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Vocalist & Multi-Instrumentalist

6TH ANNUAL Q4I WORKSHOP | JUNE 25-27 | ROME, NY

Q4I

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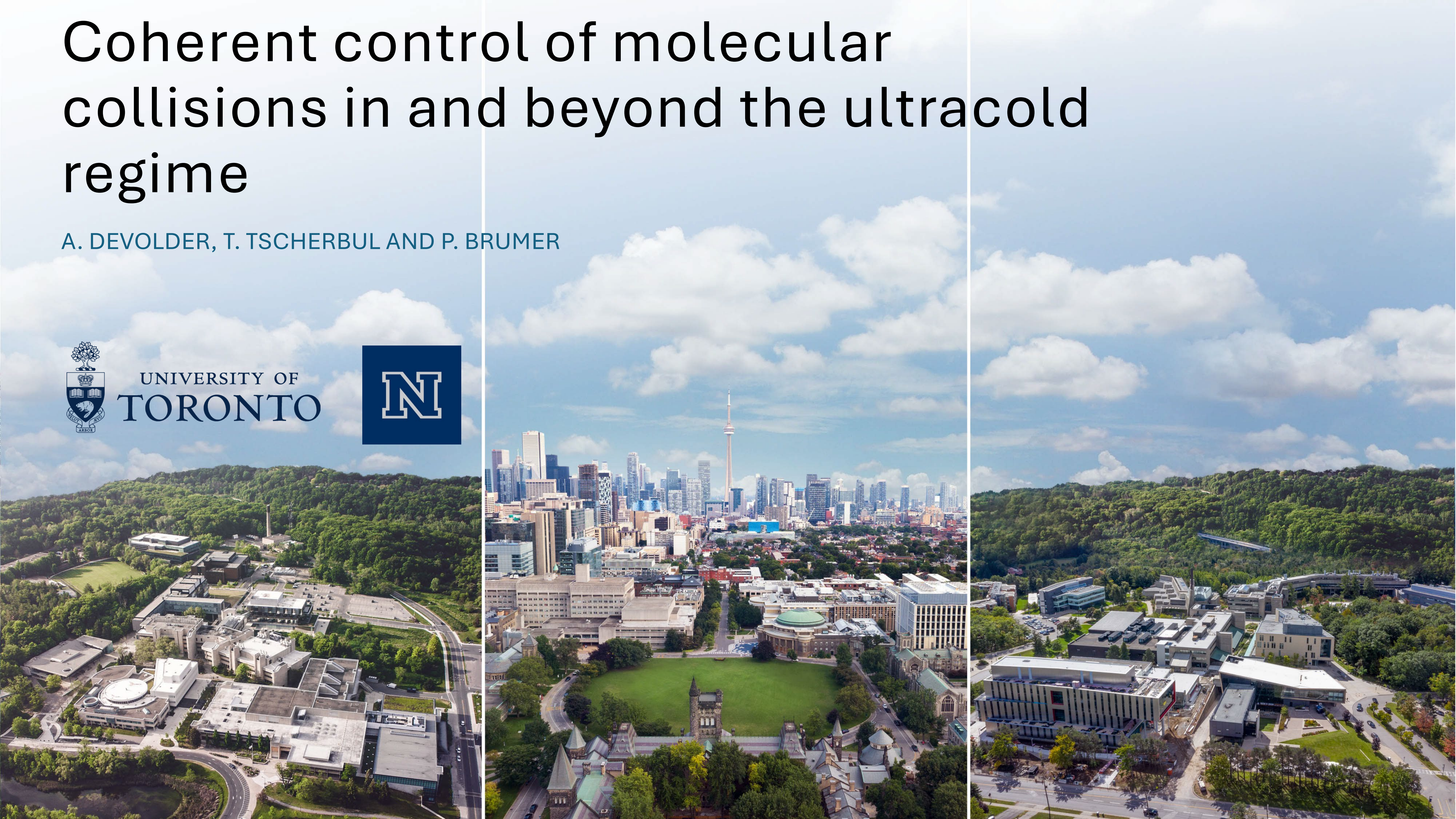
Coherent control of molecular collisions in and beyond the ultracold regime

A. DEVOLDER, T. TSCHERBUL AND P. BRUMER

UNIVERSITY OF TORONTO



Why controlling collisions?

Suppressing collisional decoherence for quantum computing/simulation

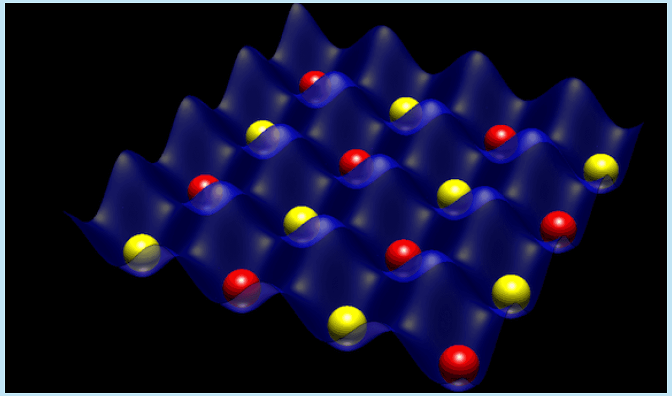


Figure from T. Porto “Cold Atoms in Optical Lattices”

Suppressing errors in precision measurement

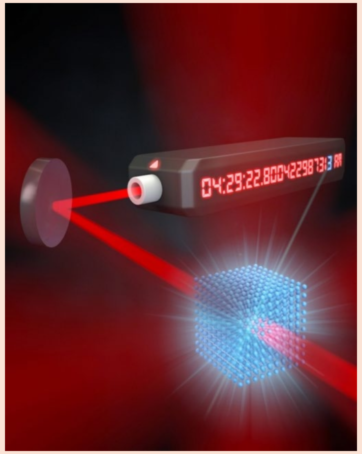


Figure from S.L. Campbell , Science, 358, 6359 (2017)

Improving the cooling of atoms/ions/molecules

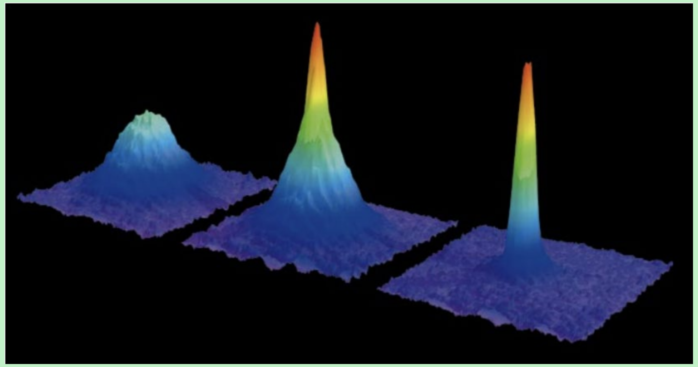


Figure from W. Keterlee, RMP,, 562, 74, 1131-1151 (2002)

Optimizing the reaction yields

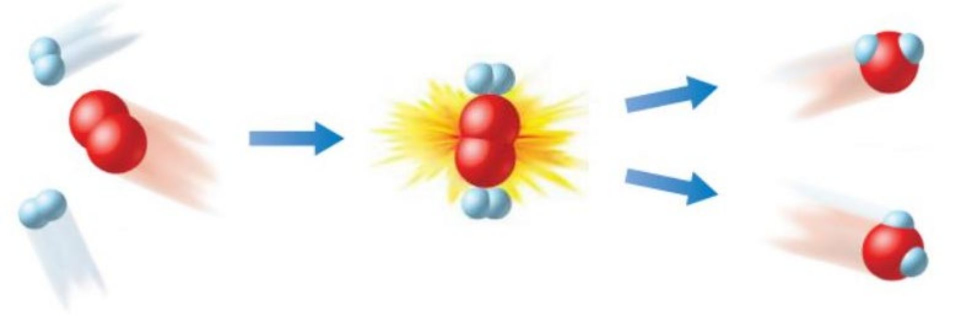


Figure from Wong Hsiung “Rate of reaction”

Collisions in quantum framework

Internal states of colliding particles (electronic, vibrational, rotational, spin states etc ...)

relative rotation of colliding particles (initial partial wave)

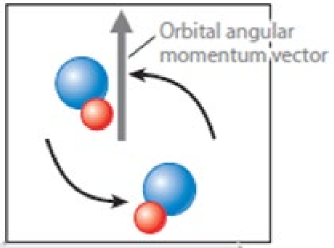
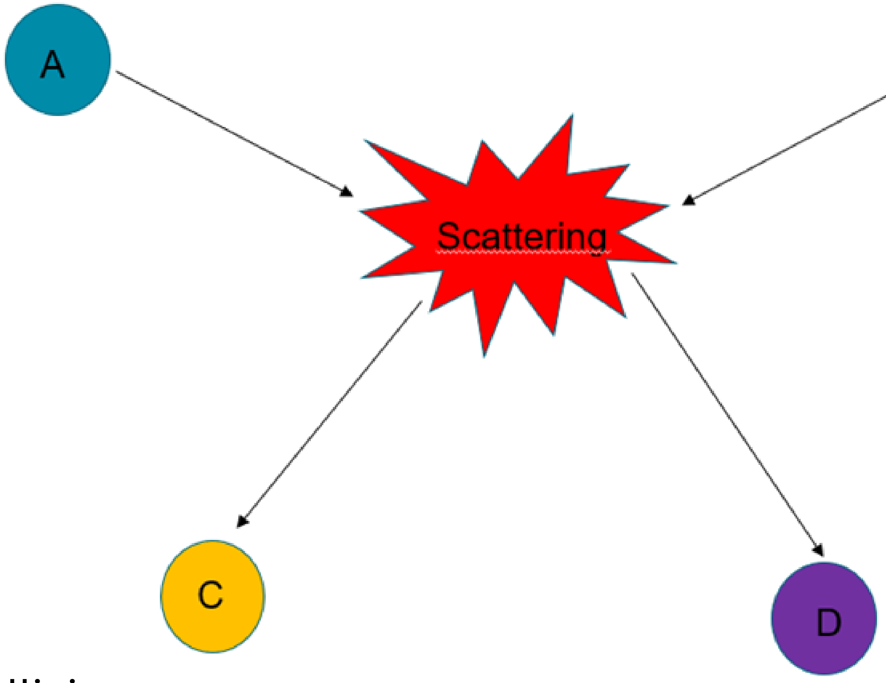


Figure from Yu Liu et al. Annu. Rev. Phys. Chem, 73, 73-96 (2022)

Before collision : $|\chi_a\rangle \otimes |\chi_b\rangle \otimes |\ell, m_\ell\rangle \otimes |e^{-ik_{AB}}\rangle$ Ingoing wave



S-matrix: transition amplitude

S-matrix is unitary

After collision :

$$\sum_{c,d,\ell' m_{\ell'}} \sqrt{\frac{k_{CD}}{k_{AB}}}\, S_{ab\ell m_\ell \to cd\ell' m_{\ell'}} |\chi_c\rangle \otimes |\chi_d\rangle \otimes |\ell', m_{\ell'}\rangle \otimes |e^{ik_{cd}}\rangle$$ Outgoing wave

Internal states of scattered particles

relative rotation of scattered particles (final partial wave)

Main observable: Cross section

In the (current) experiments, what can we control in the preparation?

- Internal state $|\chi_a\rangle|\chi_b\rangle$
- Relative momentum k_{AB}

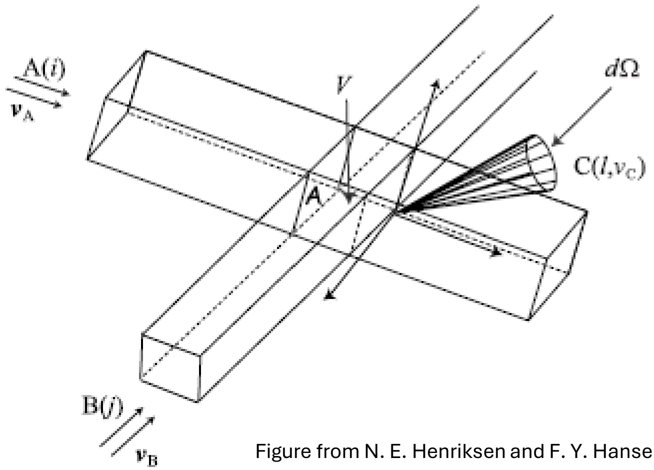


Figure from N. E. Henriksen and F. Y. Hansen “Theories of molecular reaction dynamics”

Measurement: number of molecules in state $|\chi_c\rangle|\chi_d\rangle$

Cross section $\sigma_{ab\,\rightarrow cd}$: ratio of the number of scattered particles measured in final state $|\chi_c\rangle|\chi_d\rangle$ to the number of colliding particles prepared in initial state $|\chi_a\rangle|\chi_b\rangle$

$$\sigma_{ab\,\rightarrow cd} = \frac{\pi}{k_{ab}^2} \sum_{\ell,m_\ell} \sum_{\ell',m'_\ell} \left|T_{ab\ell m_\ell \rightarrow cd\ell' m'_\ell}\right|^2$$

