

Roadmap for rare-earth quantum computing

Kinos et al, [arXiv:2103.15743](https://arxiv.org/abs/2103.15743) (2021)

Collaboration (SQUARE):

Lund, Karlsruhe, Paris, Aarhus, Barcelona, Stuttgart, Thales, Attocube

Background

Many combinations of rare-earth ions + hosts:

- Eu for long coherence times
- Er for telecom wavelength
- Pr for gates (simplicity)
- Yb, Nd, Ce, Er for single ion detection

For QC, one single system is needed

... but can still make use of multiple species for different roles!



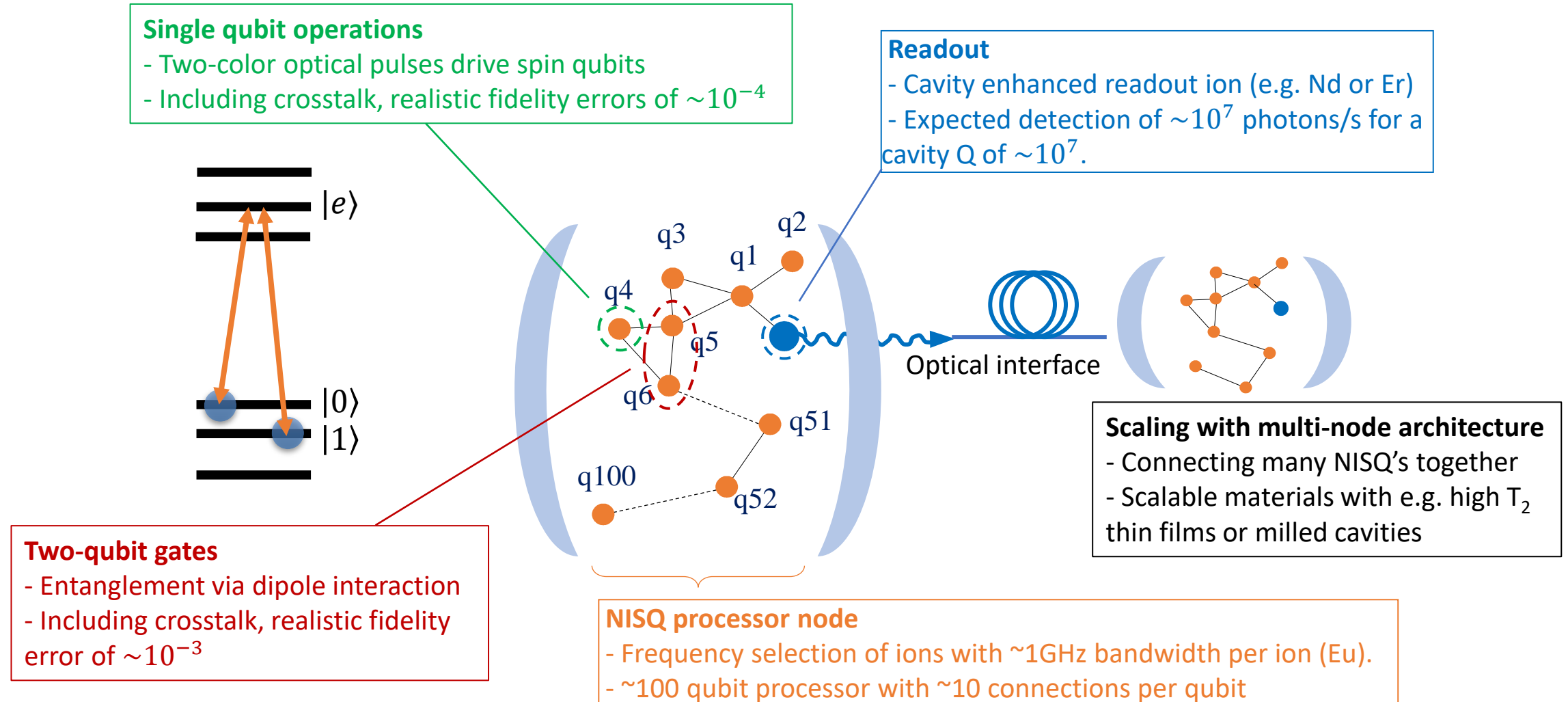
Purpose

- Describe *one* complete REQC
- Analyze strength/weaknesses
- Identify path(s) forward

