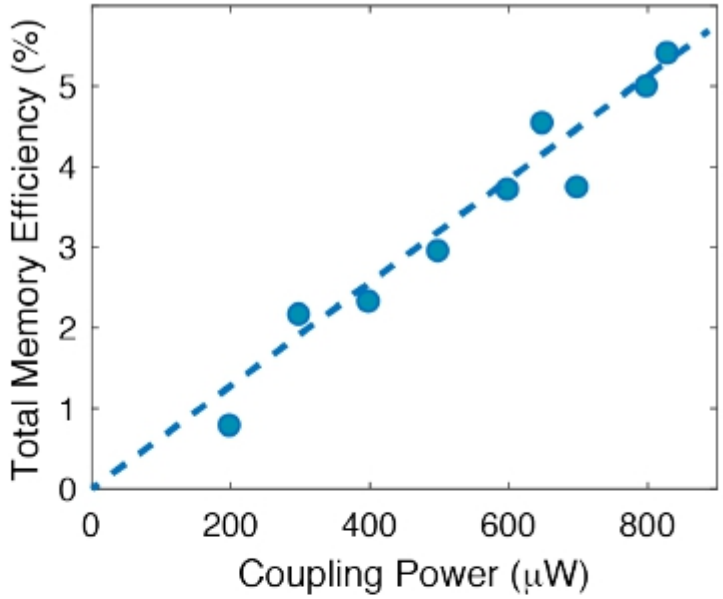


ORCA Results



Preliminary Results

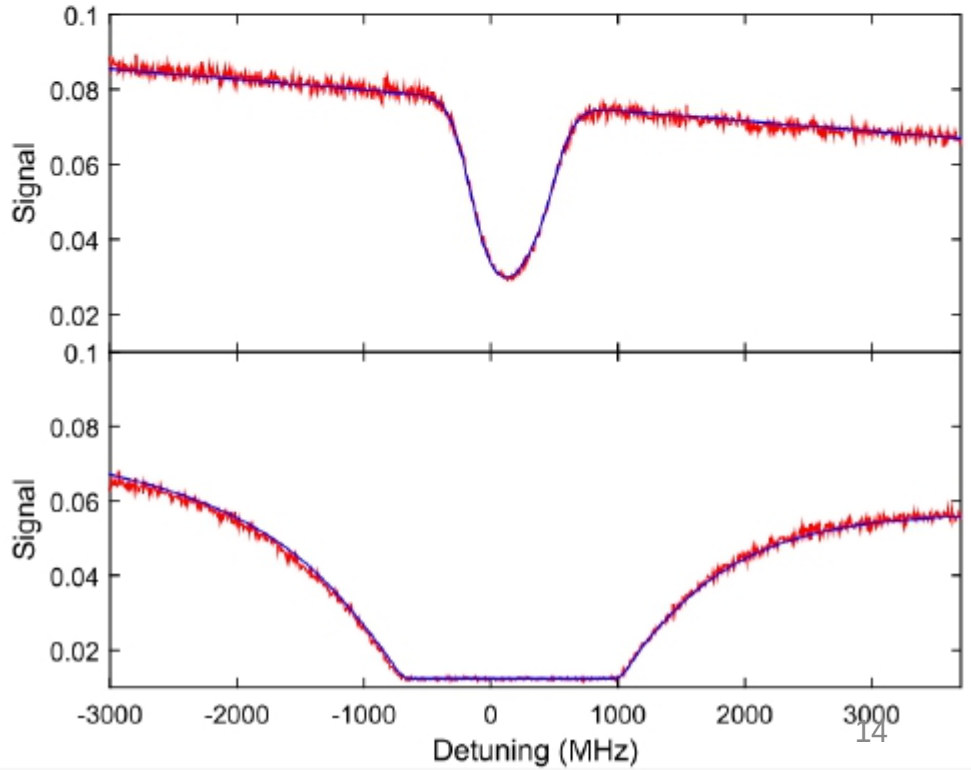
ORCA Improvements



- Increased Coupling Power

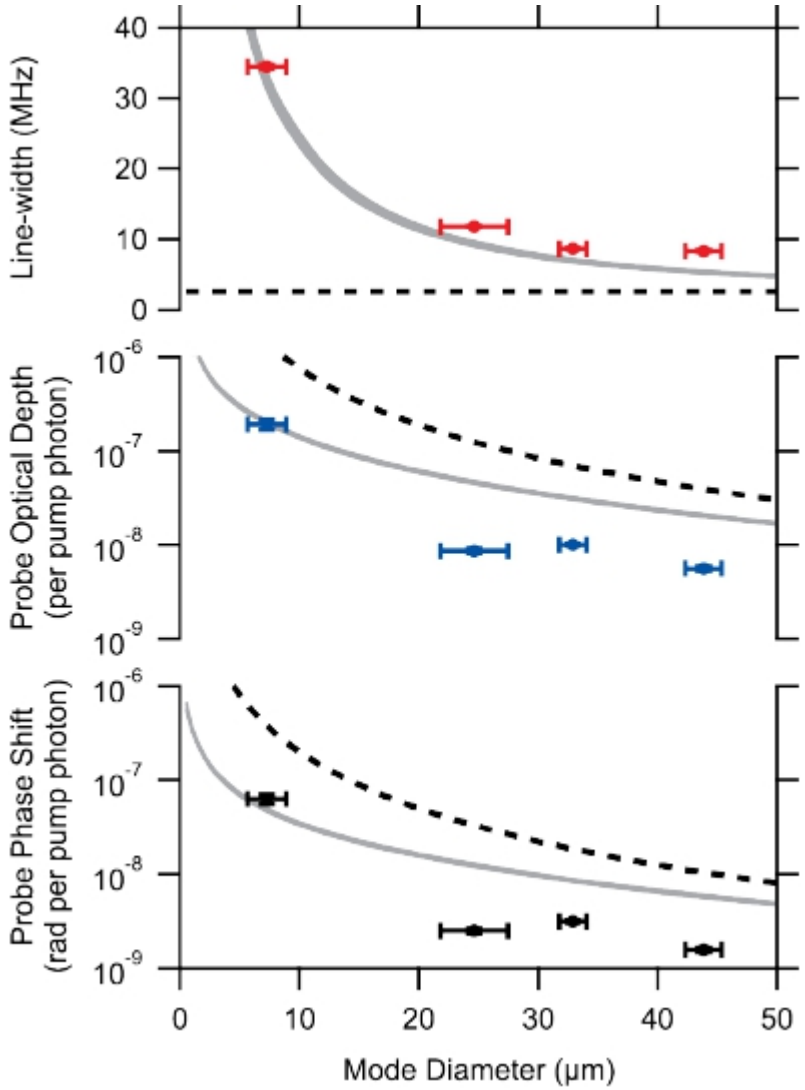
- Laser-Induced Atomic Desorption

  Kaczmarek *et al*,Optics Letters 40,005582 (2015)



ORCA Improvements

- Increased Coupling Power
- Laser-Induced Atomic Desorption
  Kaczmarek *et al*,Optics Letters 40,005582 (2015)
- Different Fibres
  Perrella *et al*,Phys.Rev. Applied 9,044001 (2017)



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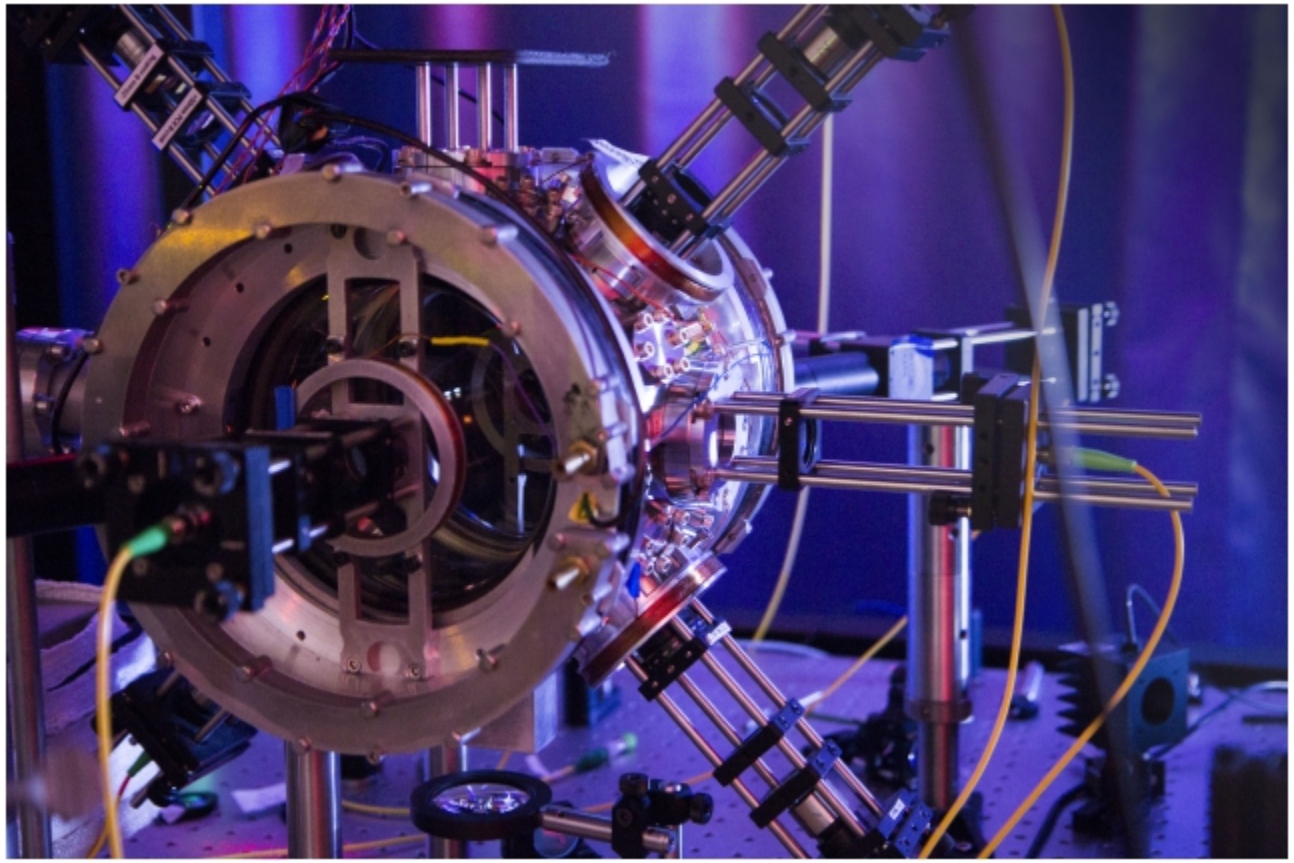
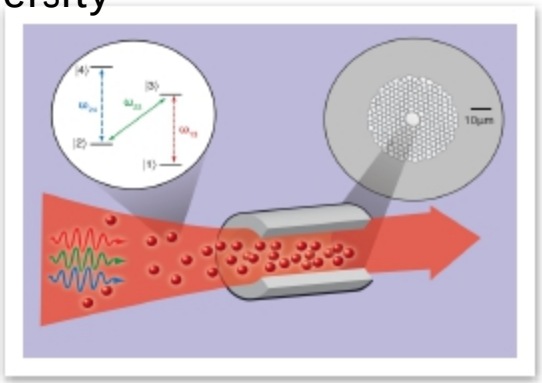
Cold Atoms in Fibre