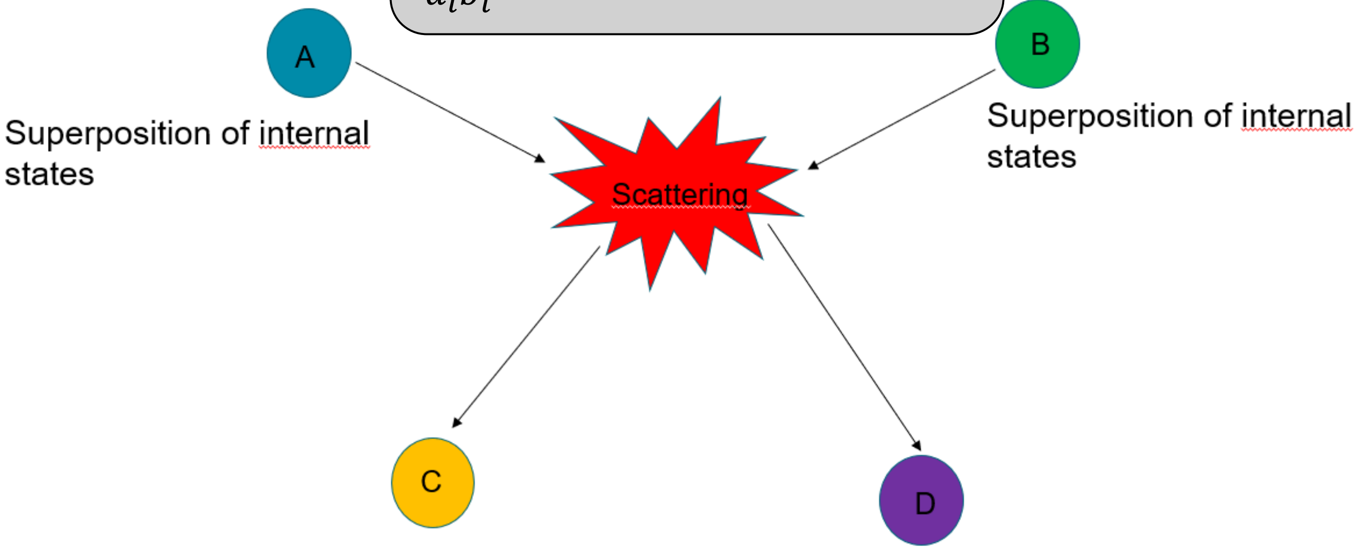
$$T_{ab\ell m_\ell \rightarrow cd\ell' m'_\ell} = \delta_{ab\ell m_\ell \rightarrow cd\ell' m'_\ell} - S_{ab\ell m_\ell \rightarrow cd\ell' m'_\ell}$$

Incoherent sum over the initial partial wave because impossibility to prepare at a specific $|\ell, m_\ell\rangle$

Incoherent sum over the final partial wave because impossibility to measure a specific $|\ell', m_{\ell'}\rangle$

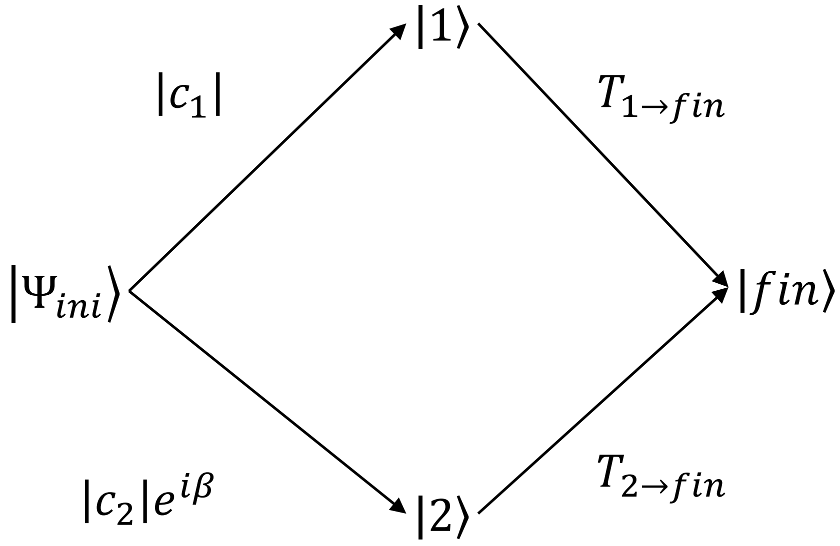
Coherent control of collisions

$$\sum_{a_i b_i} \left|C_{a_i b_i}\right| e^{i\beta_{a_i b_i}} \left|\chi_{a_i}\right\rangle \left|\chi_{b_i}\right\rangle$$



Superposition of internal states

Superposition of internal states



Create different paths which interfere with each other
~ collisional interferometer

Direct term

Interference term

$$\sigma_{sup\to cd} = \frac{\pi}{k^2} \sum_{\ell, m_\ell} \sum_{\ell', m'_\ell} \left(\sum_{a_i b_i} \left|C_{a_i b_i}\right|^2 \left|T_{a_i b_i \ell m_\ell \to cd \ell' m'_\ell}\right|^2 + \sum_{a_i b_i} \sum_{a_j b_j} \left|C_{a_i b_i}\right| \left|C_{a_j b_j}\right| e^{i\left(\beta_{a_i b_i} - \beta_{a_j b_j}\right)} T^*_{a_i b_i \ell m_\ell \to cd\, \ell' m'_\ell} T_{a_j b_j \ell m_\ell \to cd\, \ell' m'_\ell} \right)$$

$\uparrow$

Controlled by tuning the relative phases

Type of superpositions

Interference if :

- Same internal energy → Superposition of degenerate magnetic sublevels (m-superposition)

$$\left|\psi_A\right\rangle = \frac{1}{\sqrt{2}}\left(\cos\eta\left|m_1^A\right\rangle + \sin\eta\, e^{i\beta}\left|m_2^A\right\rangle\right)$$

$$\left|\psi_B\right\rangle = \frac{1}{\sqrt{2}}\left(\sin\eta\left|m_1^B\right\rangle + \cos\eta\left|m_2^B\right\rangle\right)$$

- Same internal projection

$$\left|\Psi_{nent}\right\rangle = \Big|\psi_A\rangle\otimes\left|\psi_B\right\rangle = \frac{1}{2}\left(\cos\eta\sin\eta\left|m_1^A, m_1^B\right\rangle + cos^2\eta\left|m_1^A, m_2^B\right\rangle + sin^2\eta e^{i\beta}\left|m_2^A, m_1^B\right\rangle + \cos\eta\sin\eta\left|m_2^A, m_2^B\right\rangle\right)$$

Interference

$$m_1^A + m_2^B = m_2^A + m_1^B$$

Example with spin-half particles:

$$\left|\Psi_{nent}\right\rangle = \Big|\psi_A\rangle\otimes\left|\psi_B\right\rangle = \frac{1}{2}\left(\cos\eta\sin\eta\,|\uparrow,\uparrow\rangle + cos^2\eta|\uparrow,\downarrow\rangle + sin^2\eta e^{i\beta}|\downarrow,\uparrow\rangle + \cos\eta\sin\eta\,|\downarrow,\downarrow\rangle\right)$$

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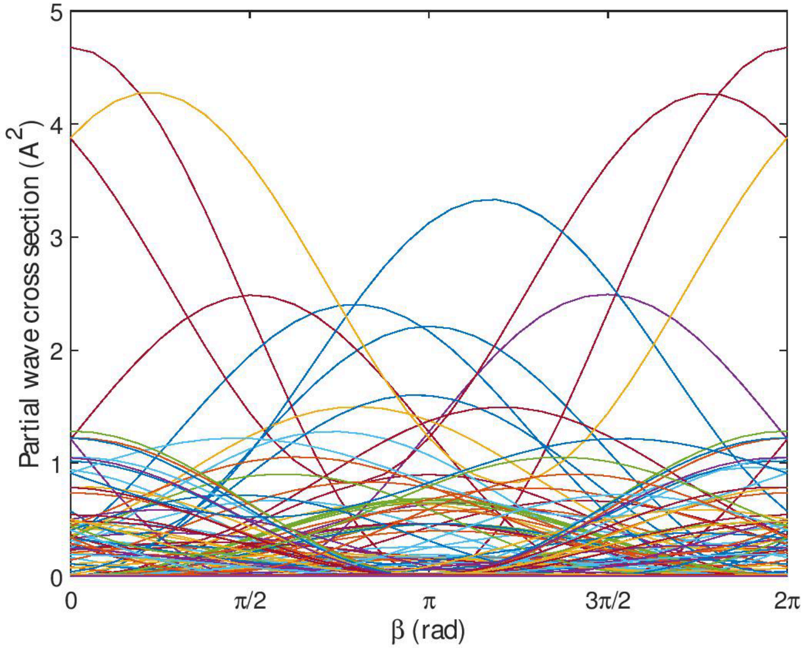
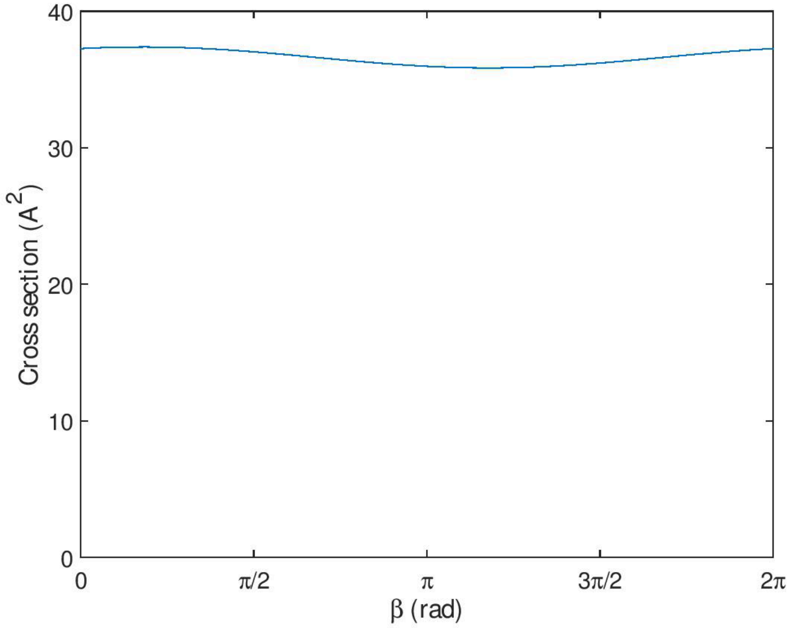
Partial wave expansion challenge

$$\sigma_{sup\rightarrow cd} = \frac{\pi}{k_{ab}^2}\sum_{\ell,m_\ell}\sum_{\ell',m'_\ell}\left|\sum_i cos^2\eta T_{m_1^A m_2^B \ell m_\ell\rightarrow cd\,\ell' m'_\ell} + sin^2\eta\, e^{i\beta} T_{m_2^A m_1^B \ell m_\ell \rightarrow cd\,\ell' m'_\ell}\right|^2 + \sigma_{sat}$$

Different control between partial waves → Cancellation of interference terms

Example with 50 partial waves (Rb-Rb scattering at 1K):





How to solve it?

Strategies

3 Strategies :

- Ultracold regime
- Resonance
- Phase-locking mechanism

Strategies

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Ultracold regime

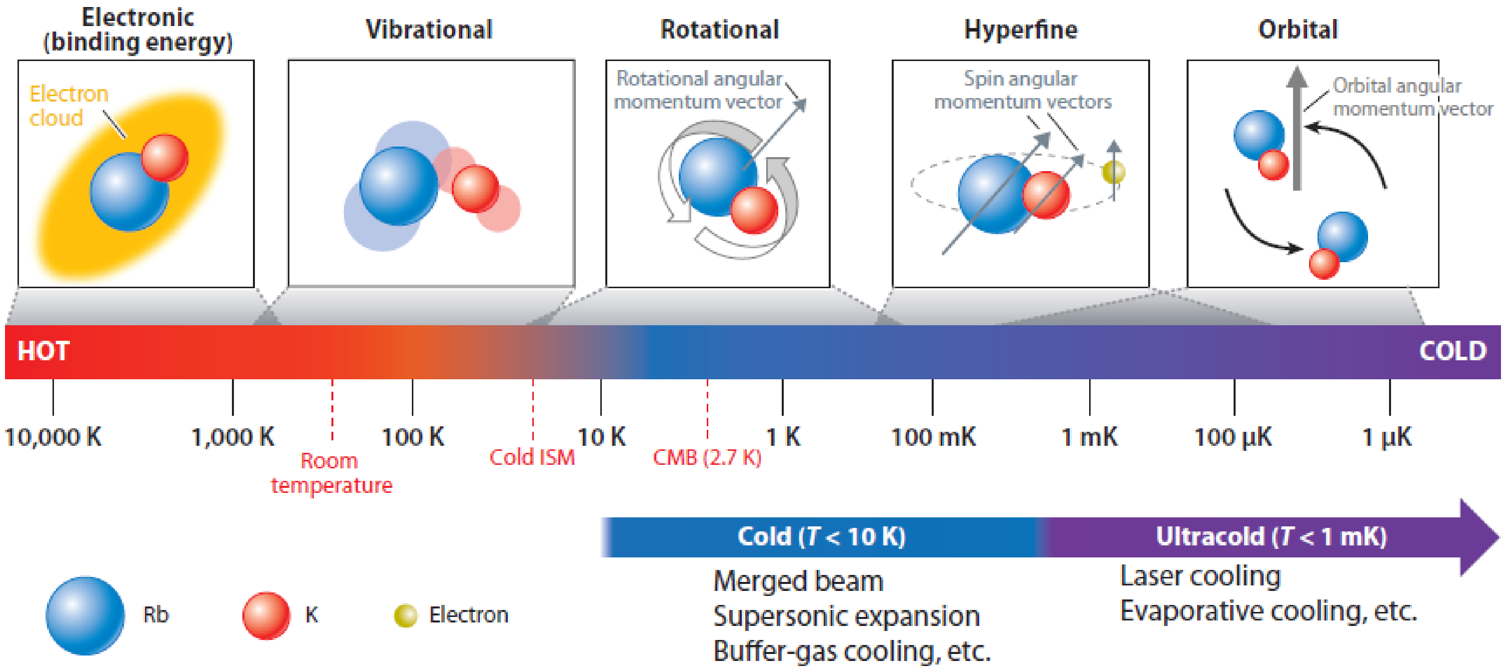


Figure from Yu Liu et al. Annu. Rev. Phys. Chem, 73, 73-96 (2022)

Why so cold ?