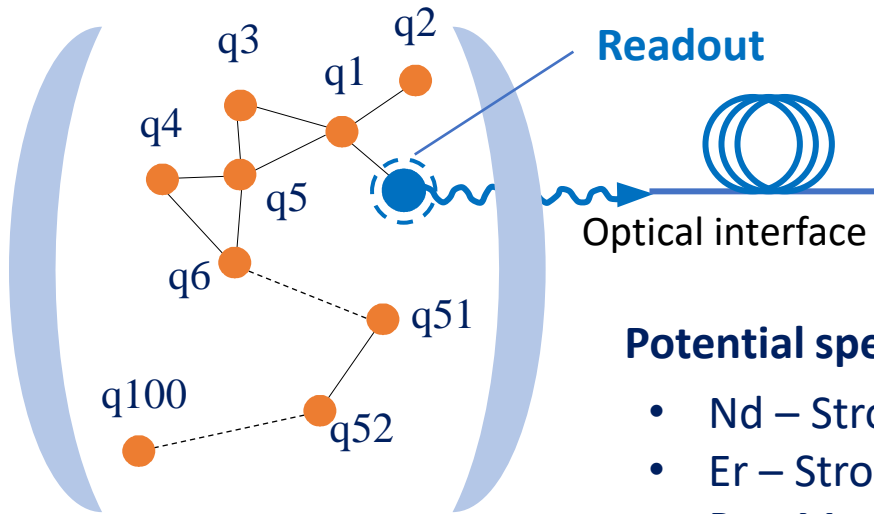
Goals

- Give numbers for current estimates
- Act as reference work for future upgrades
- May allow more focused progress

Roadmap for REQC – Overview



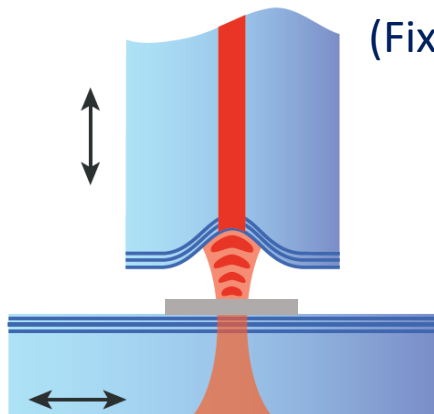
Roadmap for REQC – Readout



Potential species:

- Nd – Strong signal
- Er – Strong signal, telecom wavelength
- Pr – Moderate signal, no electron spin

Purcell enhancement by micro-cavity



(Fixed nano-beams/WGM disc/scanning open)

Advantages:

- Can use different spatial locations
- Material/wavelength versatility

Main challenge:

- More sensitive to vibrations

Readout duration and fidelity

- cavity Q of $\sim 10^6 - 10^7$ (Nd and Er)
- Mode volume $\sim 1 - 10 \lambda^3$

Najer et al, Nature 575, 622 (2019)

→ $\sim 10^7$ photons/s, $T_{1,enh} \sim 100$ ns

- Bayesian method uses each detector click

Debnath et al, PRA 103, 043705 (2021)

→ Fid $\sim 95\%$ after $10 \mu\text{s}$

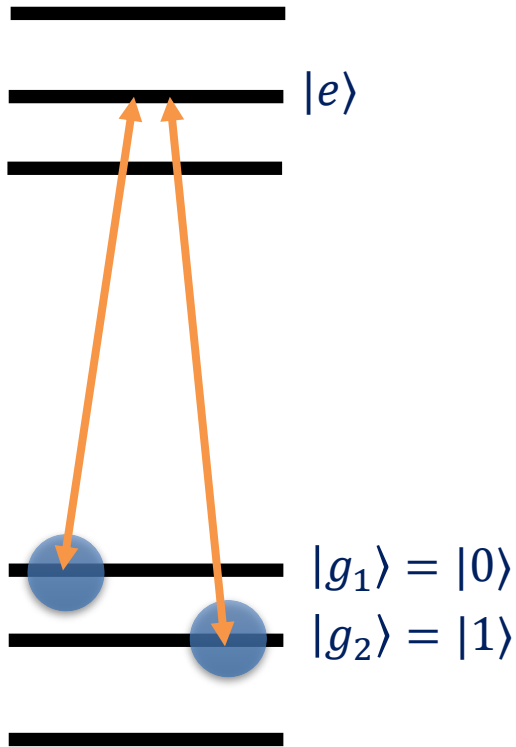
limited by excited state decay (2 ms)

- Use one qubit as buffer stage, 3 times

Walther et al, PRA 92, 022319 (2015)