- Reduced Velocity (100 m/s → mm/s)
- Increased Lifetime (100 ns → 10 ms)



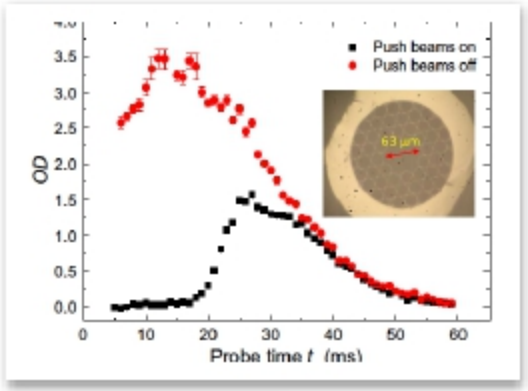
Cold Atoms in HCF - State of the Art

Peyronel *et al* IEEE JSTQE **18**, 1747 (2012)
Harvard University



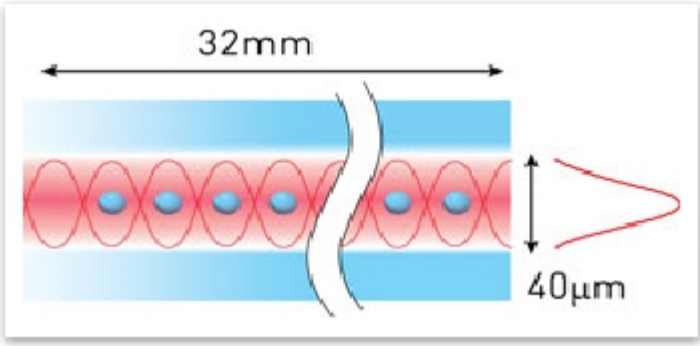
OD: 180
N_A: 3×10^4

Xin *et al* Sci Adv **4**, e1701723 (2018)
Nanyang Technology University

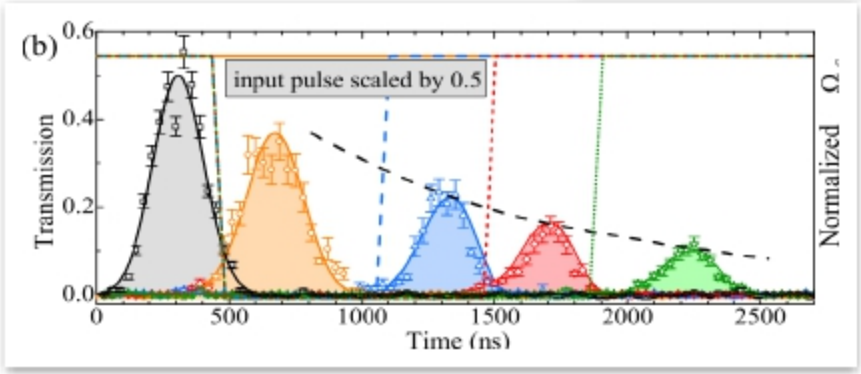


OD: 1.5
N_A: 2×10^4

Okaba et al Nature Commun **5**, 4096 (2014)
University of Tokyo & RIKEN Institute

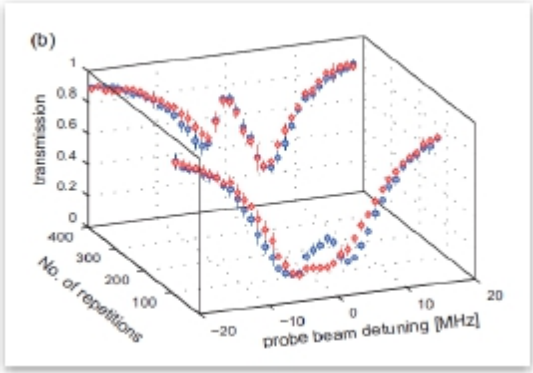


OD: 1
N_A: 1×10^3



OD: 1000
N_A: 2.5×10^5

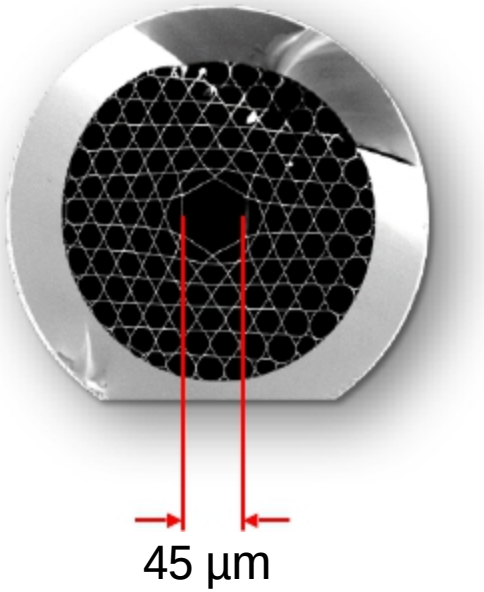
Blatt *et al* PRA **94**, 043833 (2016)
Institut für Angewandte Physik,
Technische Universität Darmstadt

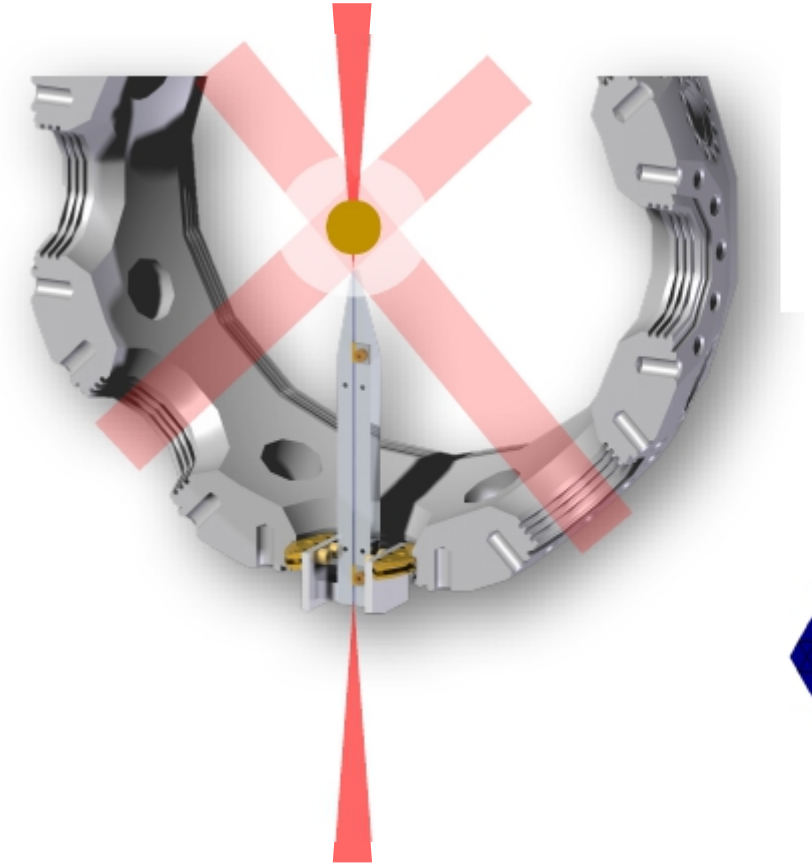


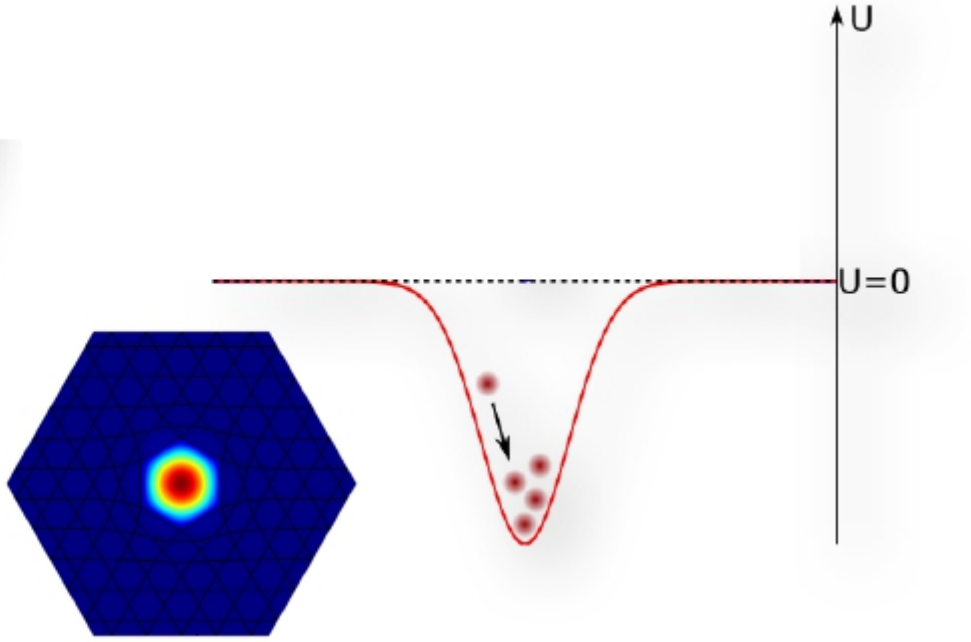
OD: 26
N_A: 5×10^4

Langbecker *et al* PRA **96**, 041402 (2017)
Institut für Physik,
Johannes Gutenberg-Universität