- Enhanced quantum behaviour at these temperature
- Better control on all degrees of freedom
- Increasing precision of measurements

Application:

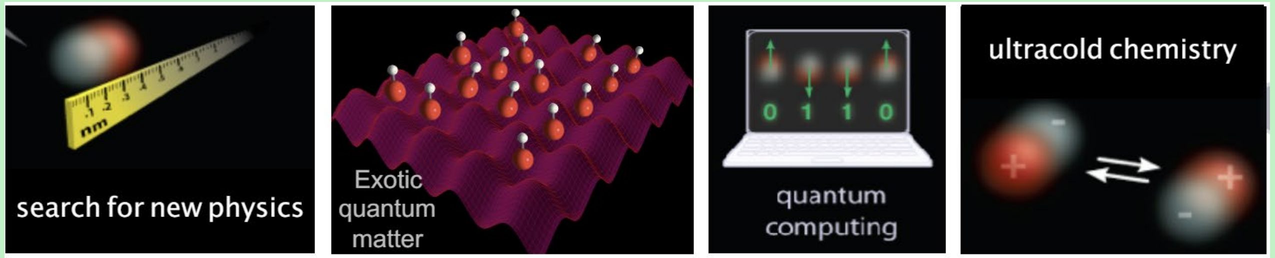


Figure from K.K. Ni "Ultracold Molecules for physics and chemistry"

Partial waves and ultracold temperature

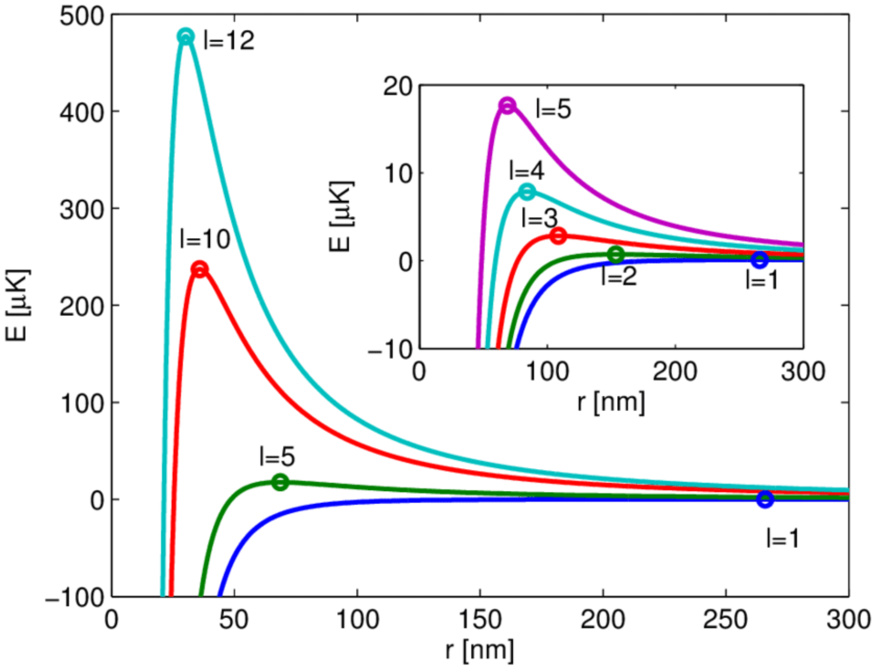


Figure from Z. Meir's thesis "Dynamics of a single, ground-state cooled and trapped ion colliding with ultracold atoms: A micromotion tale"

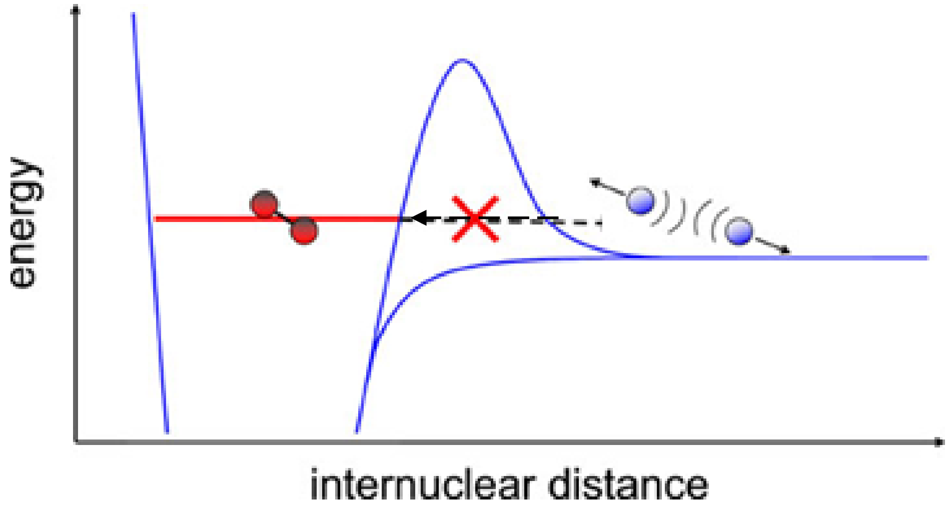
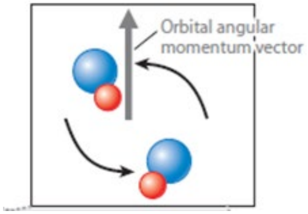


Figure from R. Krems "Molecules in Electromagnetic fields"



$$V_{eff} = V + \frac{\ell^2}{2\mu r^2}$$

If relative kinetic energy < rotational barrier height, minor contribution to σ

At ultracold temperature, only $\ell = 0$

Example : $O_2 - O_2$ scattering

One molecule in a superposition of $|M_S = -1\rangle$ and $|M_S = 0\rangle$:

$$\left|\Psi_1\right\rangle = (\cos\eta\,|M_S = 0\rangle + \sin\eta\,|M_S = -1\rangle)$$

Other molecule in a superposition of $|M_S = 0\rangle$ and $|M_S = +1\rangle$:

$$\left|\Psi_2\right\rangle = \left(\cos\eta\,|M_S = 0\rangle + \sin\eta\, e^{i\beta}|M_S = +1\rangle\right)$$

The total internal wavefunction :

$$\left|\Psi_{ini}\right\rangle = \left[\left(cos^2\eta\;|0,0\rangle + sin^2\eta\; e^{i\beta}|-1,+1\rangle\right) + \sin\eta\cos\eta\; e^{i\beta}(|0,+1\rangle + |-1,0\rangle)\right]$$

Control part

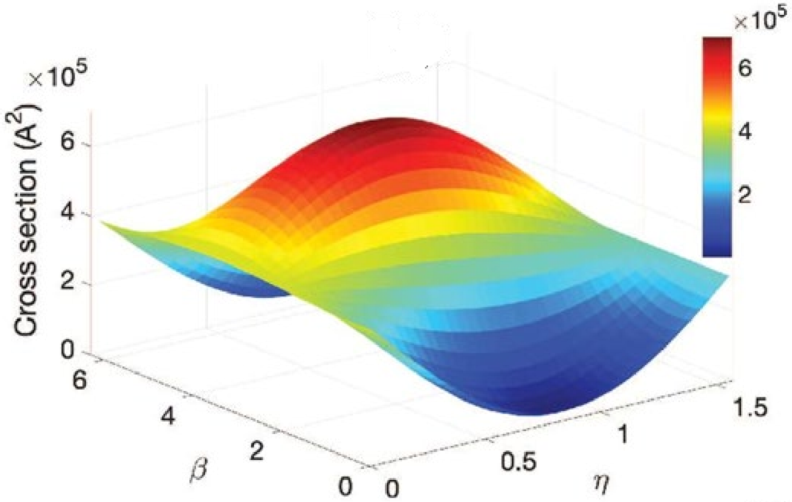
Satellite terms

Final state: $|0,0\rangle$ and $|-1,+1\rangle$

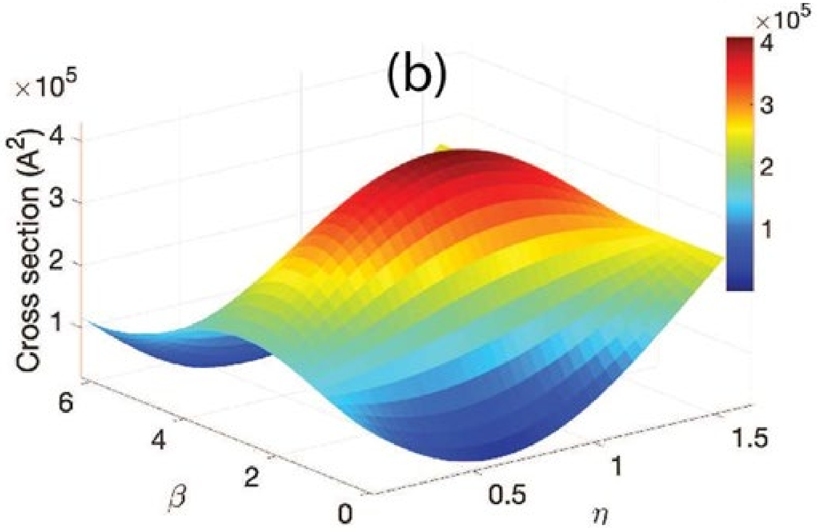
Devolder A. et al. PRL, 126, 153403 (2021)

Complete destructive interference of cross-sections

$\sigma_{sup \to 00}$

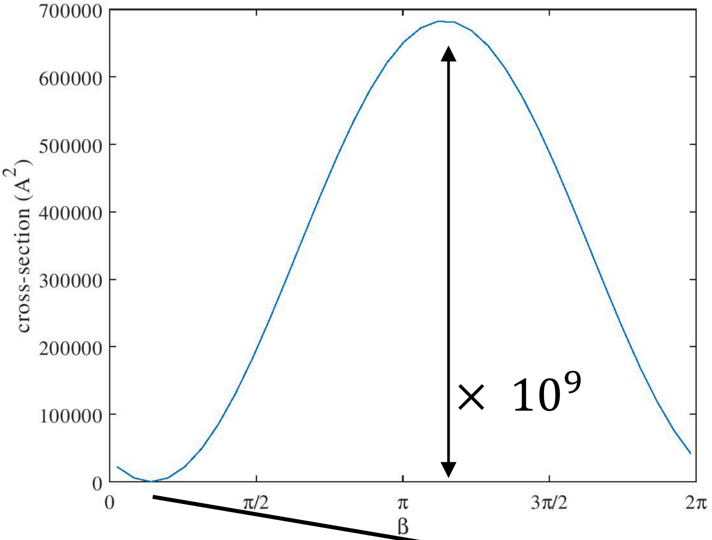


$\sigma_{sup \to -1+1}$



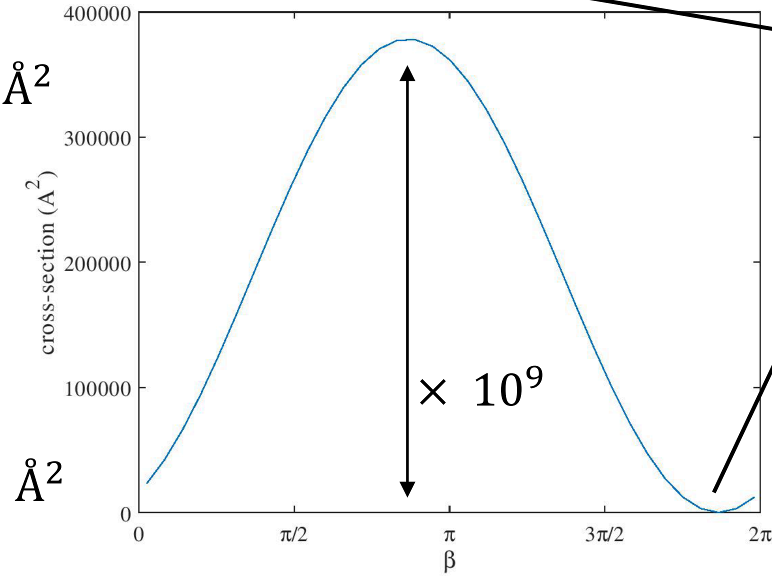
$\sigma_{max} = 682392\ \text{Å}^2$

$\sigma_{min} = 0.0002\ \text{Å}^2$



$\sigma_{max} = 377977\ \text{Å}^2$

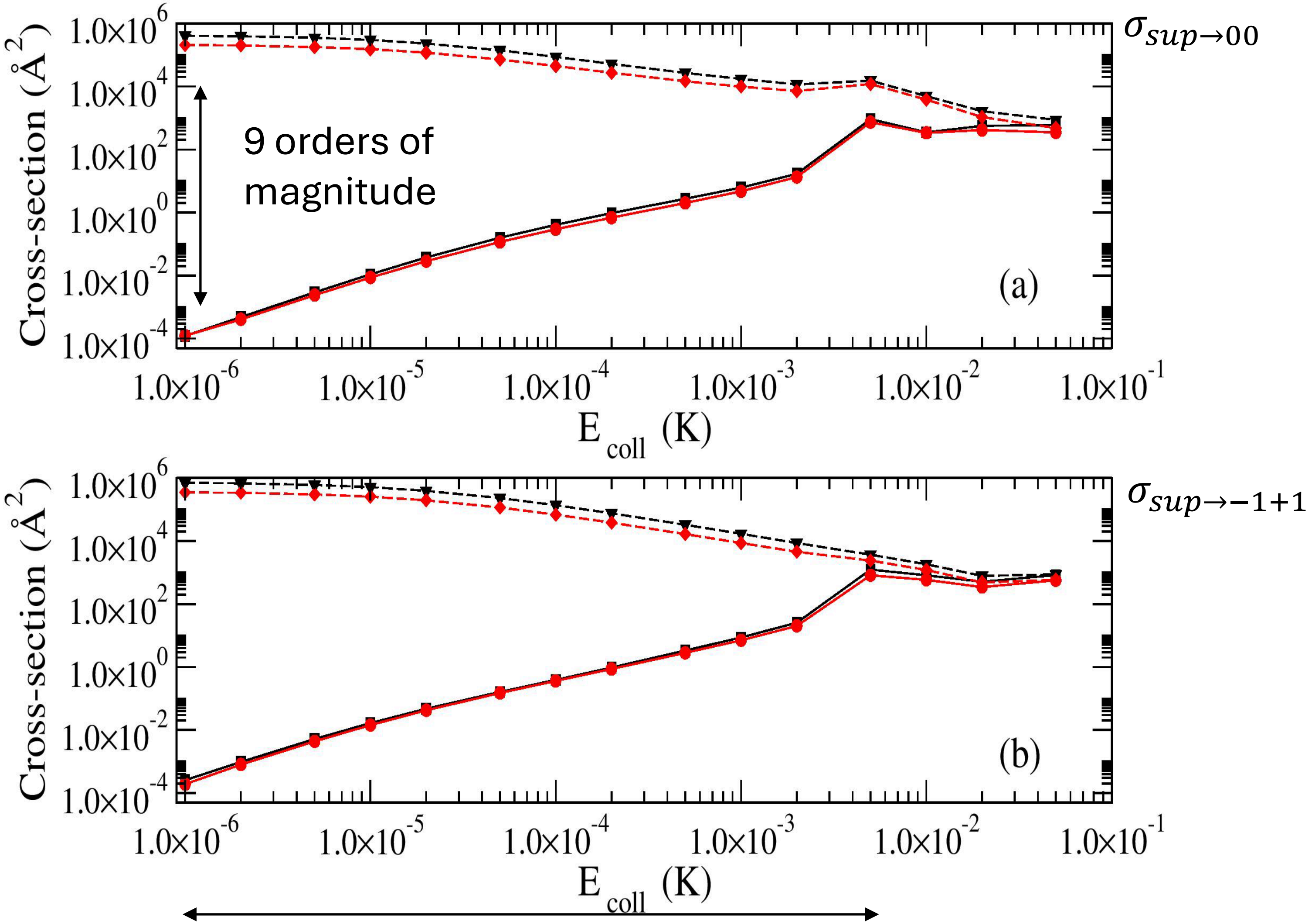
$\sigma_{min} = 0.0001\ \text{Å}^2$



Complete destructive interference

Devolder A. et al. PRL, 126, 153403 (2021)