→ Fid $\sim 99.9\%$ after $40 \mu\text{s}$

Roadmap for REQC – Single qubit operations

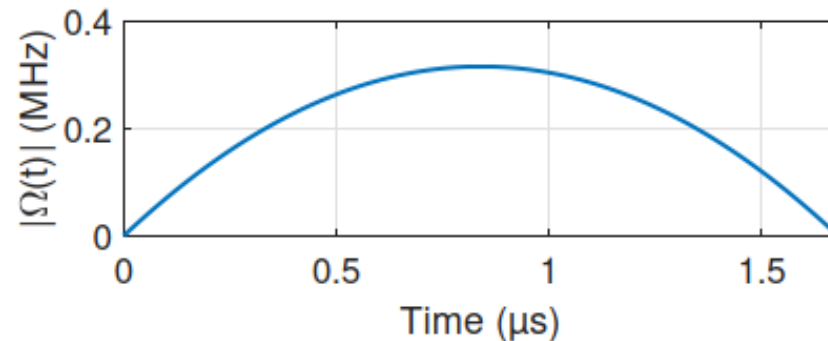


High fidelity required for quantum error correction

Challenges

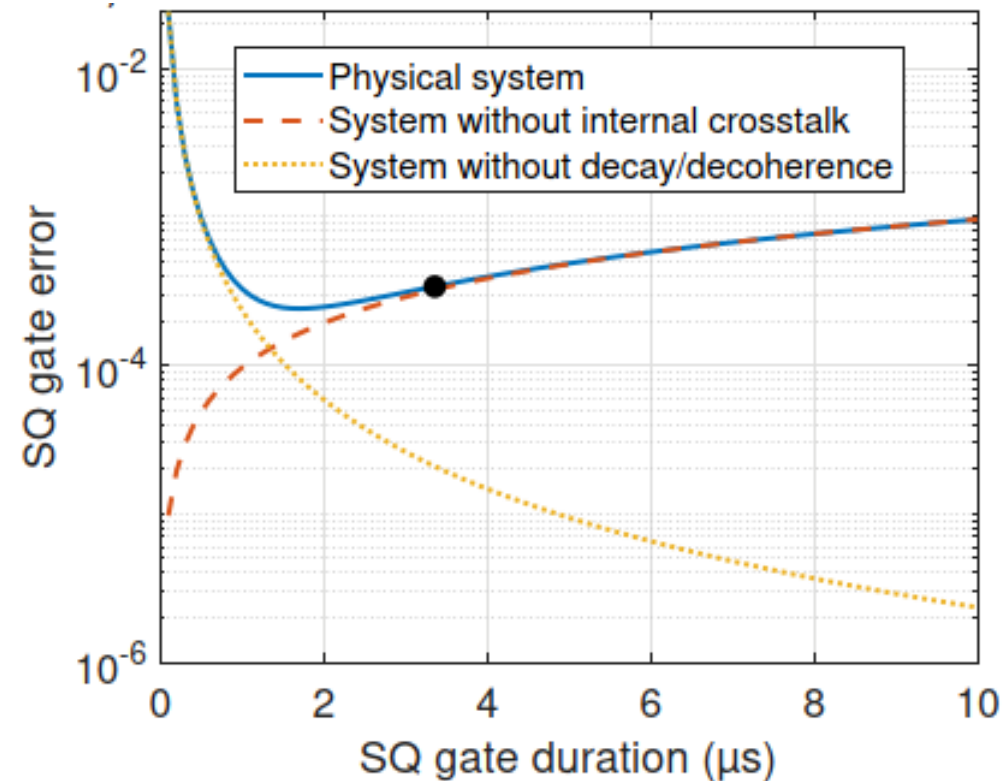
- Short pulse to avoid decay
 - High bandwidth
- Avoiding overlap with other levels (internal crosstalk)
- Avoid exciting other frequencies (external crosstalk)
- Built in robustness?
 - Not needed if carefully calibrated

Cut Gaussian:



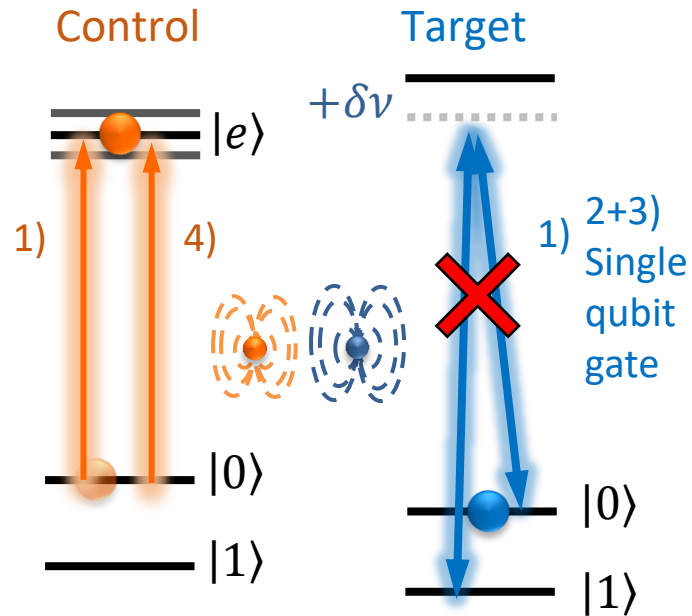
Simulations results

- Eu:YSO
- Including all crosstalk channels
- Adam Kinos (manuscript in preparation)



Roadmap for REQC – Two qubit operations

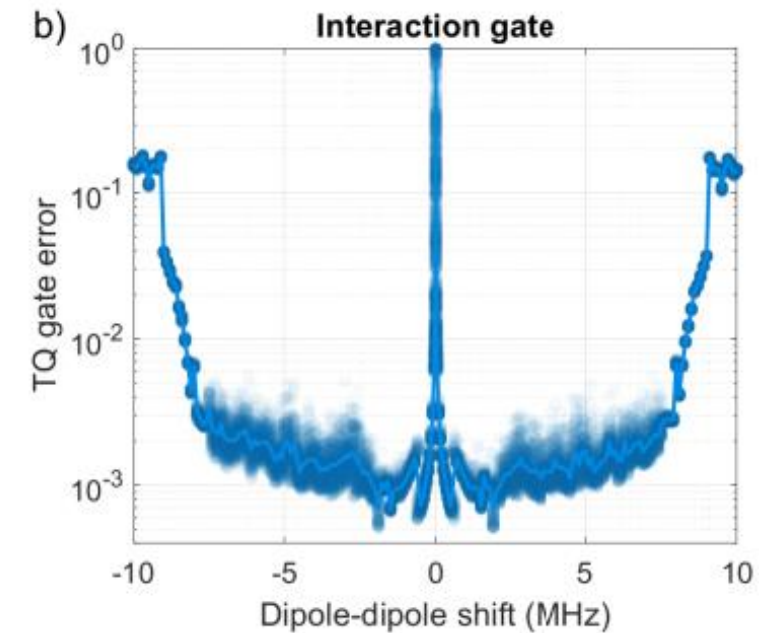
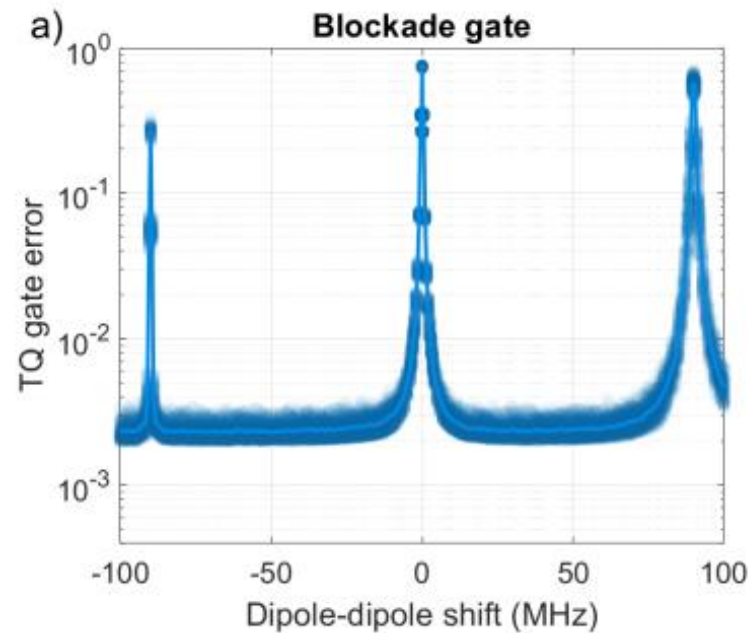
Dipole ion-ion interactions:



- Blockade gate
- Interaction gate
simultaneous excitation +
wait time
= conditional phase shift on ee