Cold Atoms in Fibre Set-Up

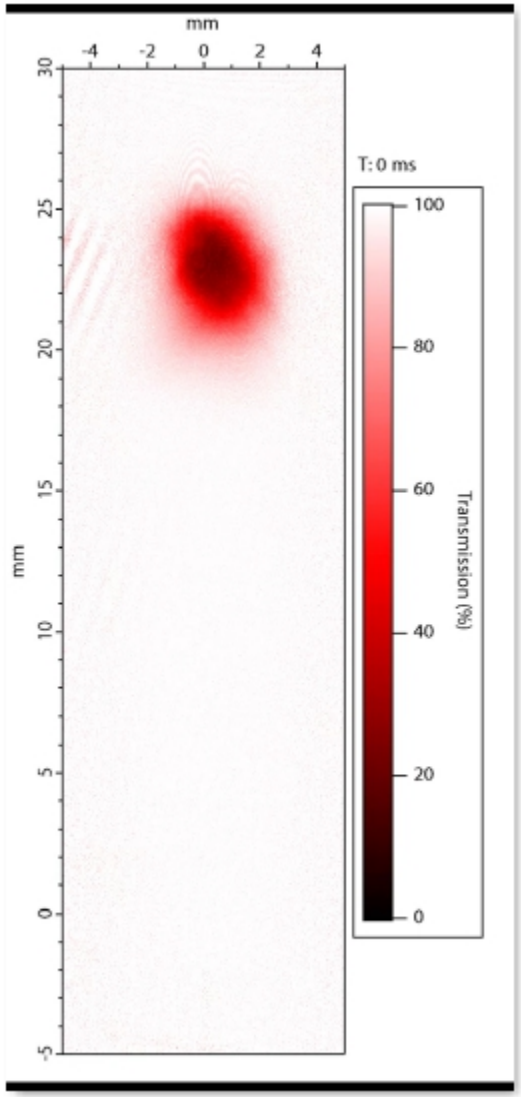






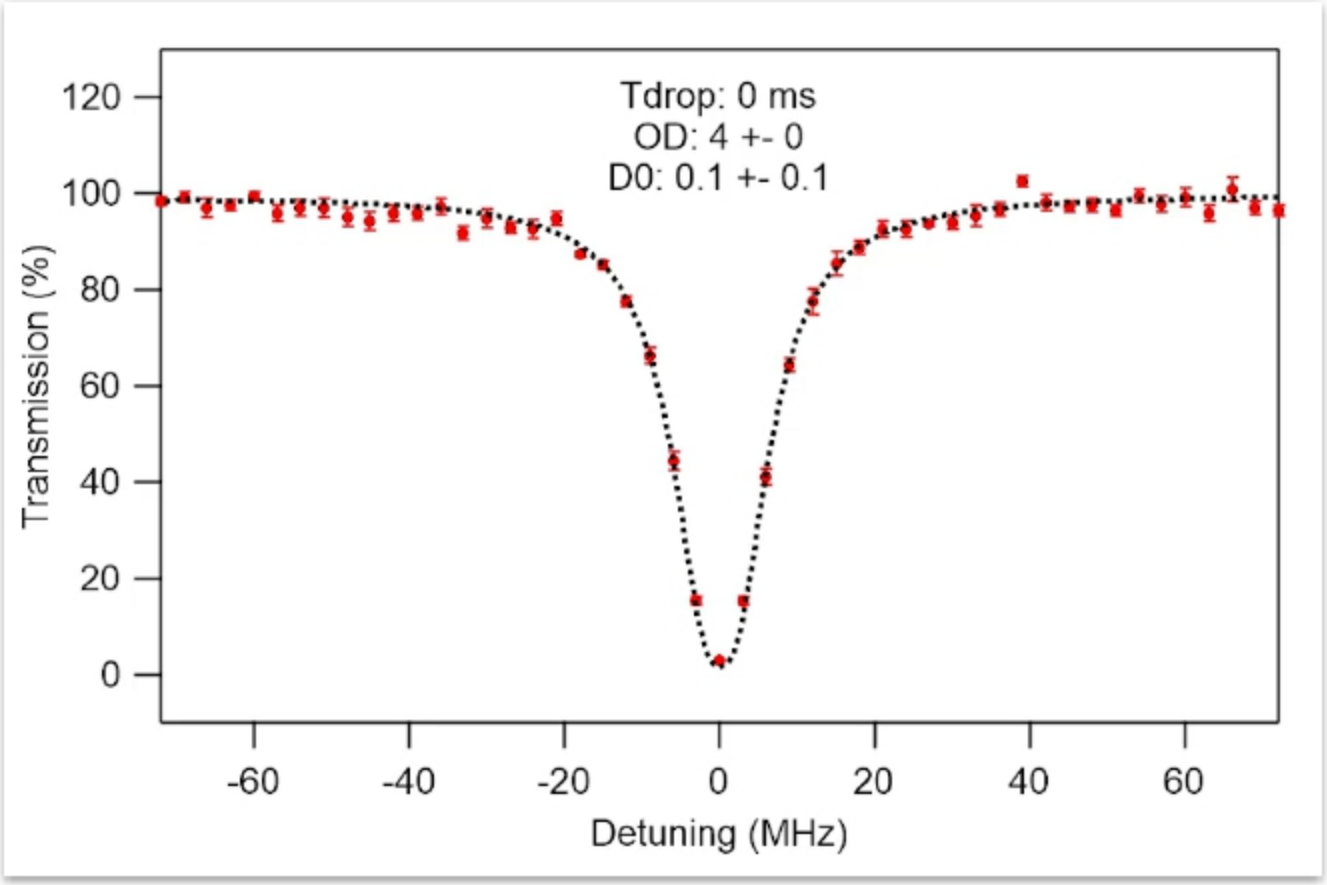
Hilton *et al.*, Physical Review Applied **10**, 044034 (2018)

Cold Atoms in Fibre Loading



Hilton *et al.*, Physical Review Applied **10**, 044034 (2018)