Complete destructive interference of cross-sections



Ultracold regime

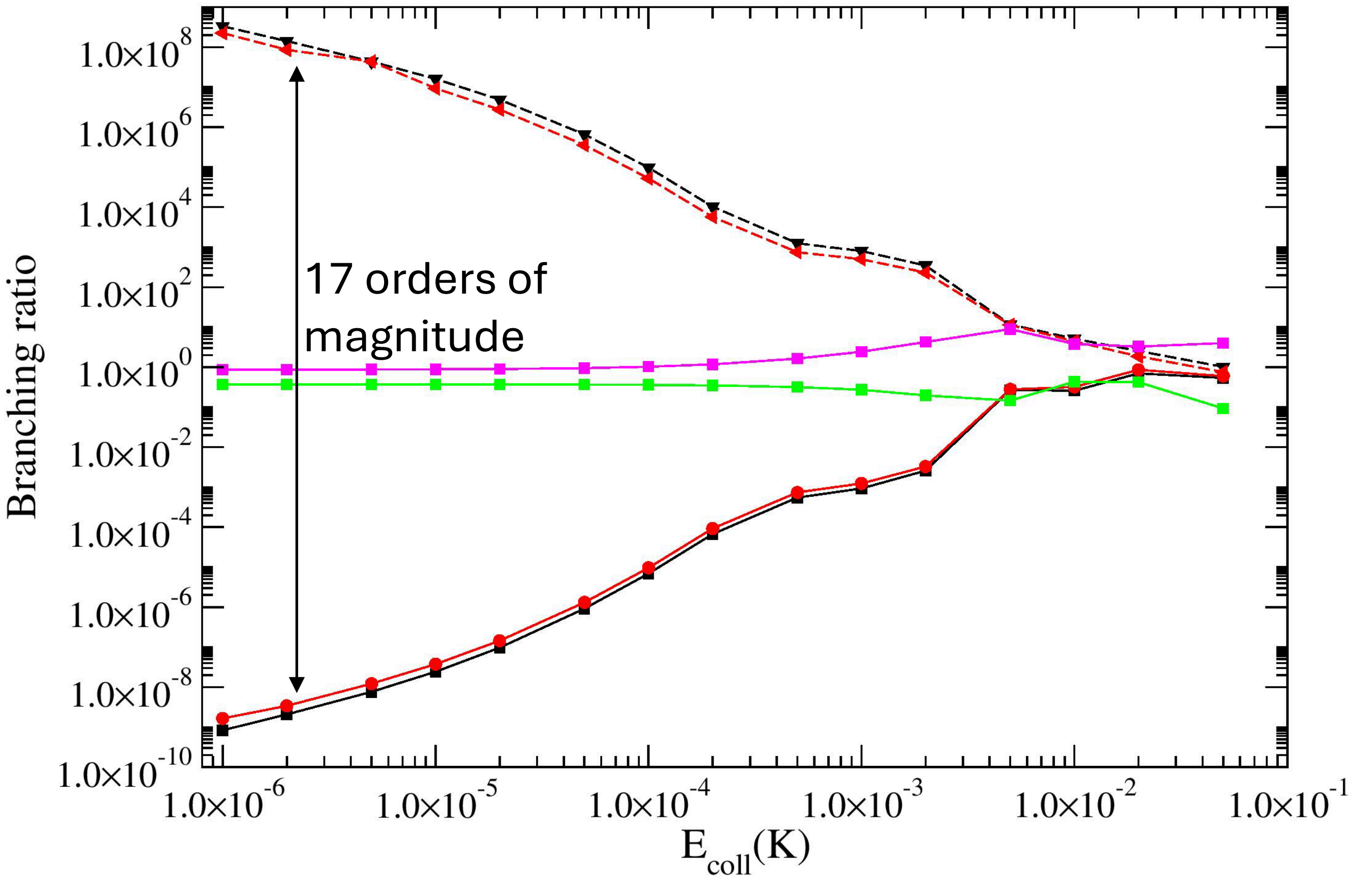
Devolder A. et al. PRL, 126, 153403 (2021)

Complete control of branching ratio

One set of parameter (η, β) → suppression
2st processus → Branching ratio =∞

Complete control of branching ratio

One set of parameter (η, β) → suppression
1st processus → Branching ratio = 0


17 orders of magnitude

⇒ Ultracold regime is ideal for coherent control

Devolder A. et al. PRL, 126, 153403 (2021)

Strategies

3 Strategies :

- Ultracold regime
- Resonance
- Phase-locking mechanism

Shape resonance

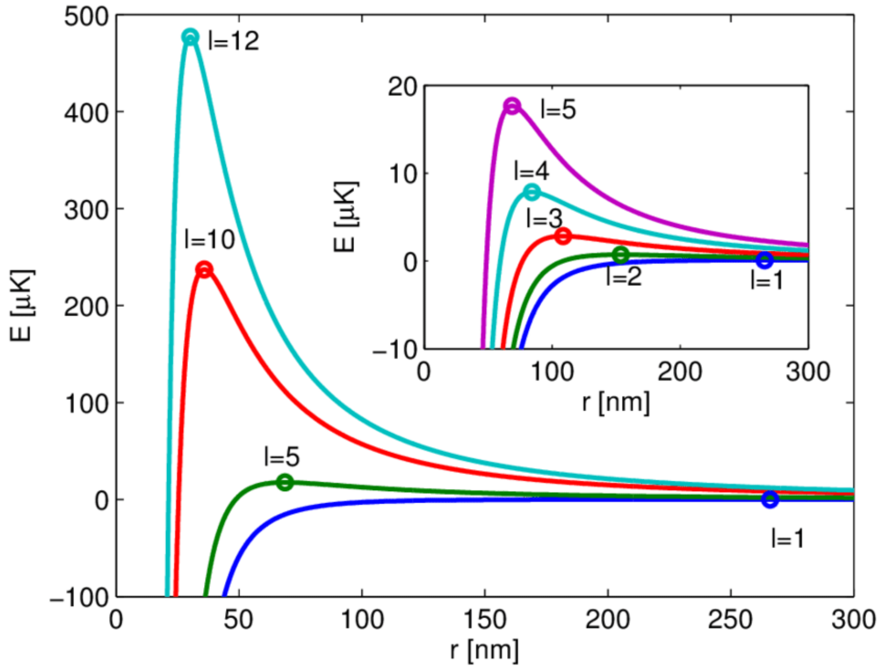


Figure from Z. Meir's thesis "Dynamics of a single, ground-state cooled and trapped ion colliding with ultracold atoms: A micromotion tale"

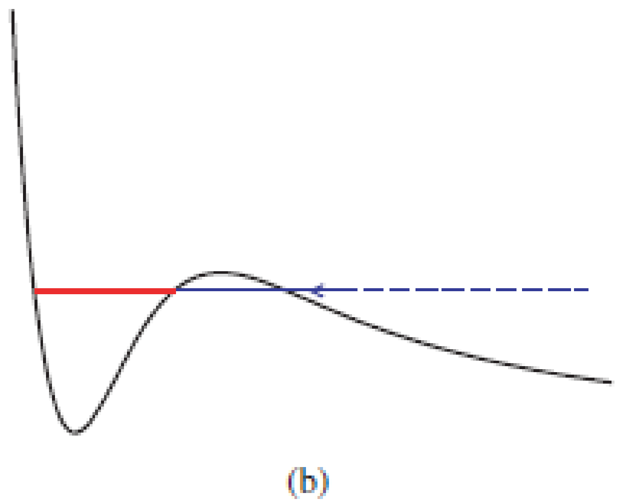


Figure from R. Krems "Molecules in Electromagnetic fields"

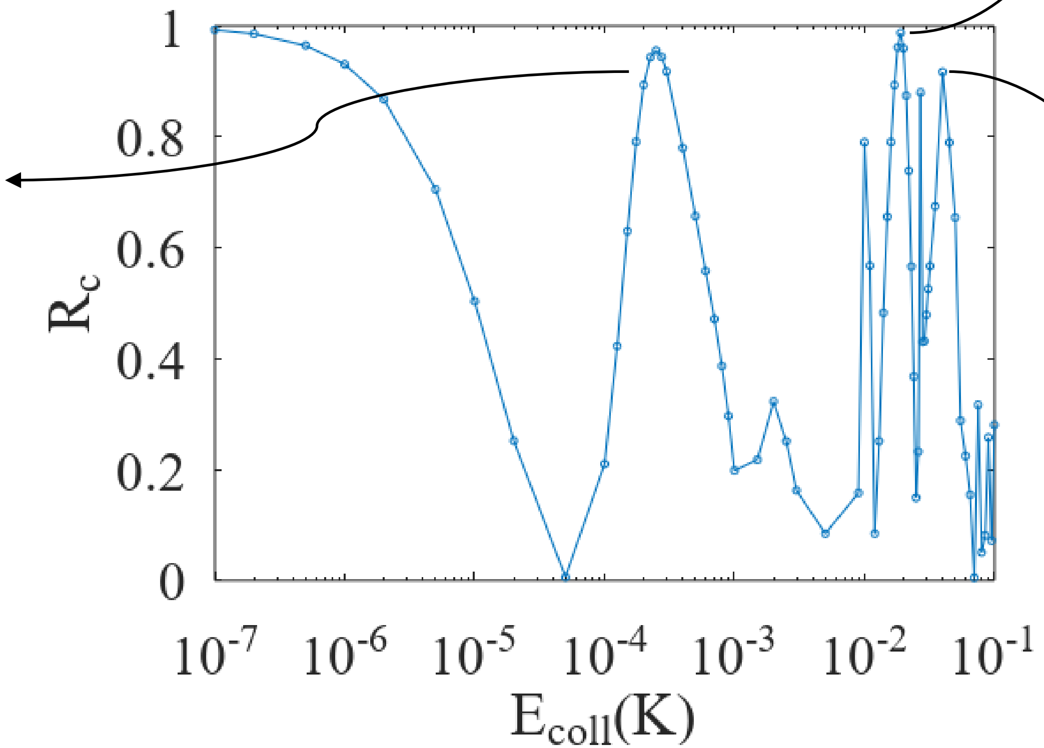
Quasi-bound state occurring due to the presence of the centrifugal barrier

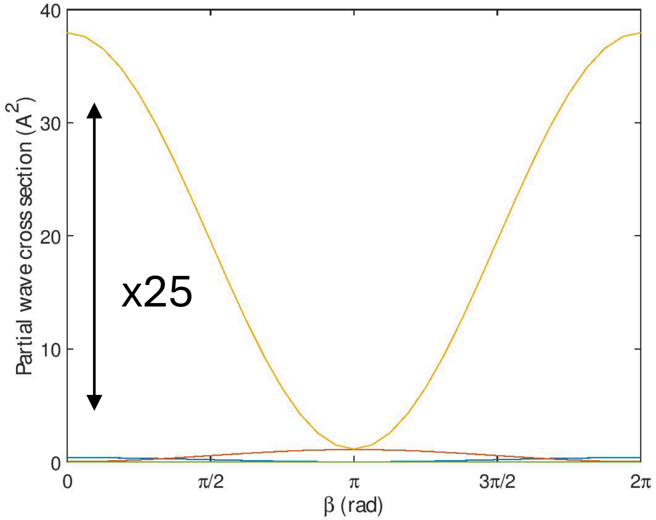
One predominant partial wave → ideal for coherent control

Devolder A. et al. J. Phys. Chem. Lett., 14, 8, 2171-2177 (2023)

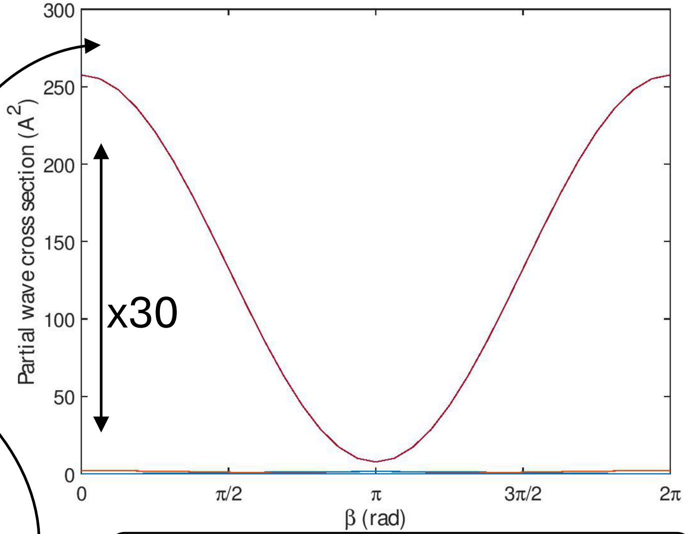
Coherent control around shape resonance

Scattering of a ground state ^{87}Rb atom (F=1) and a hyperfine excited ^{87}Rb atom (F=2) → two ground state ^{87}Rb atoms (F=1)

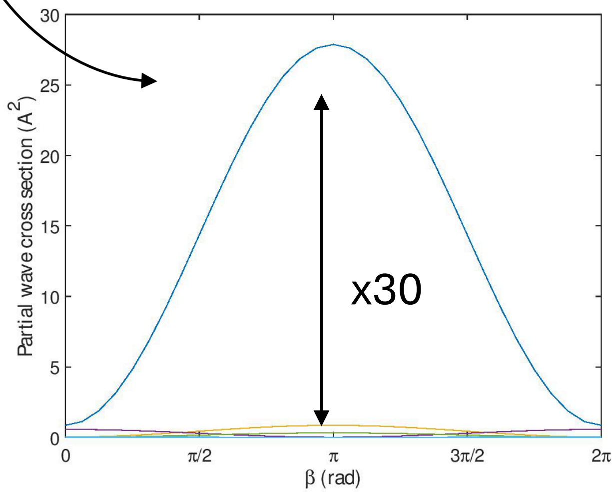




Shape resonance ℓ=2



Shape resonance ℓ=6



R_c: control index
$R_c = 0$ no control
$R_c = 1$ complete control

Shape resonance ℓ=7

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Devolder A. et al. J. Phys. Chem. Lett., 14, 8, 2171-2177 (2023)