Simulations results

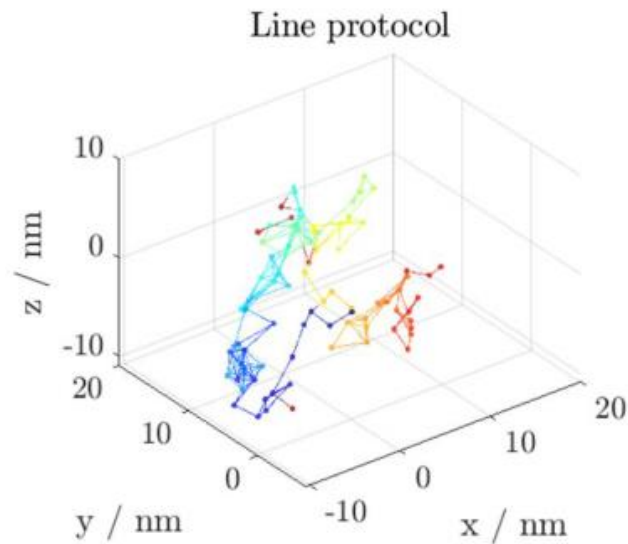
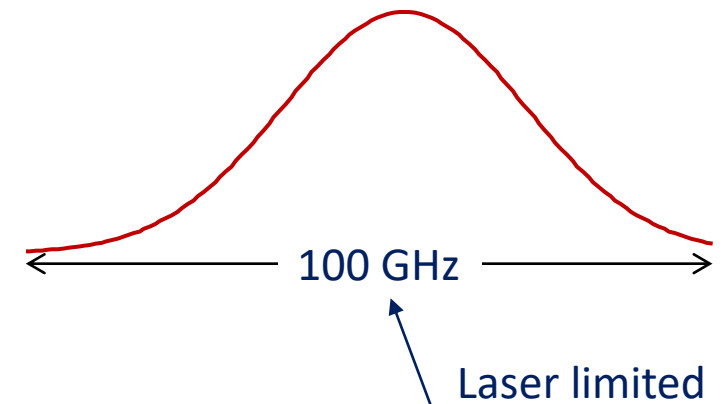
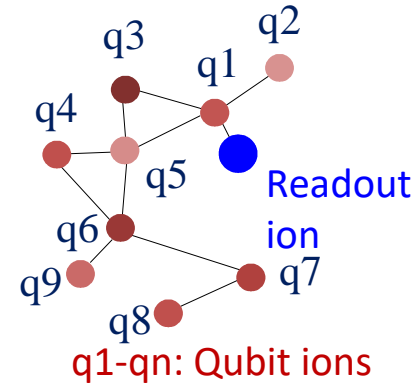
- Eu:YSO
- Including all crosstalk channels
- Adam Kinos (manuscript in preparation)
- Bandwidth usage per qubit ~ 1 GHz (Eu)



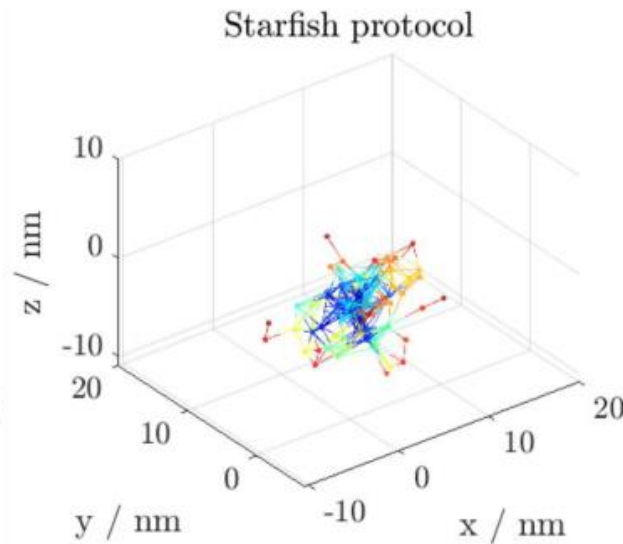
Shift scales as $\frac{1}{r^3} \rightarrow r \sim 2 - 10$ nm