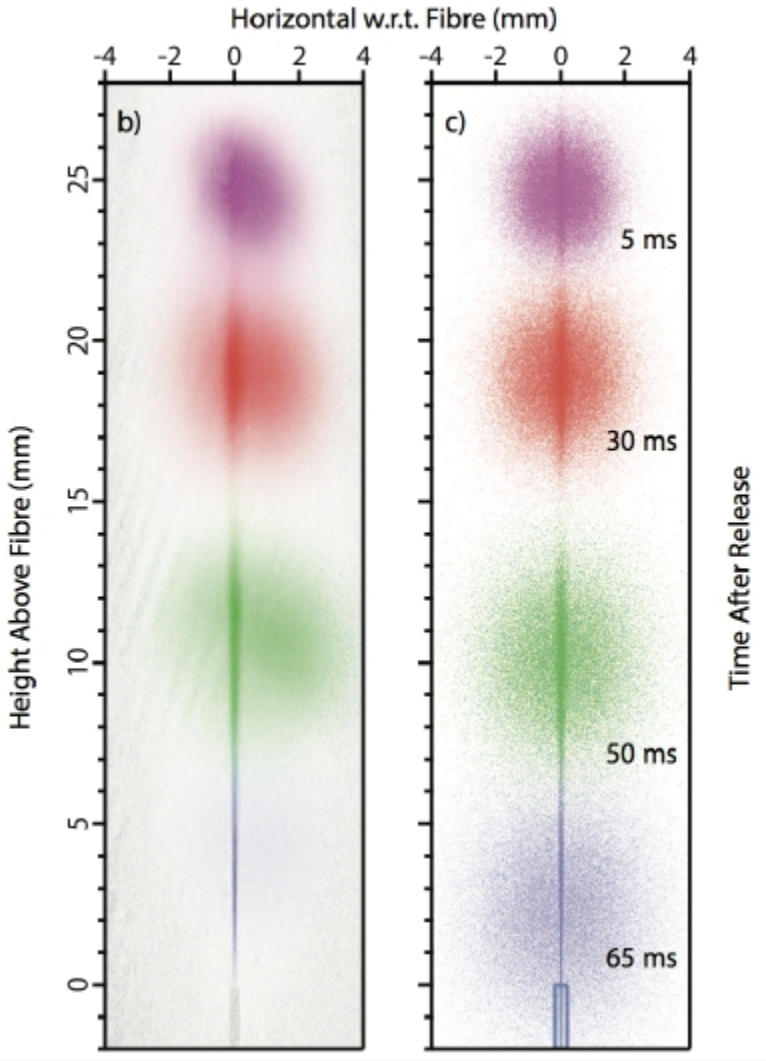
Cold Atoms in Fibre Absorption

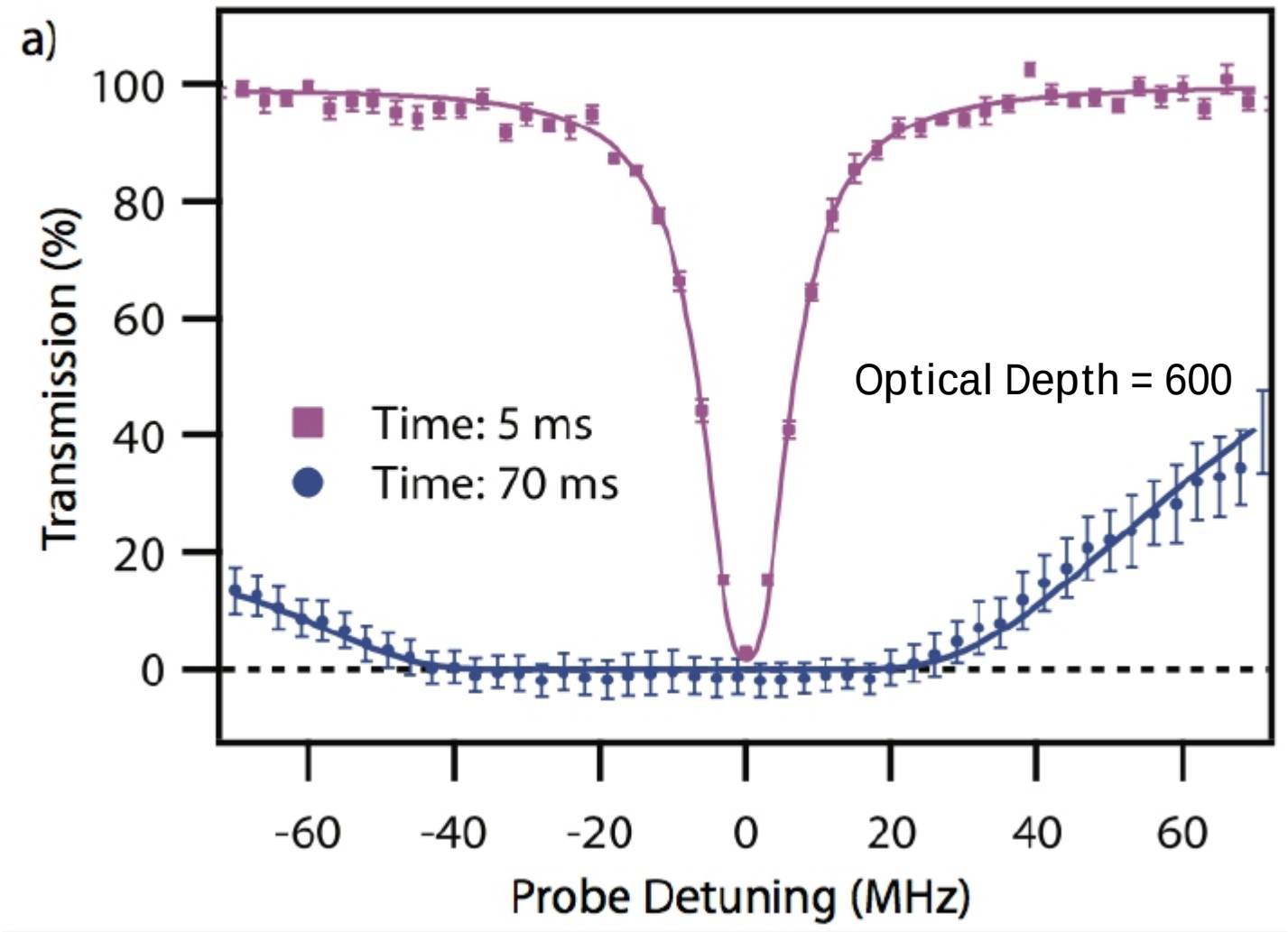


Peak OD = 600

Hilton *et al.*, Physical Review Applied **10**, 044034 (2018)

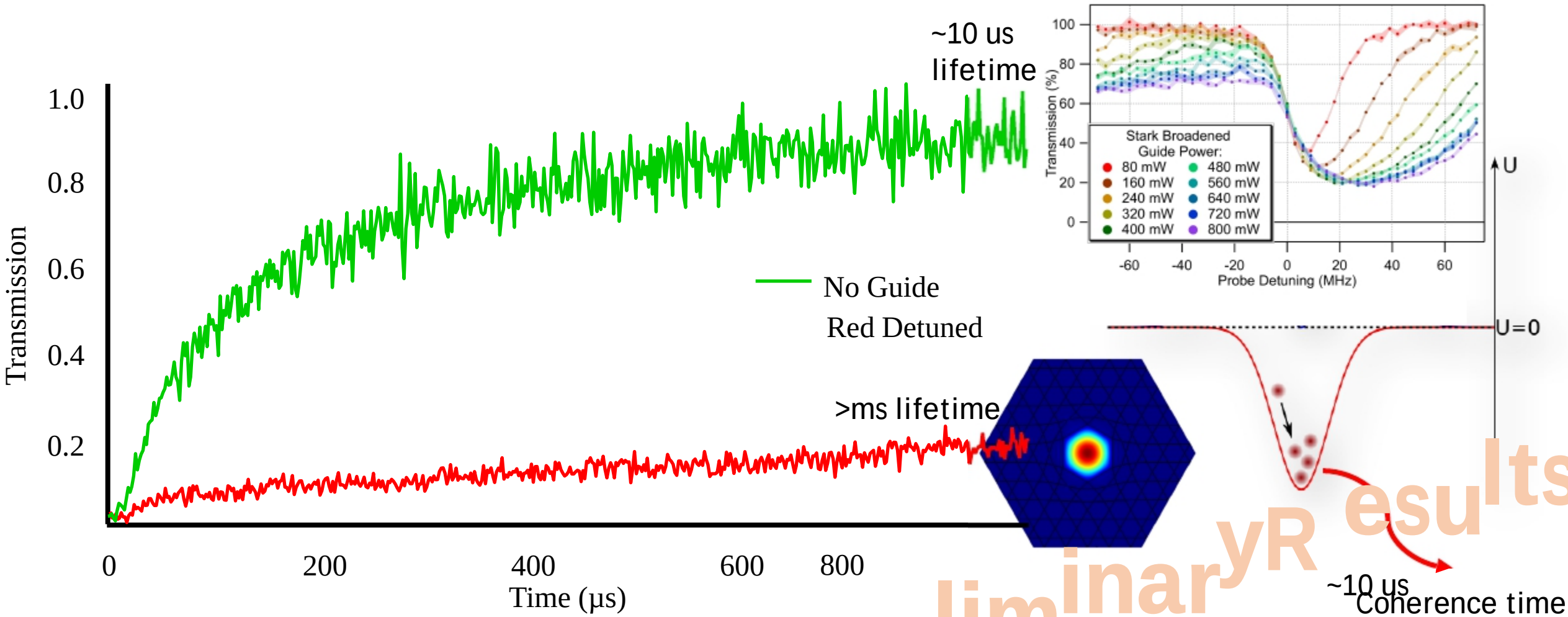
Cold Atoms in Fibre Absorption





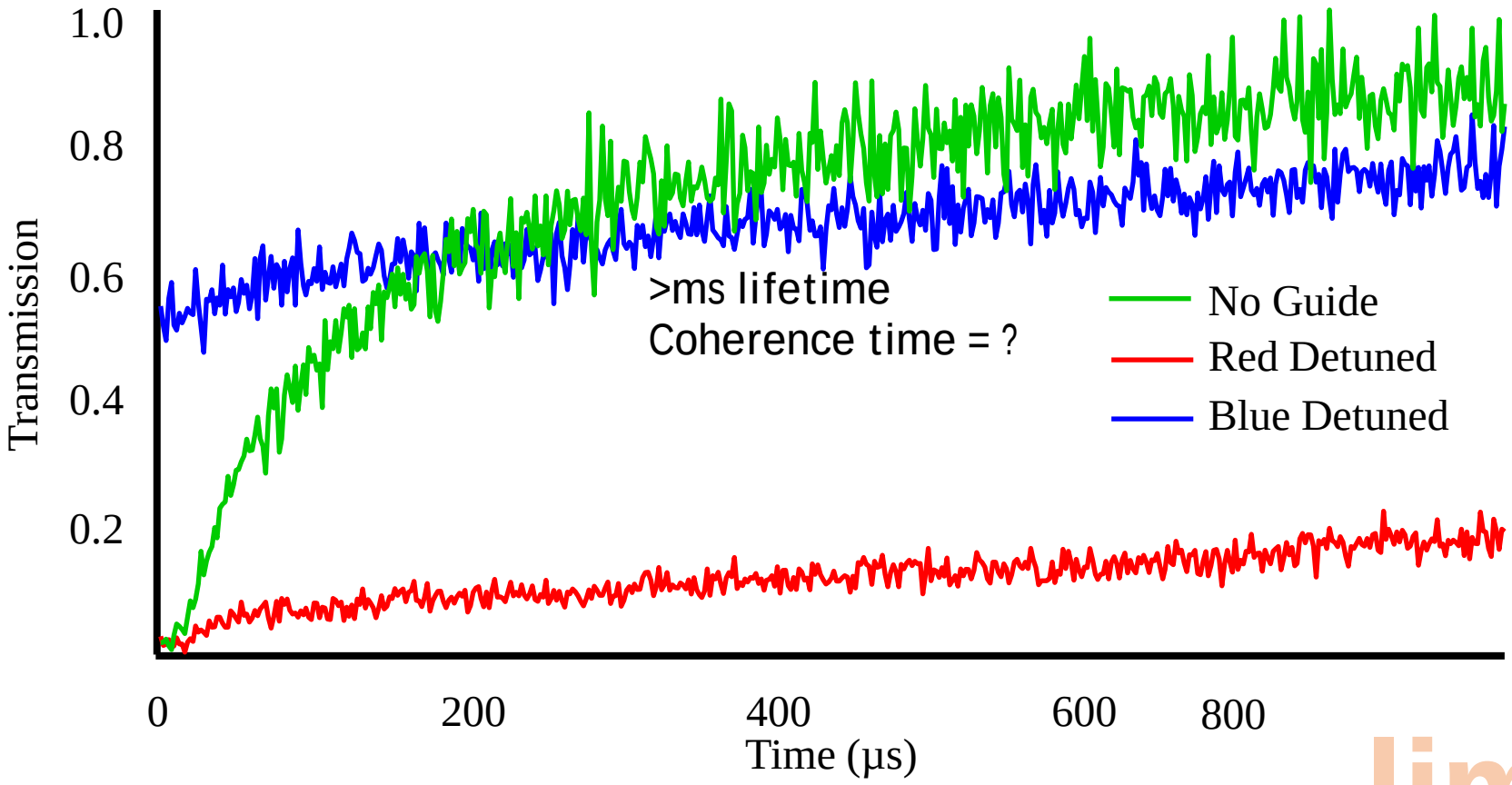
Hilton *et al.*, Physical Review Applied **10**, 044034 (2018)