Strategies

3 Strategies :

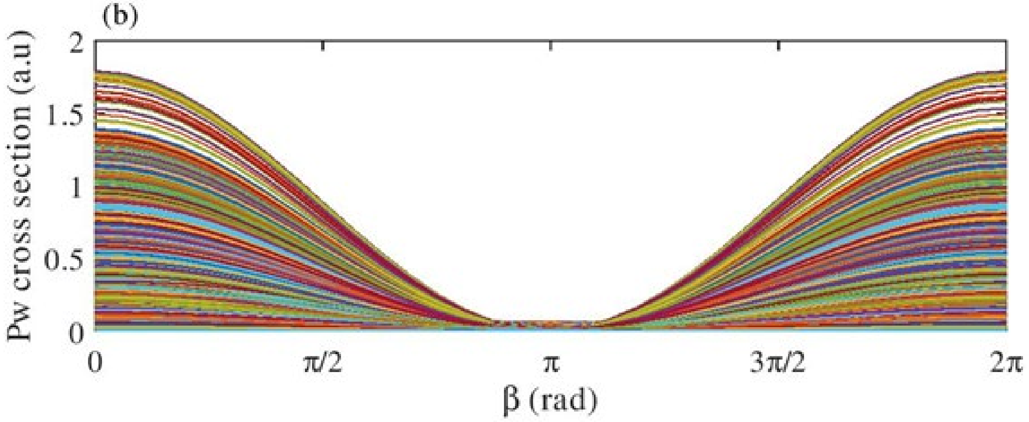
- Ultracold regime
- Resonance
- Phase-locking mechanism

Partial wave phase locking mechanism

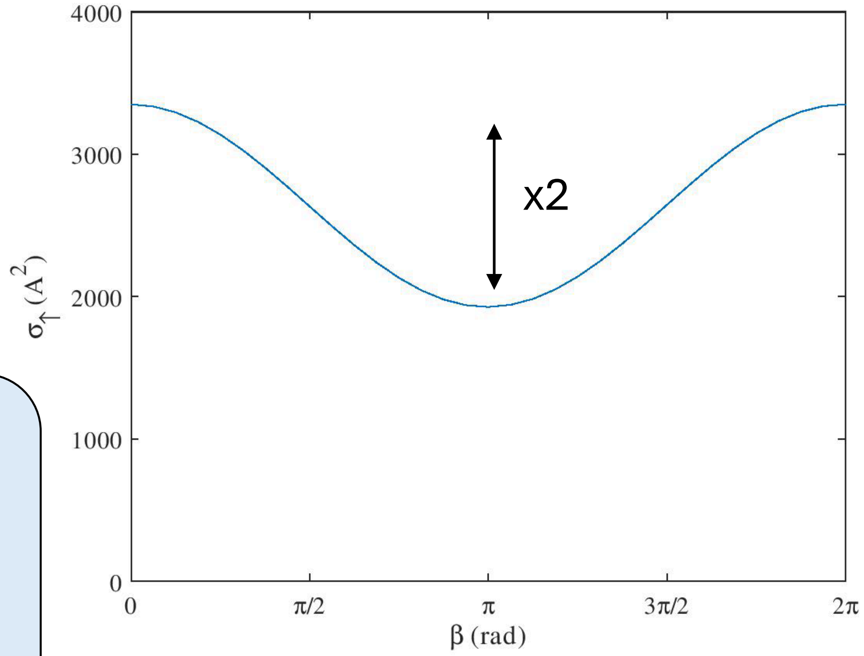
Phase locking of partial wave contributions: synchronization of the control of every partial waves

Partial wave phase-locking discovered in spin-exchange and spin-relaxation in atom-ion collisions (T. Sikorsky et al. PRL 173402 (2018) and R. Côté PRL 173401 (2018))

Collisions between ^{87}Rb atom (F=2) and a ground state $^{88}Sr^{+}$iom (S=1/2) :

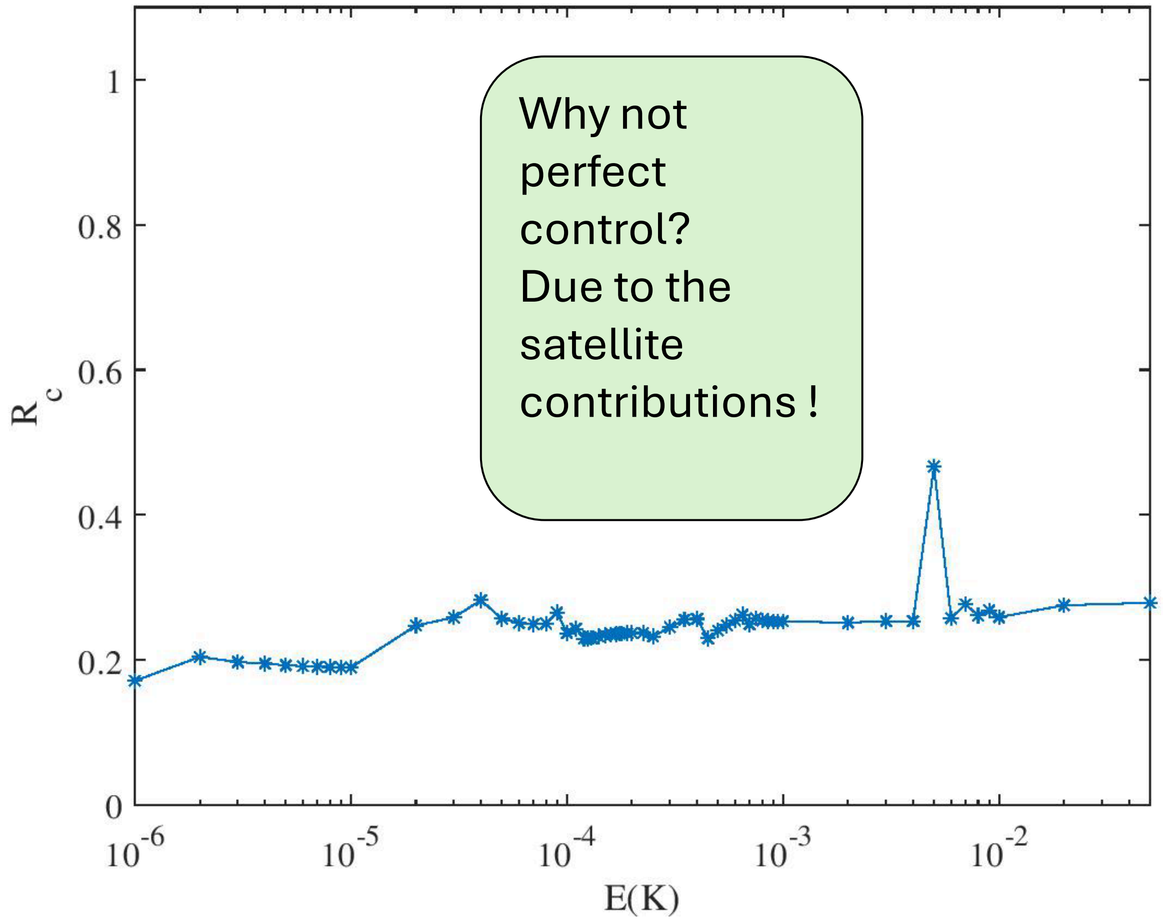


E=50 mK
80 partial waves and 5000 contributions !



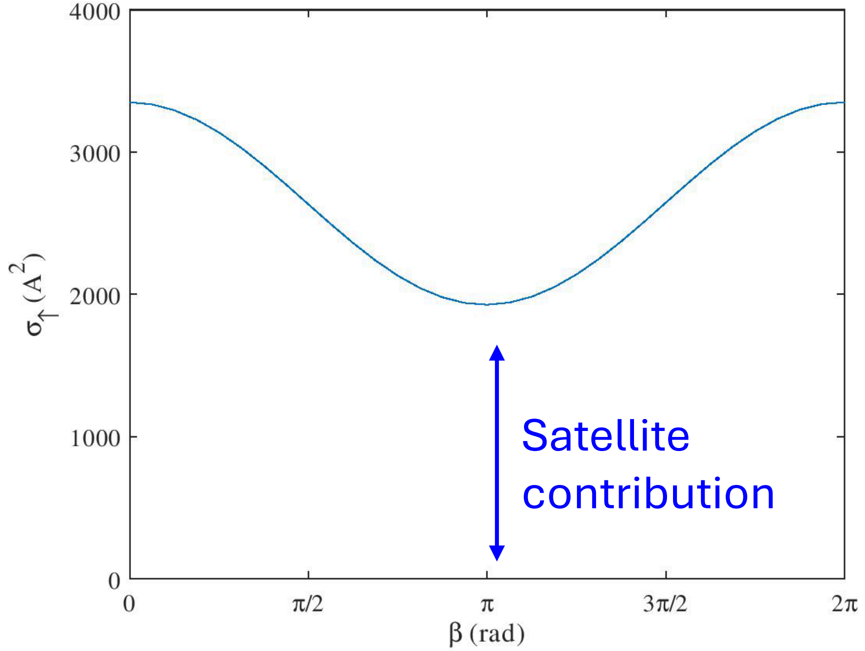
A. Devolder et al. PRR 5, L042025 (2023)

Robust coherent control beyond ultracold regime



Why not perfect control? Due to the satellite contributions !

Control robust against the increase of collisional energies



Satellite contribution

Solution: entangled superpositions

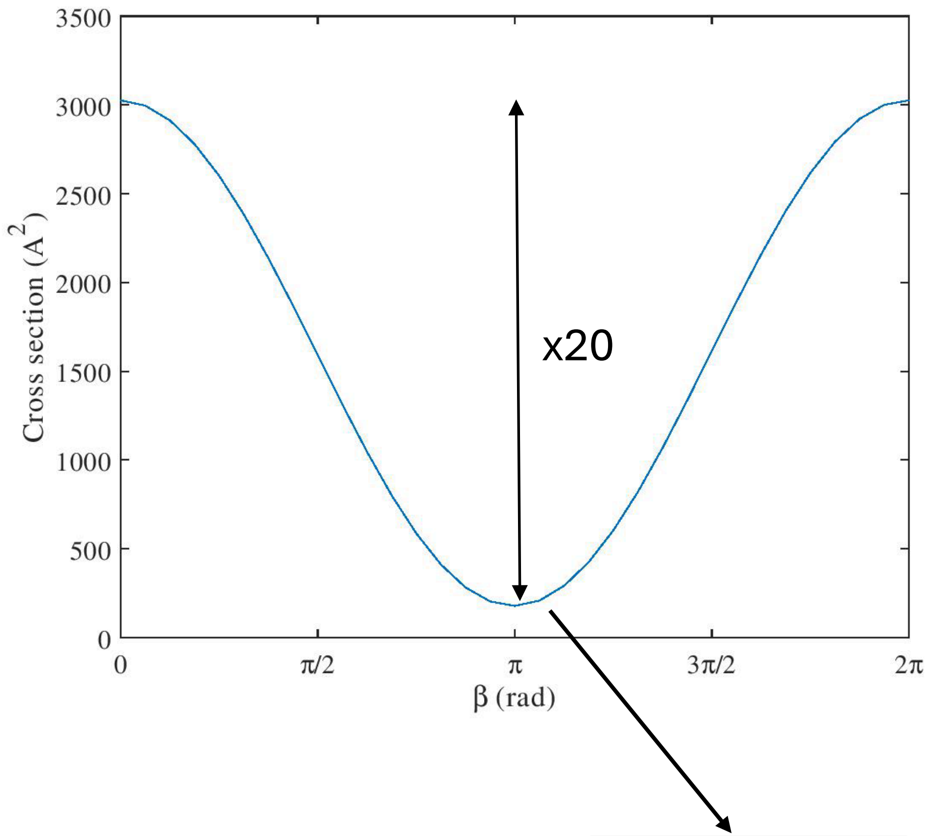
$$|\Psi_{ent}\rangle = \frac{1}{\sqrt{2}}\left(\left|m_1^A, m_2^B\right\rangle + e^{i\beta}\left|m_2^A, m_1^B\right\rangle\right)$$

No more satellite terms!