Roadmap for REQC – NISQ processor node

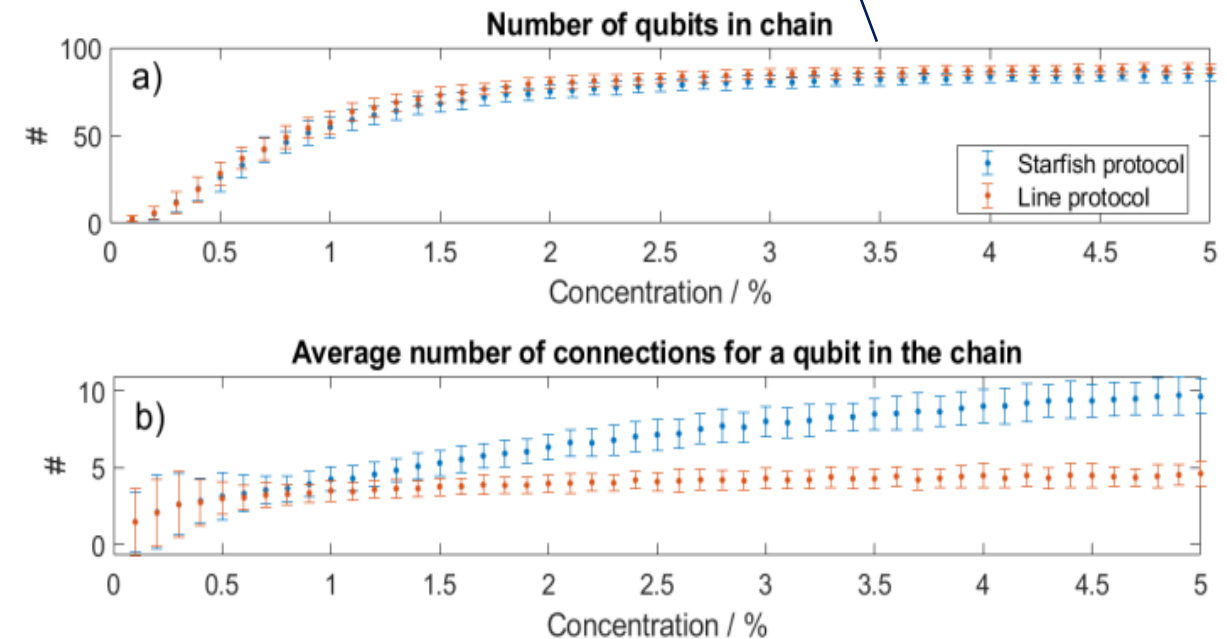
- Use dipole interaction to map out controlling ions
- Search qubit channels to switch off fluorescence
- Remove overlapping channels (optical pumping)
- Two search paths (Kinos, manuscript in prep):



Always switch off the previous qubit

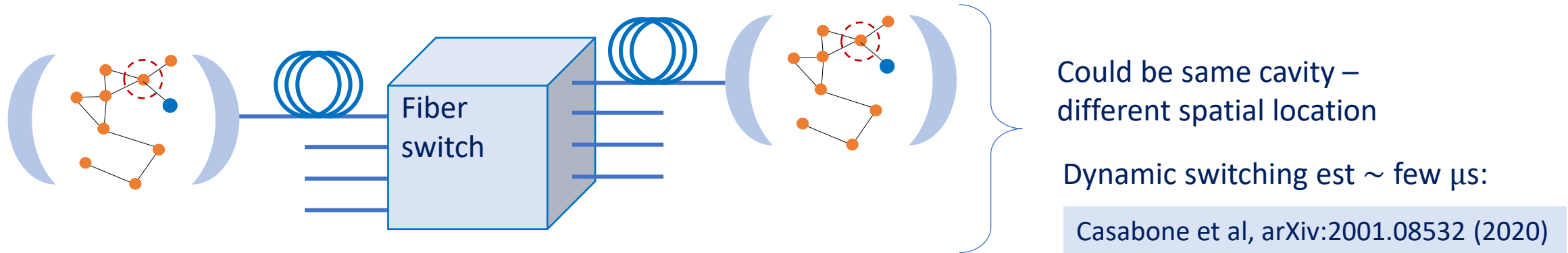


Exhaust switch-off on the first qubit



Early results – Interaction gates should increase this!

Roadmap for REQC – Connecting multiple nodes



Main idea:

- Best protocol still under investigation
- Share ideas with many other platforms for QC
- Closest ions in each NISQ node entangled

Debnath et al, PRA 103, 043705 (2021)

- Distillation ensures high fidelity
- Entanglement within nodes by gates

Optical integration a strength of the RE platform

- Many wavelengths, including telecom
- Nano-structures allow efficient coupling
- Nano-structures may allow integrated photonics

→ polished down bulk crystals ensures long T_2

Merkel et al, PRX 10, 041025 (2020)

Still many ideas to improve all components
– Now the improvements have a context



Thank you for your attention!

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