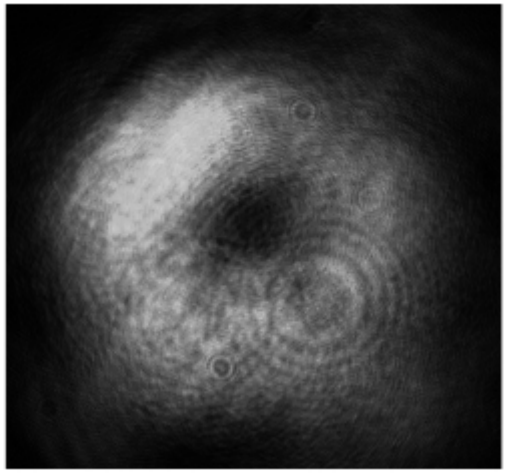
Long-Lived Cold Atoms in Fibre?



Hilton *et al.*, Physical Review Applied **11**, 024065 (2019)

Long-Lived Cold Atoms in Fibre?

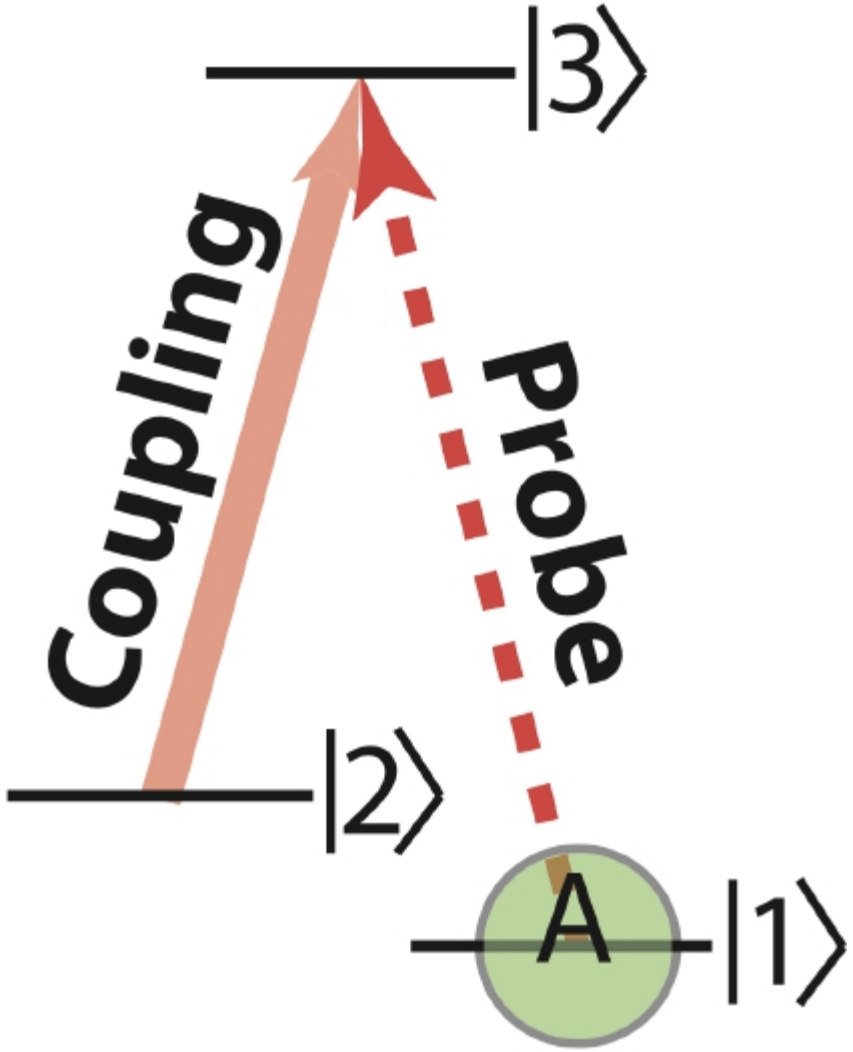


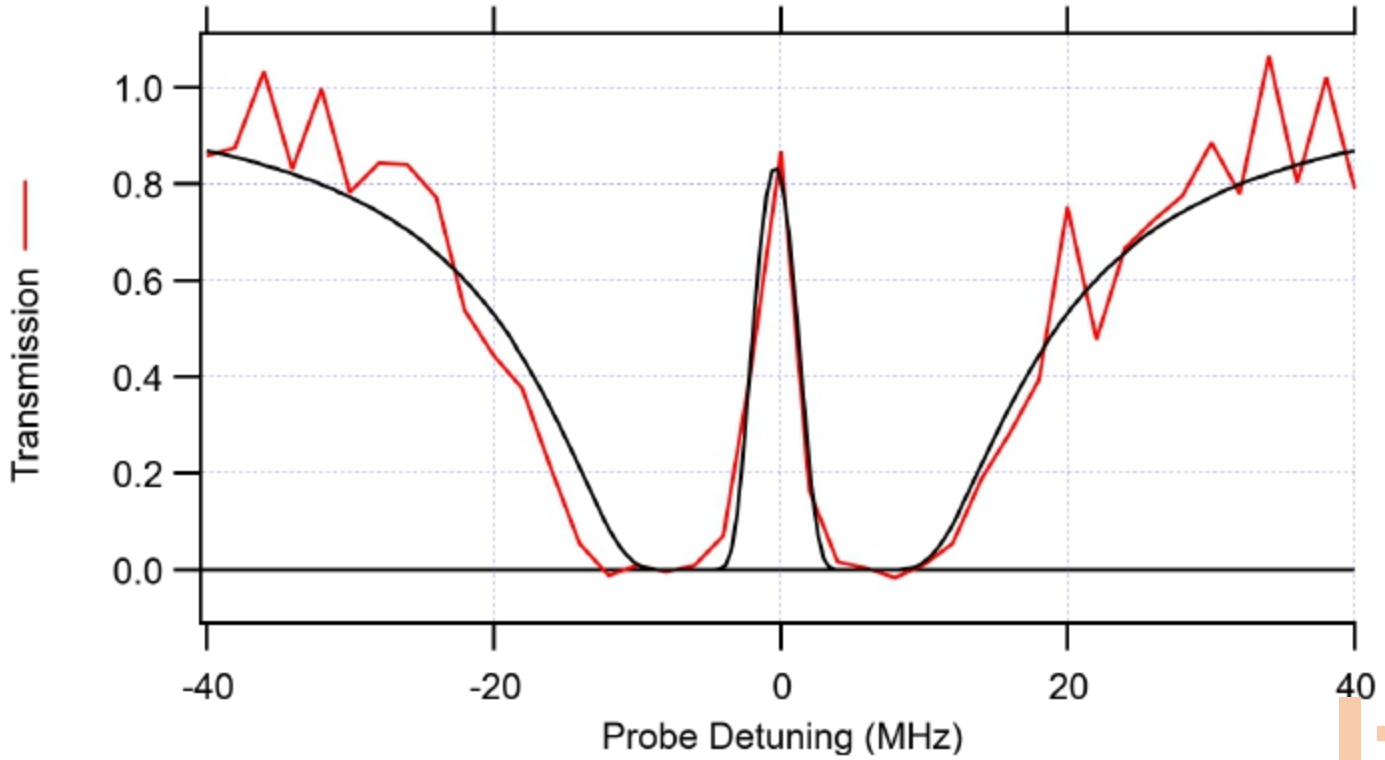


Dipole beam through HCF
(50% coupling efficiency)