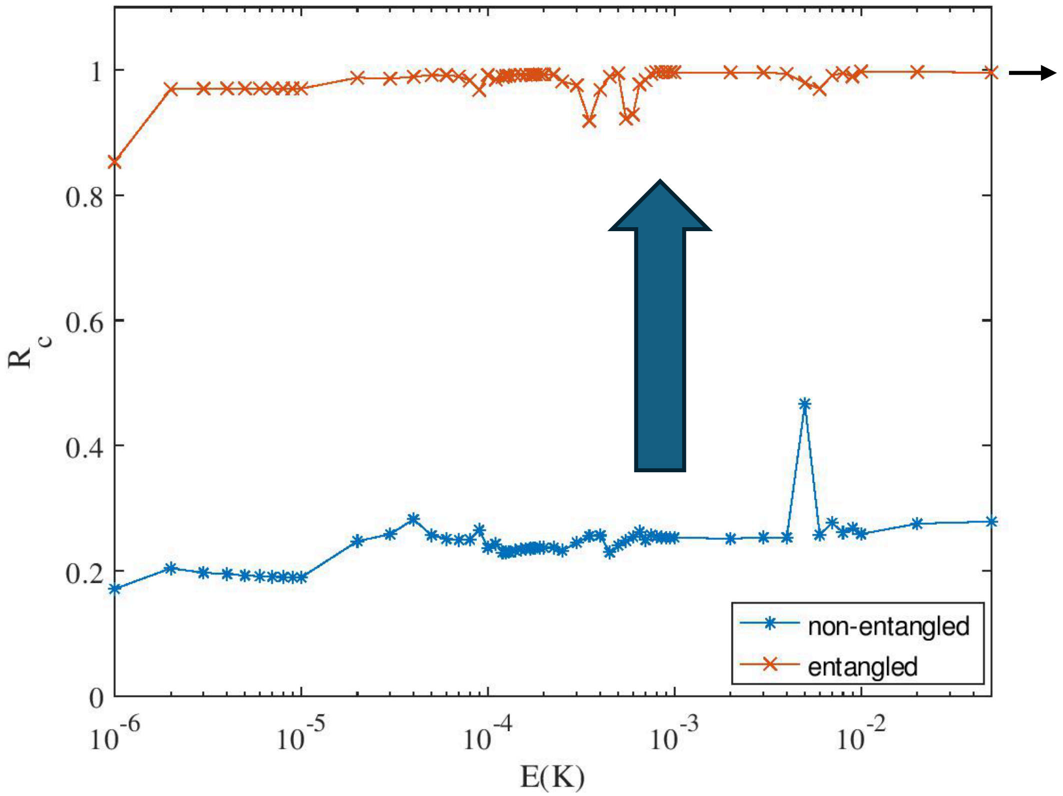
A. Devolder et al. PRR 5, L042025 (2023)

Coherent control with entangled superposition

E=50 mK



Destructive interference



Complete control at any collisional energy

A. Devolder et al. PRR 5, L042025 (2023)

Conclusions

- Preparation of initial superposition open the ways of control of molecular collisions via quantum interference

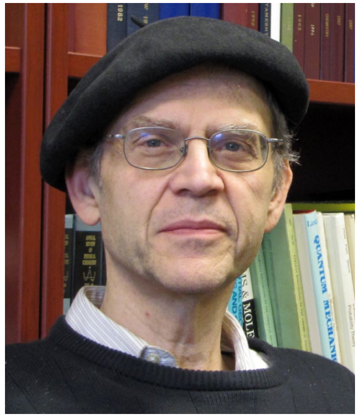
- Challenge from the partial wave expansion

- Resolved if:

- One dominant partial wave $\ell, m_\ell, \ell'\ , m'_\ell$ (ultracold regime and shape resonance)

- Synchronized control for every partial waves $\ell, m_\ell, \ell'\ , m'_\ell$ (Partial wave phase locking mechanism)

- Enhancement of the control with entangled superposition



Thank you for your attention

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DR. TING REI TAN

Senior Lecturer
University of Sydney

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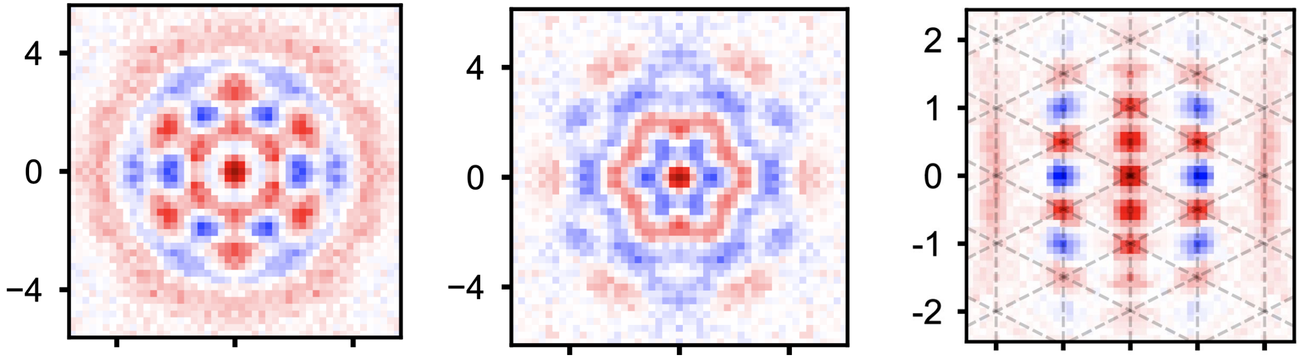
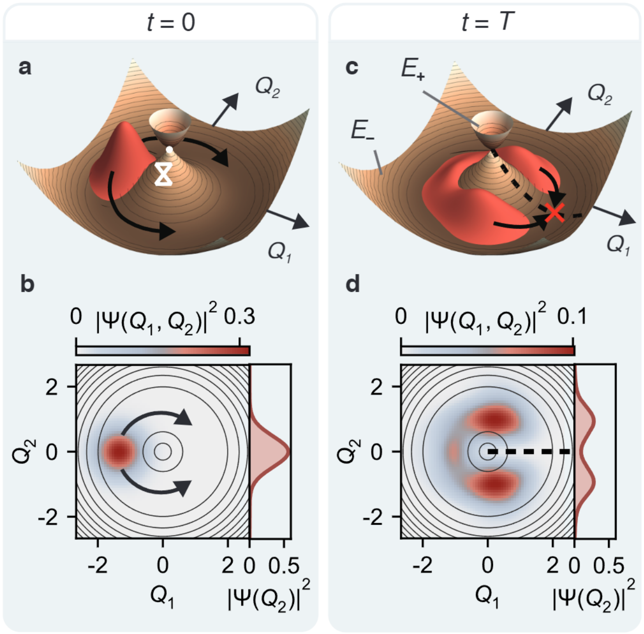
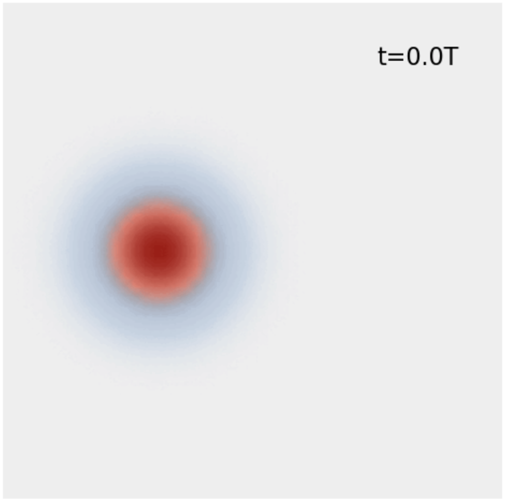
Quantum information science with trapped-ion mechanical oscillator



Ting Rei Tan

Quantum Control Laboratory (QCL)





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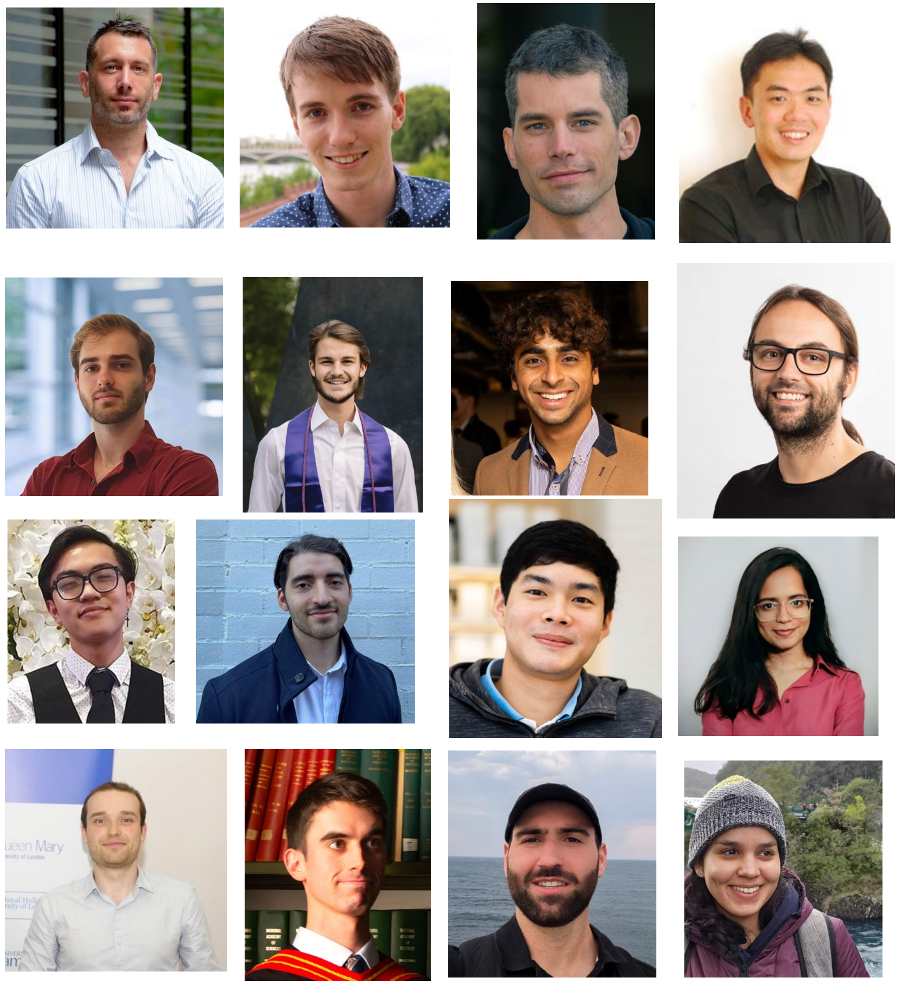
Quantum Control Laboratory – the team



Experiment (QCL)

Paul trap team:

Christophe Valahu
Tomas Navickas (now Q-Ctrl)
Arjun Rao
Maverick Millican
Vassili Matsos
Frank Scuccimarra
Prachi Nagpal
T. R. Tan (Paul trap PI)

Theory (Usyd's Kassal group)

Vanessa Olaya-Agudelo
Ryan MacDonell (now Dalhousie)
Liam Flew
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Ivan Kassal (PI)

Collaborators:

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Juan Perez-Sanchez (UCSD)
Joel Yuen-Zhou (UCSD)

Penning trap team:

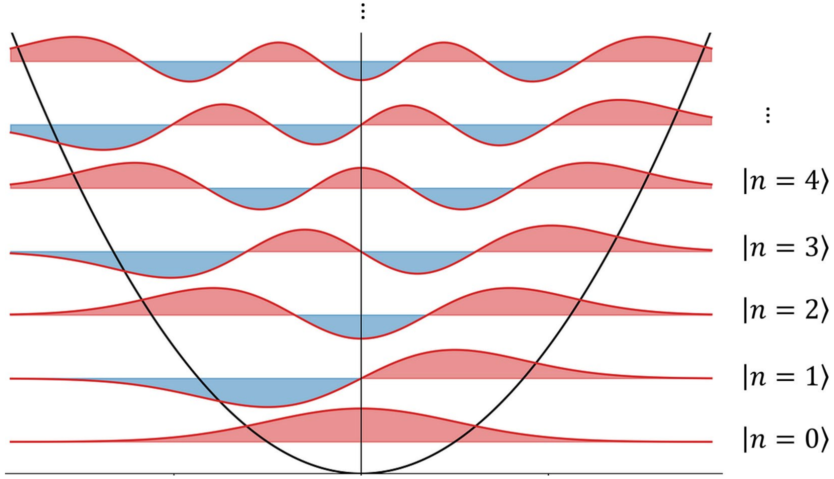
Joseph Pham
Julian Jee
Michael Biercuk
Robert Wolf (Penning trap PI)

Funders:

DST GROUP
IARPA BE THE FUTURE
Office of Naval Research ONR Science & Technology
EQUS
NSW GOVERNMENT
Science to shape the future of the Army Army Research Office 1951
LOCKHEED MARTIN
Air Force Office of Scientific Research United States Air Force
leap
SYDNEY QUANTUM ACADEMY

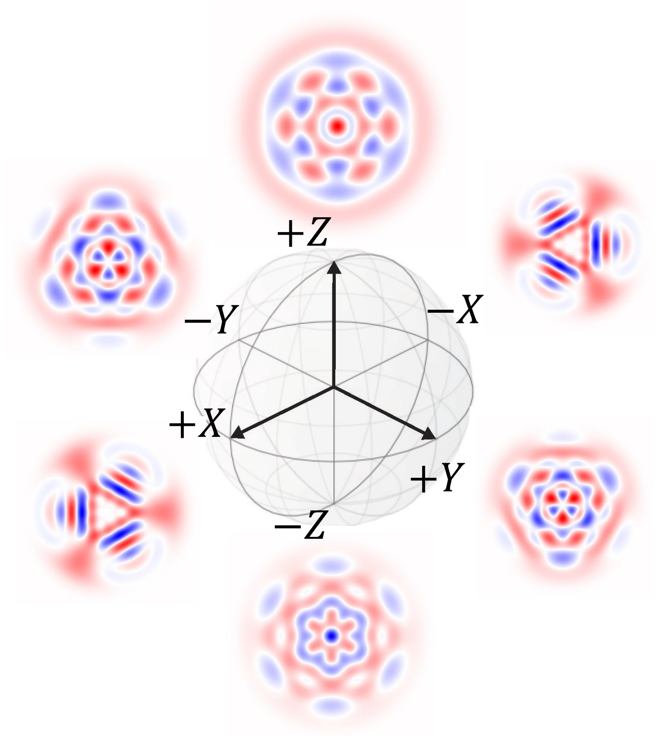
Logical Qubits in an oscillator to provide hardware resource savings