Preliminary results

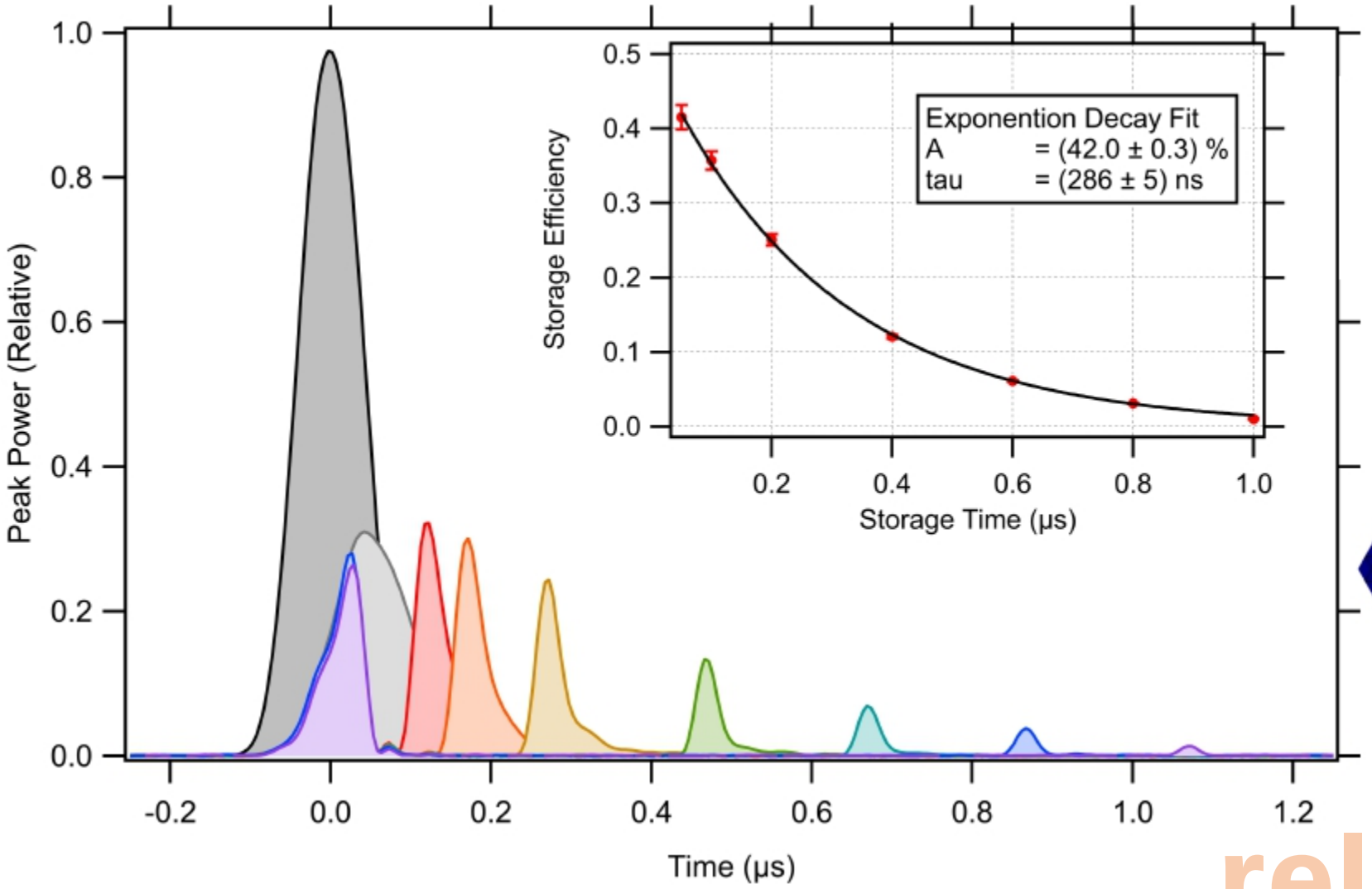
Measuring Coherence - EIT

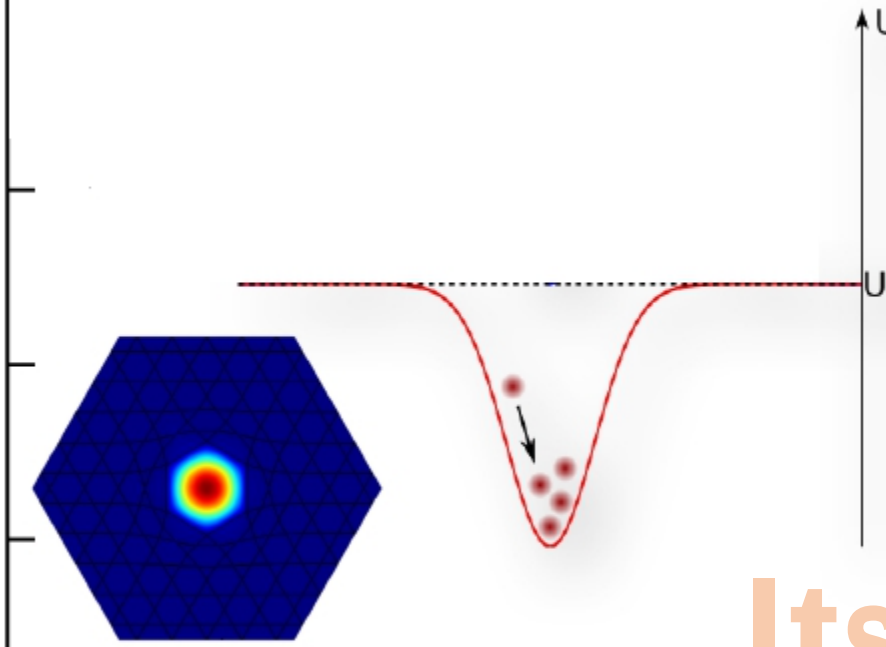




Preliminary Results

Coherence Measurement



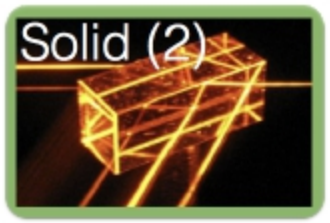


Preliminary Results

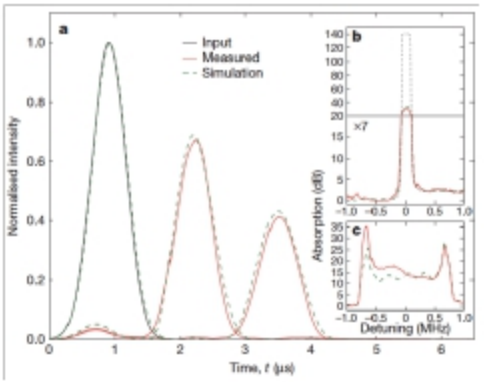
Future Work: Efficient Cold Atom Quantum Memory

- Gradient Echo Memory – efficient (87%), noise-free, flexible

Hosseini *et al*,Nature Physics 7,794 (2011);
Nature 461,241 (2009)

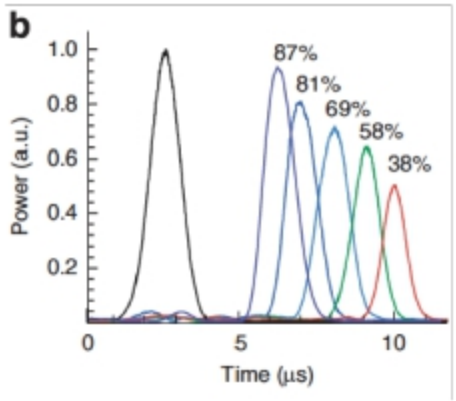


73%

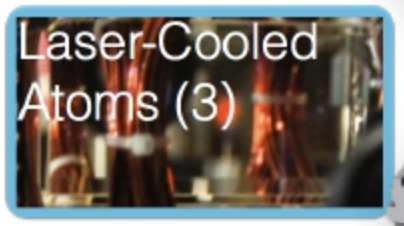


Hedges *et al*, Nature **465**, 1052 (2010)

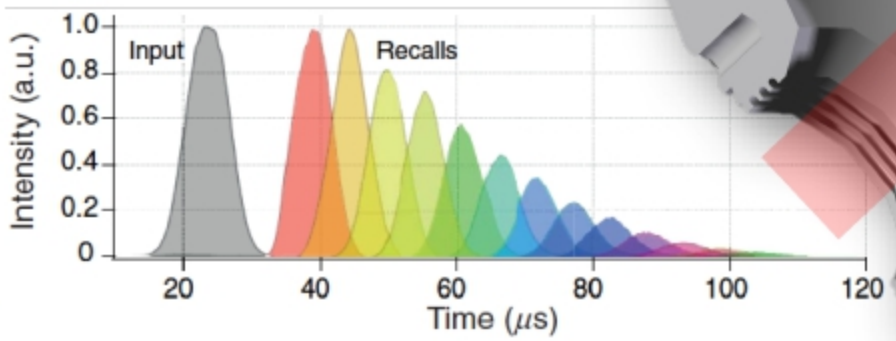
87%



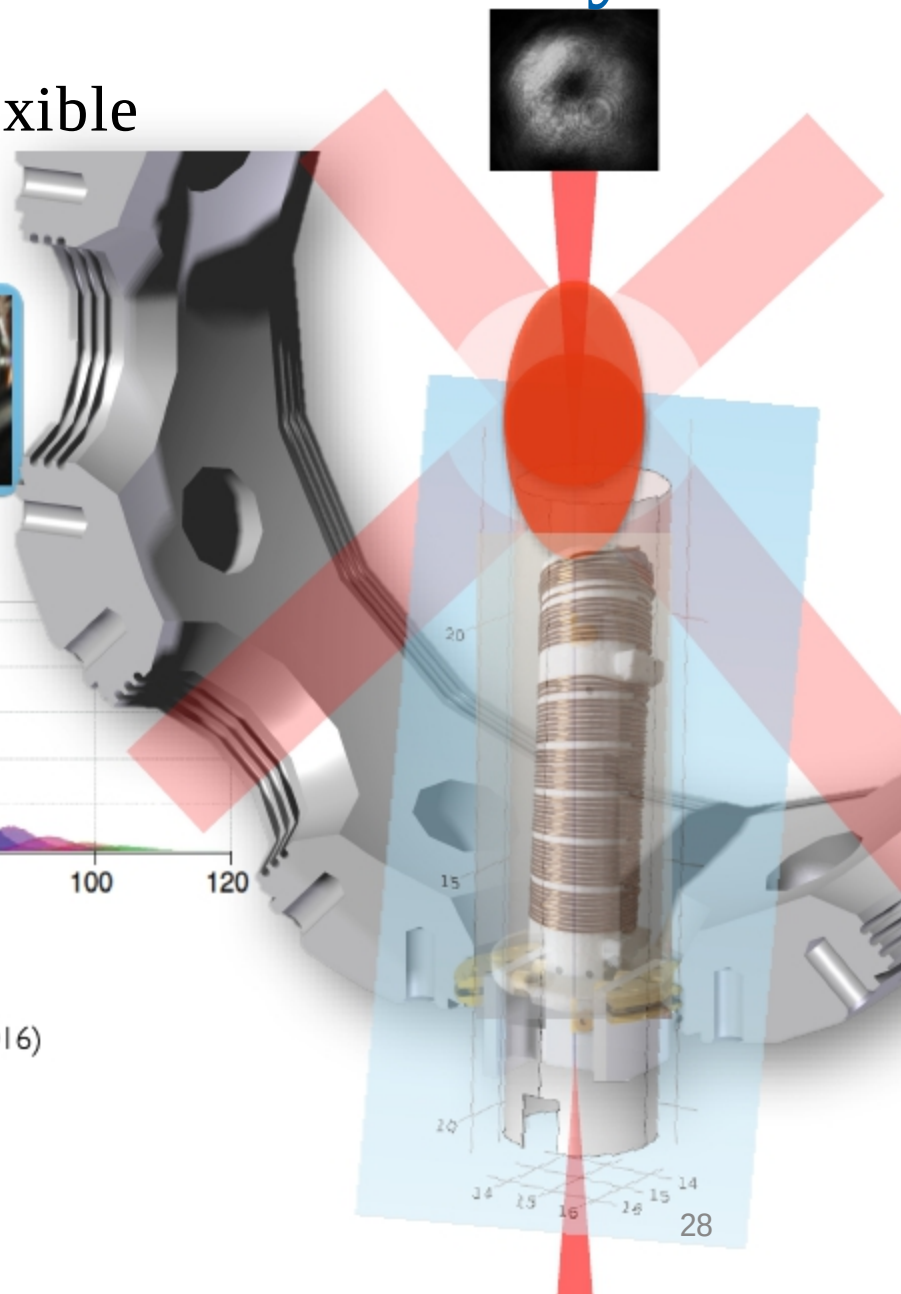
Hosseini *et al*, Nature Commun **2**, 174 (2011)



87%

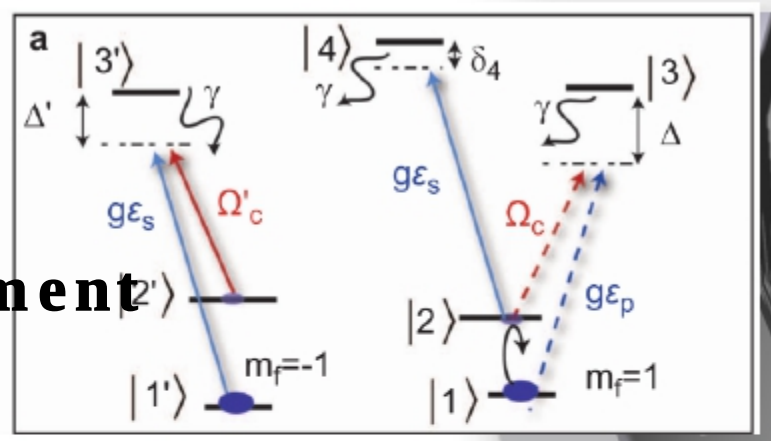


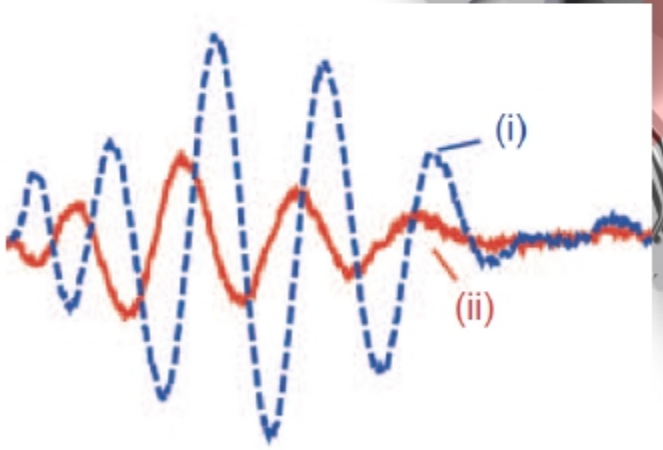
Cho *et al*, Optica **3**, 100 (2016)

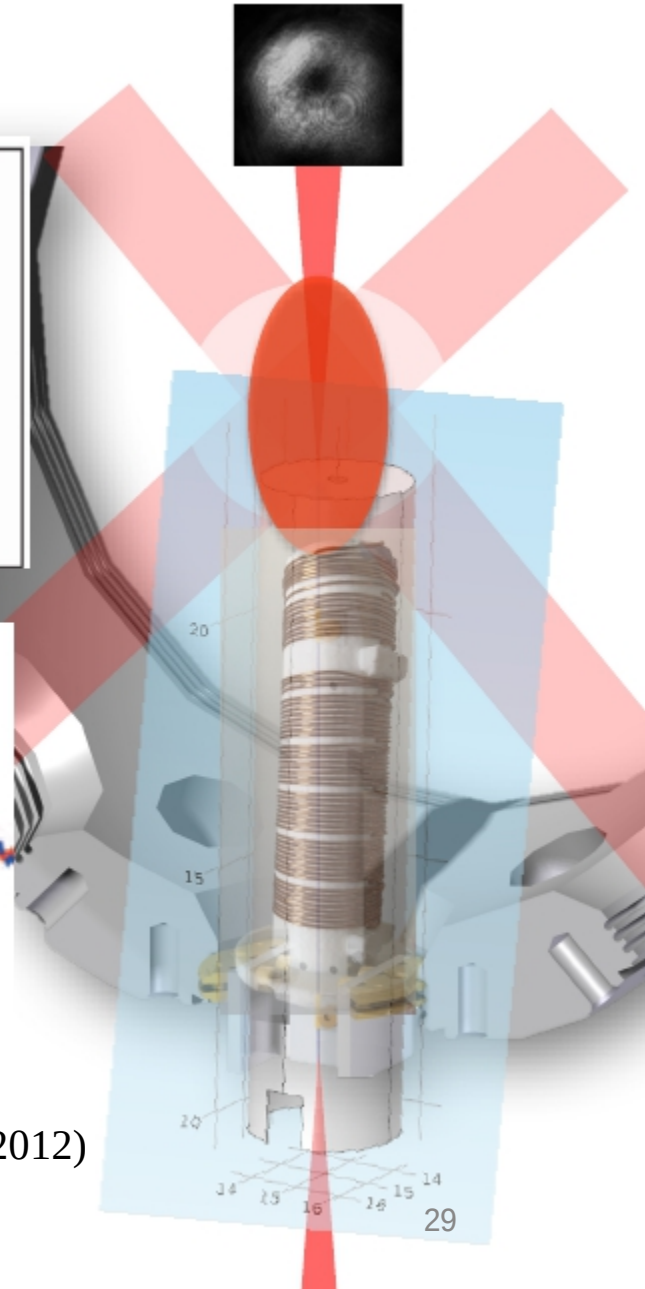


Future Work: Two-Photon Gate in QM

- Previous work: 10^{-12} rad/photon
- **Hollow-core fibre: 10^{6} improvement**
- Cold Atoms: 10^{2} improvement
- Storage (500 ns): 10^{2} improvement
- Expect 10 mrad/photon shifts
  - Sufficient for parity/phase gates