Harmonic Oscillator



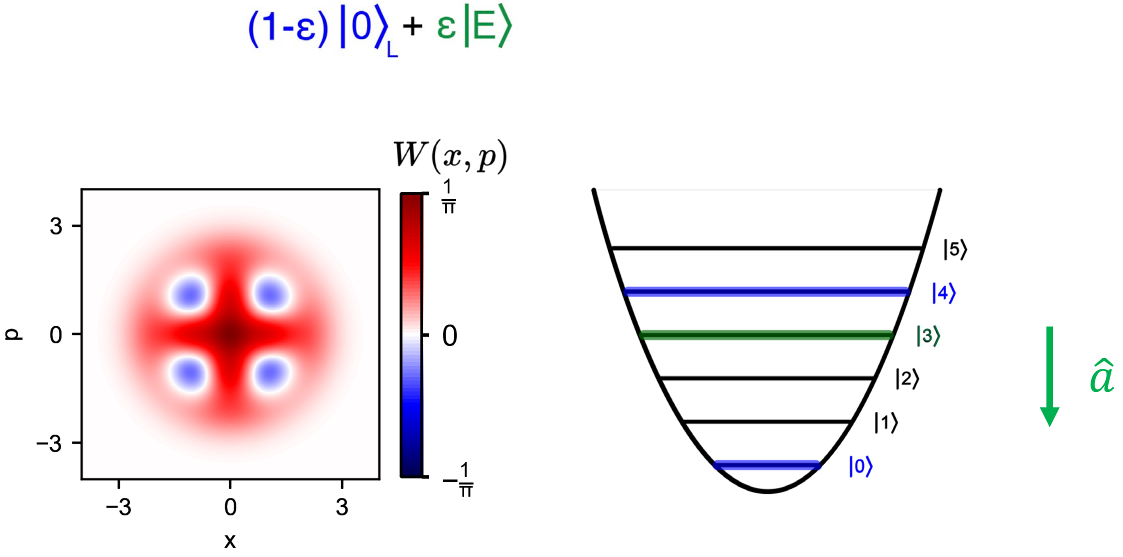
Bosonic Encoding

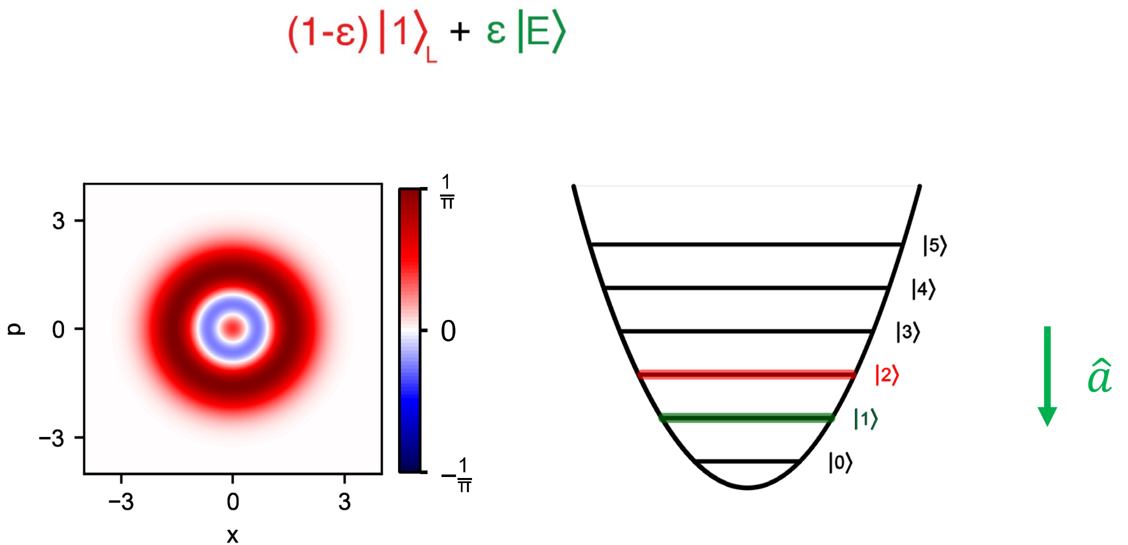
Logical Qubit



Bosonic Code Reviews:
Terhal et al. Quantum Sci and Tech (2020)
Albert, “Bosonic coding: introduction and use cases”, (2022)

Binomial





Michael et al. Phys. Rev. X (2016)

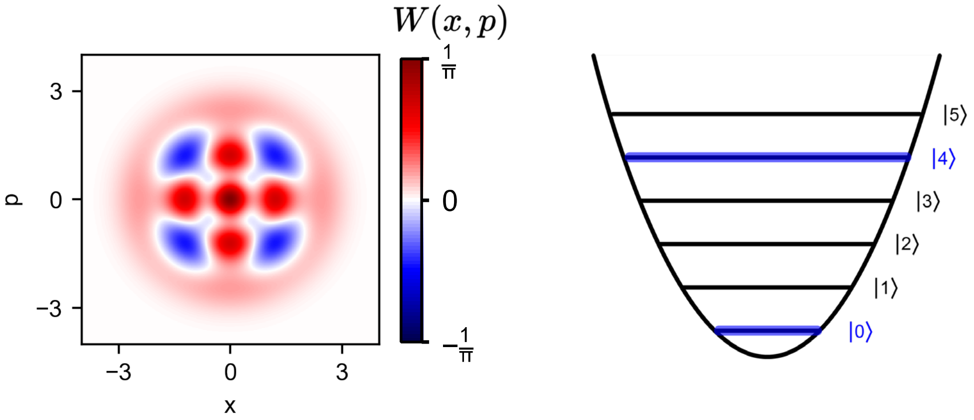
Bosonic Code Reviews:

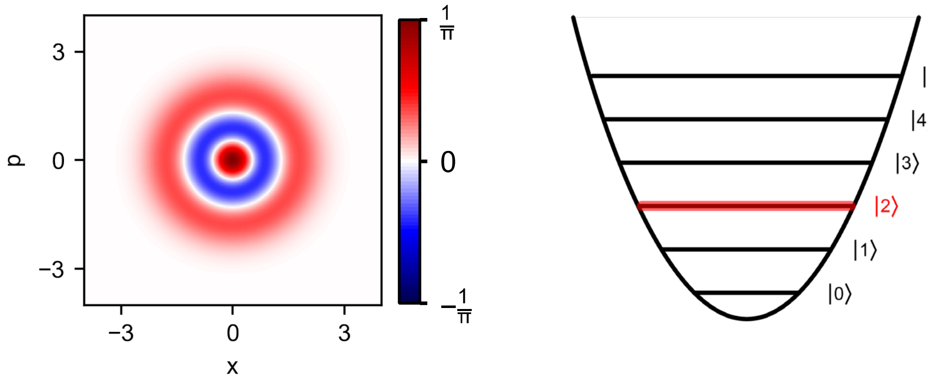
Terhal, B. et al. Quantum Sci and Tech **5** 043001 (2020)

Albert, V. arXiv 2211 05714 (2022)

Binomial

$|0\rangle_L = (|0\rangle + |4\rangle)/\sqrt{2}$ $|1\rangle_L = |2\rangle$

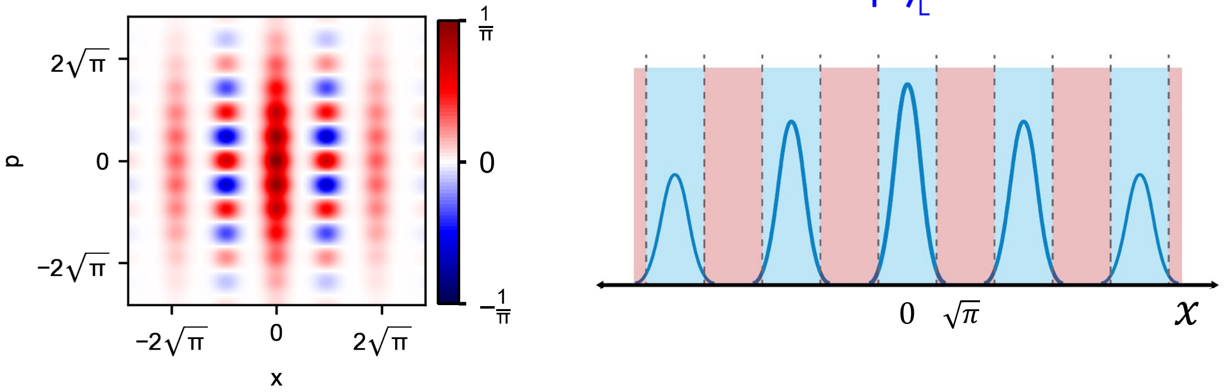




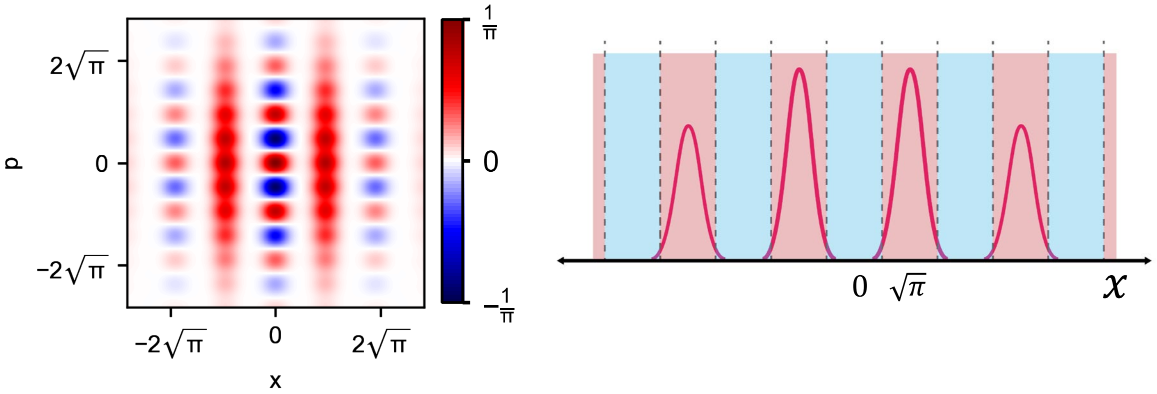
Michael et al. Phys. Rev. X (2016)

Gottesman-Kitaev-Preskill (GKP)

$|0\rangle_L$



$|1\rangle_L$



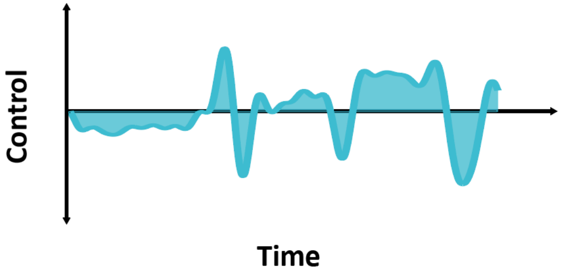
Bosonic Code Reviews:

Terhal et al. Quantum Sci and Tech (2020)

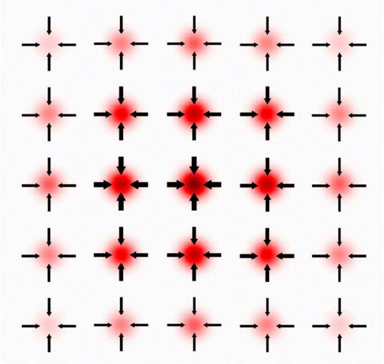
Albert, “Bosonic coding: introduction and use cases”, (2022)

Gottesman et al. Phys. Rev. A (2001)

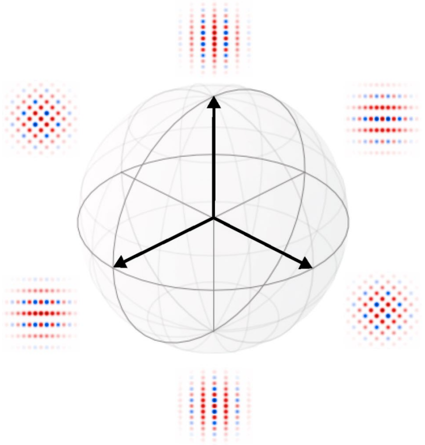
Quantum Computing with Bosonic Codes



State Preparation



Error Correction



Logical Operations

- Advantage: hardware efficient
- Key experimental challenge: difficult to control oscillators (bosonic systems)

Experimental works *(Non Exhaustive):*

Fhlümann, C. et al Nature Nature vol. 566 513–517 (2019)
Eickbusch, A. et al. Nature Physics vol. 18 1464–1469 (2022)
Kudra, M. et al. PRX Quantum vol. 3 (2022)
Tsunoda, T. et al. PRX Quantum vol. 4 (2023)
de Neeve, B. et al. Nat. Phys. vol. 18 296–300 (2022)
Sivak, S. et al. Nature vol. 616 50–55 (2023)
Ni, Z. et al. Nature vol. 616, 56–60 (2023)

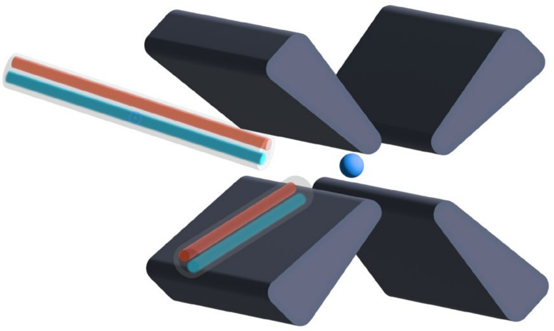
Trapped Ion Oscillator Control

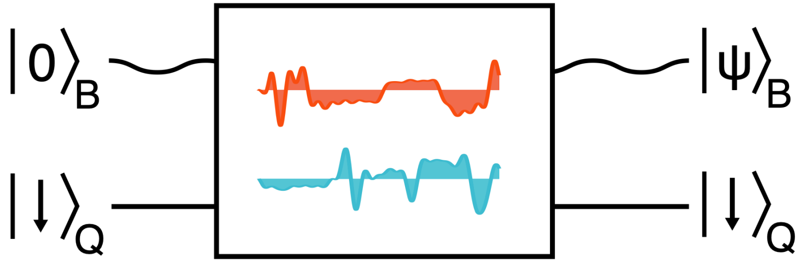
Controls

$$H_{\text{control}}(t) = \frac{\Omega}{2}\hat{\sigma}^{+}\left(\hat{a}e^{i\phi_r(t)} + \hat{a}^{\dagger}e^{i\phi_b(t)}\right) + \text{h.c.}$$

Red SB

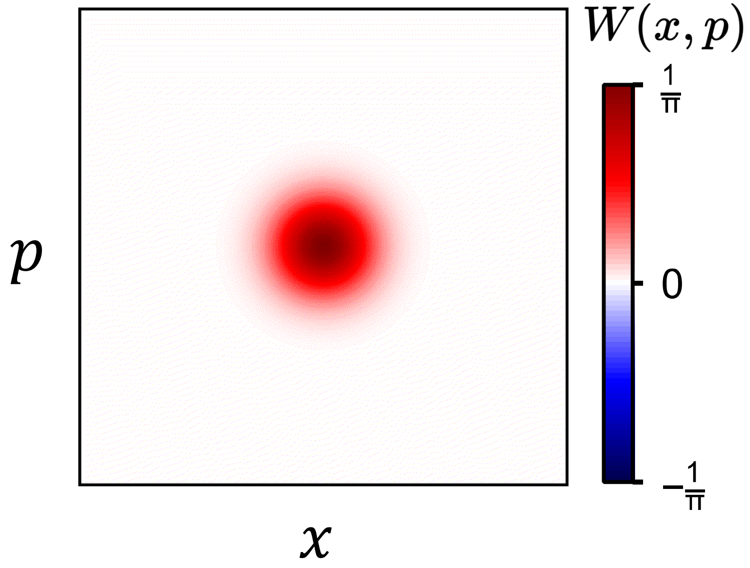
Blue SB





Optimize: $\{\boldsymbol{\phi_r}, \boldsymbol{\phi_b}\}$

Minimize: $$C = \sum_{k=-n}^{n} e^{-k^2}\left(1 - \left|\left\langle \psi_{\text{target}}, \downarrow \middle| \hat{U}_k \middle| 0, \downarrow \right\rangle\right|^2\right) + \epsilon\frac{T}{T_{\text{max}}} \qquad U_k$$