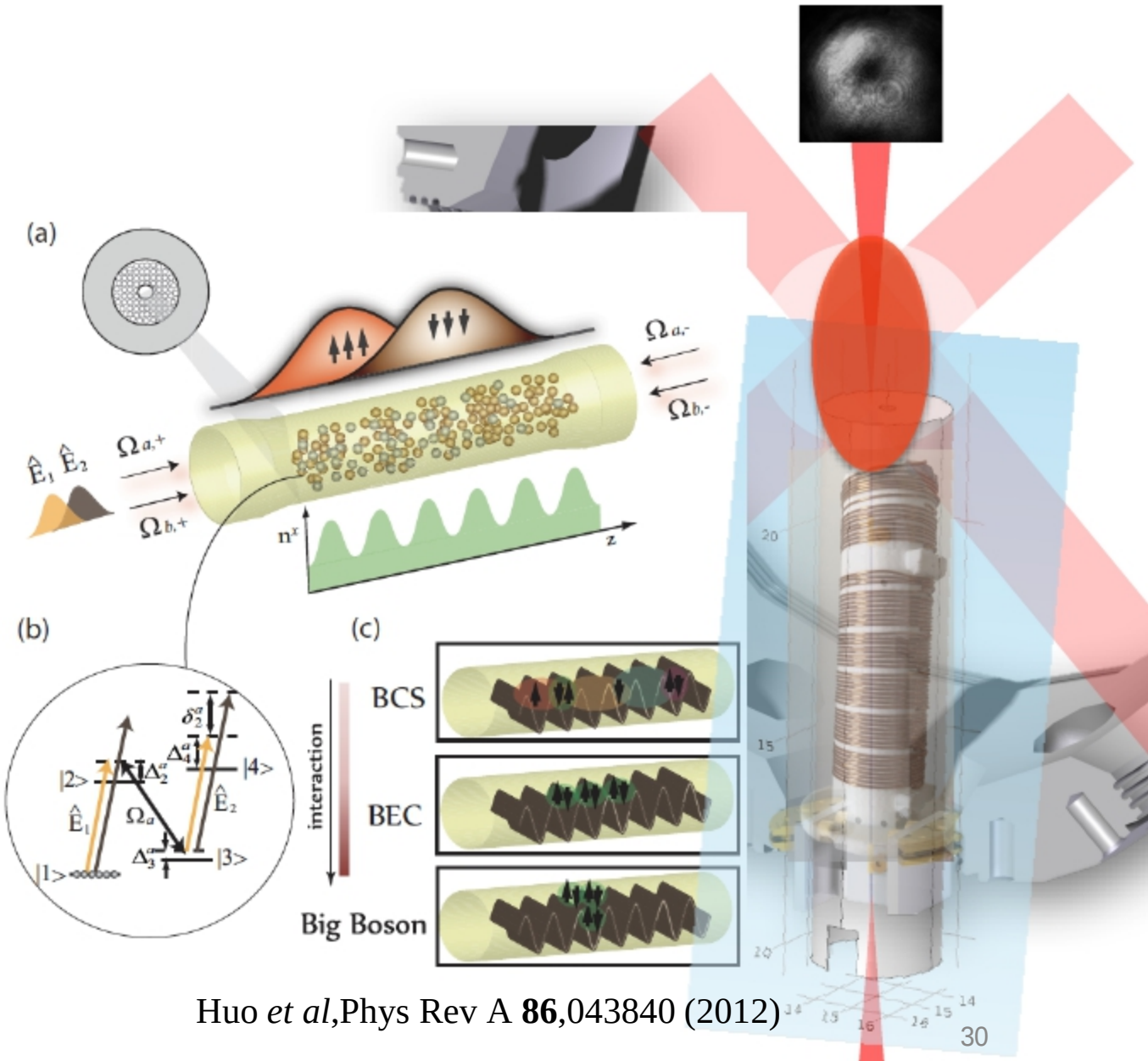


Hosseini *et al*,Light:Sci & App **1**,e40 (2012)

Future Work: Quantum Simulation with Photons

- Strongly-interaction stationary photonic qubits

- Benefits: Scalable, flexible and easy to read out



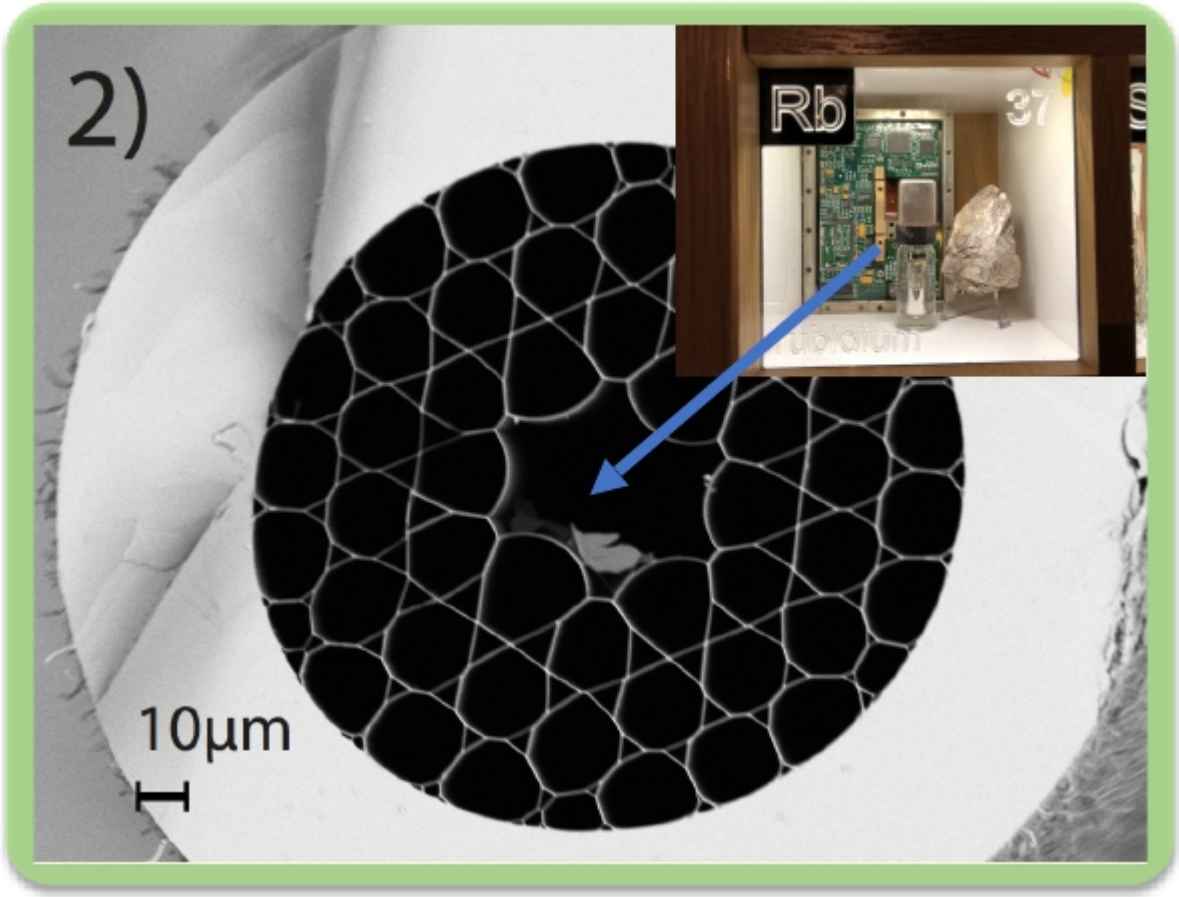
Huo *et al*,Phys Rev A **86**,043840 (2012)

Conclusions

- Warm Atoms into Hollow-Core Fibres:
  - *GHz Bandwidth, Room Temperature*
  - *~50% efficiency*
  - *20 ns coherence time (need to increase)*

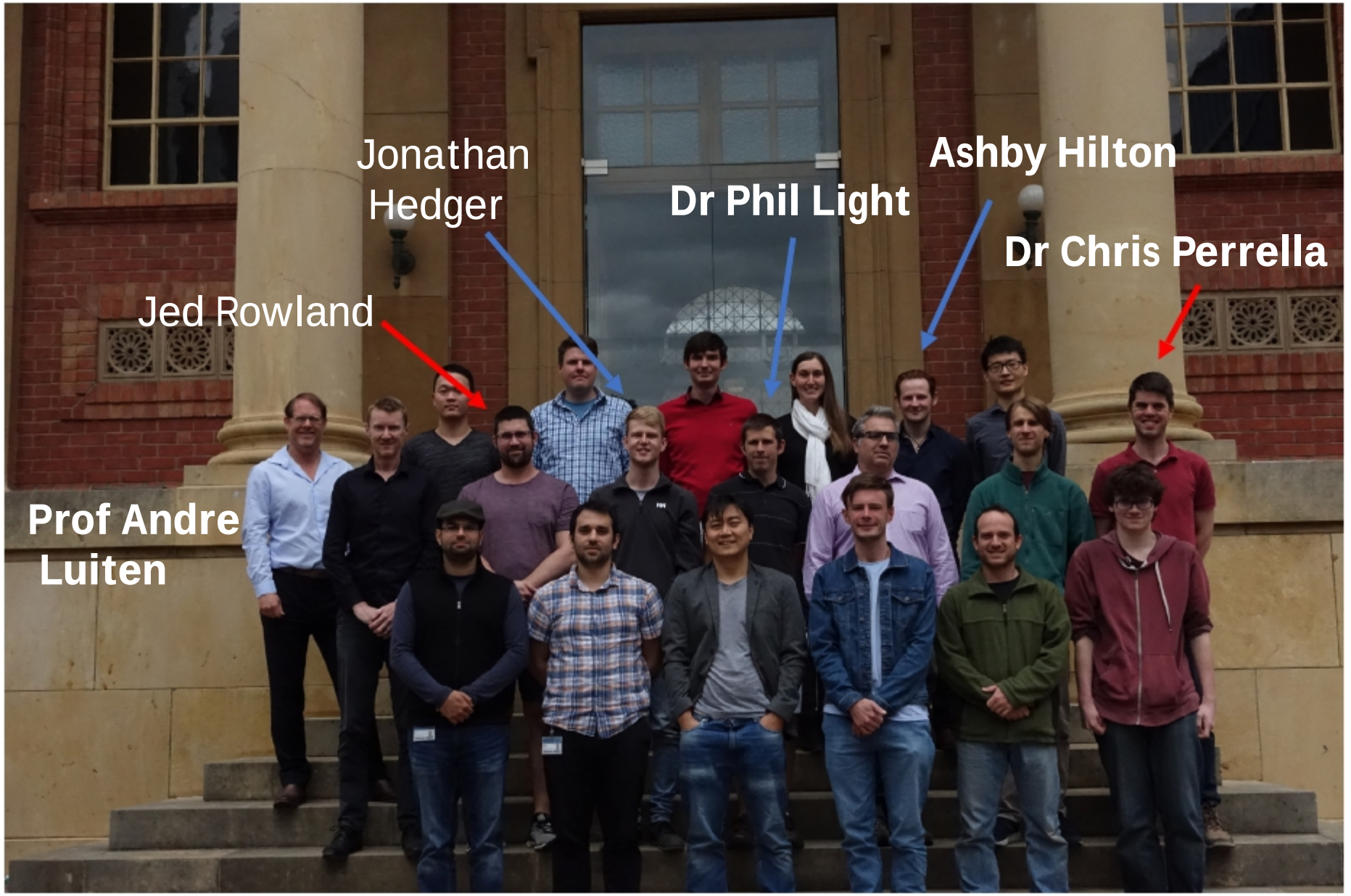
- Cold Atoms into Hollow-Core Fibres:
  - *Large Absorption in Gaussian trap (OD ~ 600)*
  - *Now: Coherence Measurements*

- Next Steps:
  - *Quantum Memory (GEM) in Hollow Trap*
  - *Extreme Atom-Light Interactions*
  - *Quantum Simulations*



Hilton *et al.*, Physical Review Applied **10**, 044034 (2018)

Thanks!



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