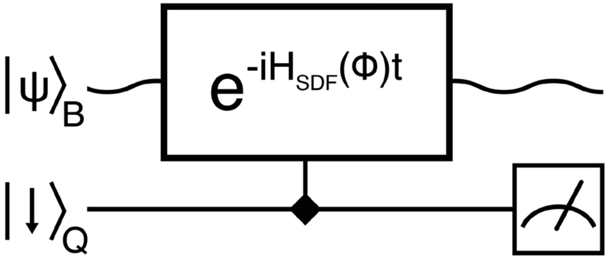
Related Control Works:

Hastrup et al. Physical Review Letters vol. 126 (2021) - (vacuum -> squeezed)
Hastrup et al. npj Quantum Information vol. 7 (2021) - (squeezed → GKP)
Eickbusch, A. et al. Nature Physics vol. 18 1464–1469 (2022) (bosonic state prep. cQED)
Kudra, M. et al. PRX Quantum vol. 3 (2022)
Lachance-Quirion, D et al. ArXiv 2310.11400

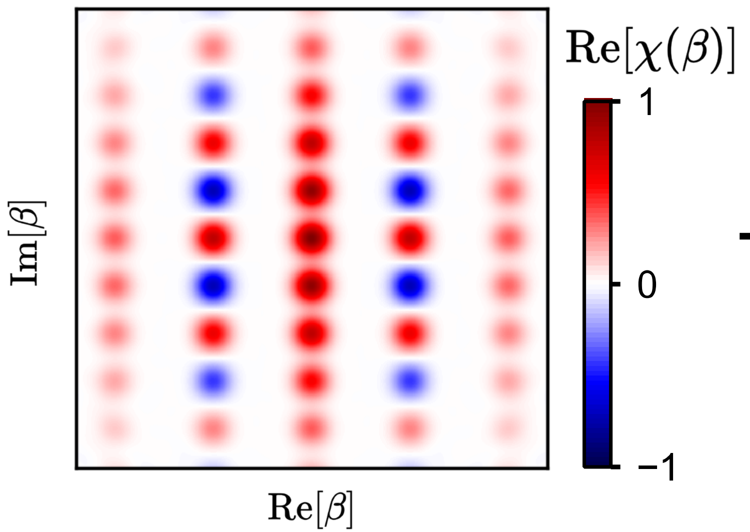
Trapped Ion Oscillator Characterization

Characterization

$$H_{\mathrm{SDF}}(\phi) \propto \Omega \hat{\sigma}_x (\cos(\phi)\hat{x} - \sin(\phi)\hat{p})$$



Characteristic Function



Convex Optimization

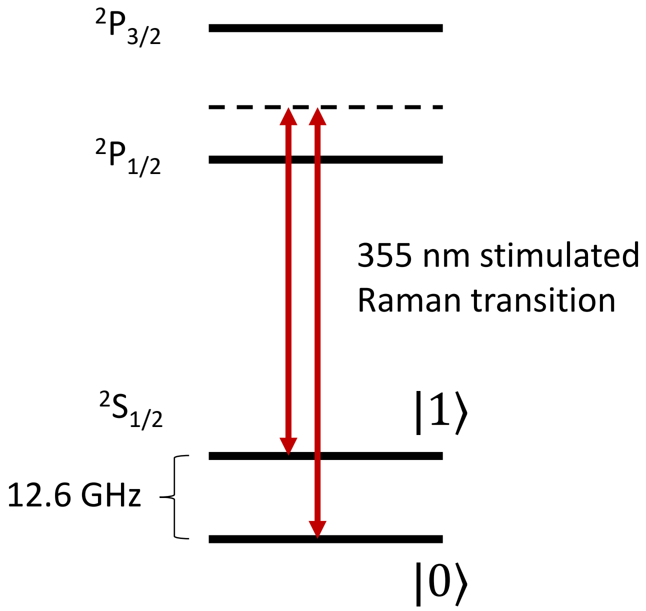
Density Matrix $\hat{\rho}$

Flühmann, C. et al. Physical Review Letters vol. 125 (2020) – (Characteristic function)
Ahmed, S. et al. Physical Review Letters vol. 127 (2021) – (Density matrix reconstruction)

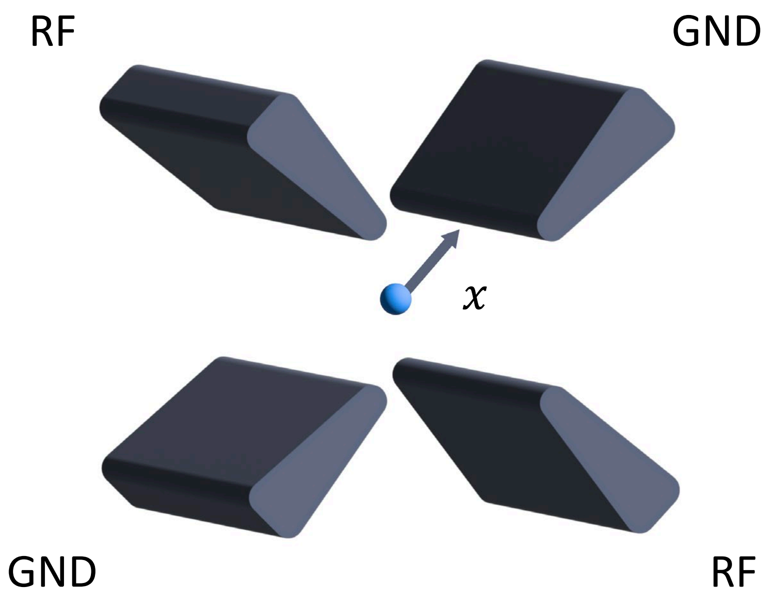
Experimental System

We use a single $^{171}\mathrm{Yb}^+$ ion :

One qubit



One bosonic mode



$$\{\Omega_x, \Omega_y\} = 2\pi \times \{1.33, 1.51\}\ \text{MHz}$$

Performance metric

Radial Mode Dephasing:
1.5ms -> 50 ms

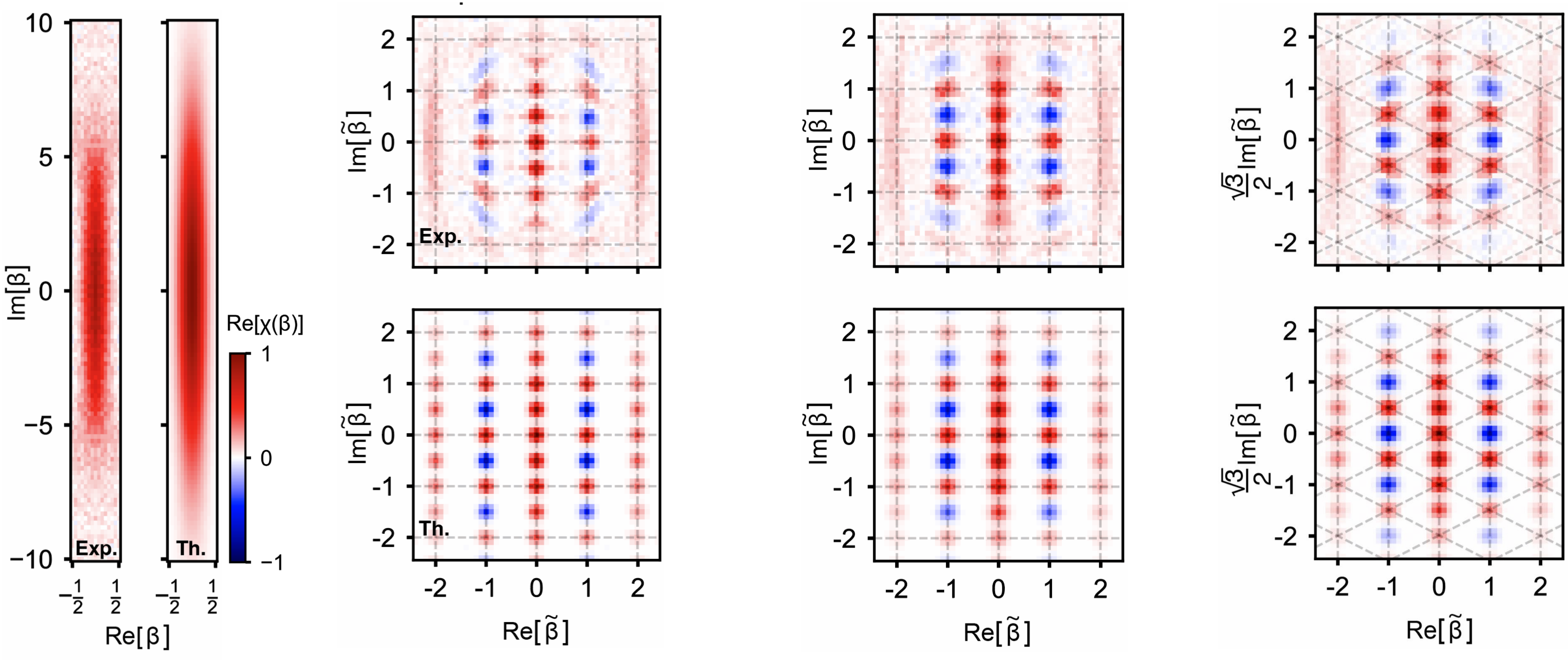
Radial Mode Motional heating:
0.2 quanta/s

Qubit Dephasing:
0.8s -> 8.7 s

Single-qubit (spin) gates
2.0×10^{-5} -> 1.6×10^{-6}

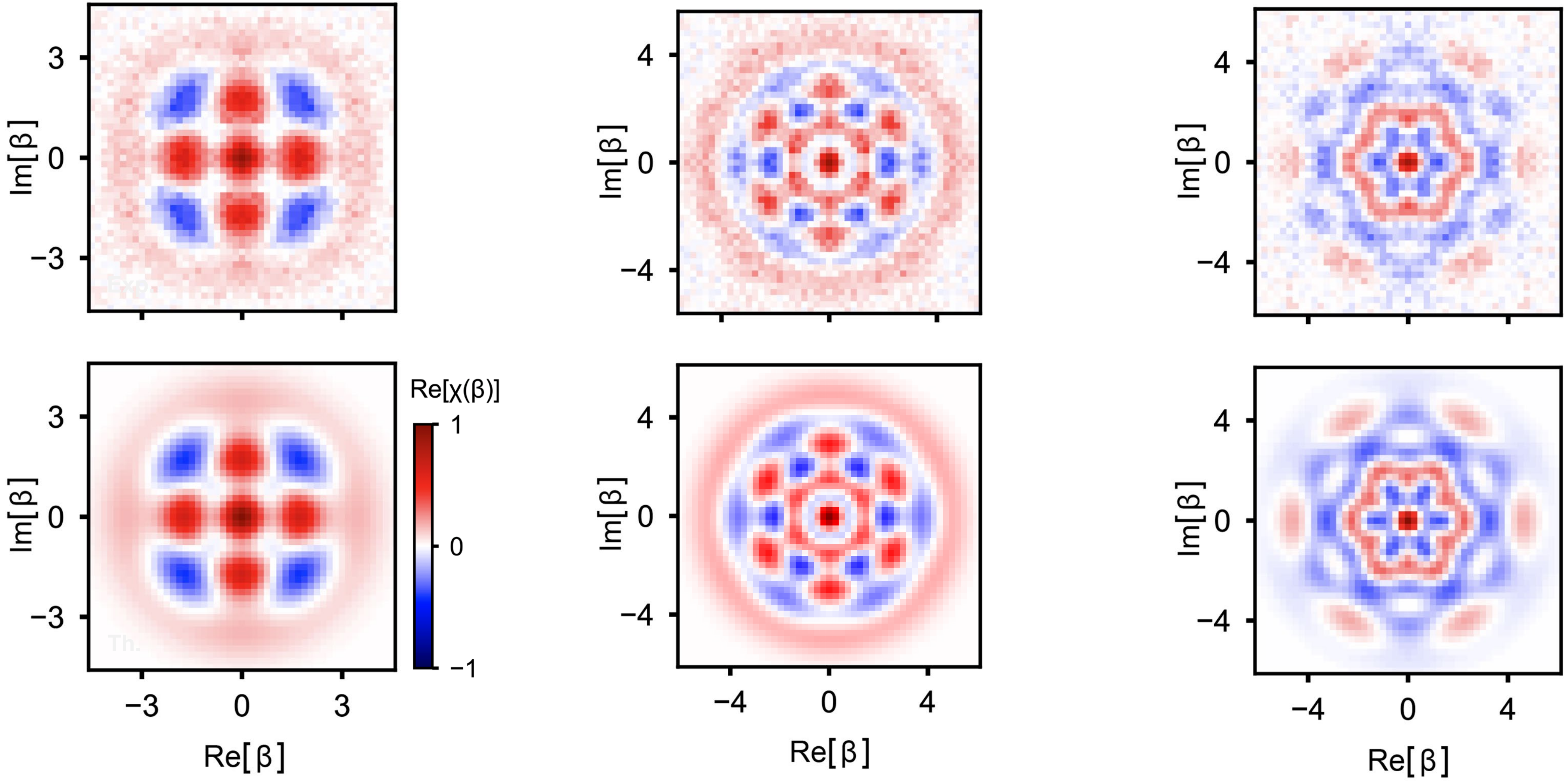
Experiment Data: Squeezed State & GKP State Preparation

Target State	Squeezed 13.5 dB	Square 12.2 dB $\|0\rangle_L$	Square 10.4 dB $\|0\rangle_L$	Hex. 10.4 dB $\|0\rangle_L$
Squeezing (dB)	12.91(5)	$\{5.5(2)_X, 6.3(3)_Z\}$	$\{7.5(2)_X, 7.5(2)_Z\}$	$\{6.5(3)_X, 6.3(4)_Z\}$
Fidelity	0.753(4)	0.60(1)	0.83(1)	0.77(3)
Logical Fidelity	-	0.90(1)	0.940(8)	0.92(1)

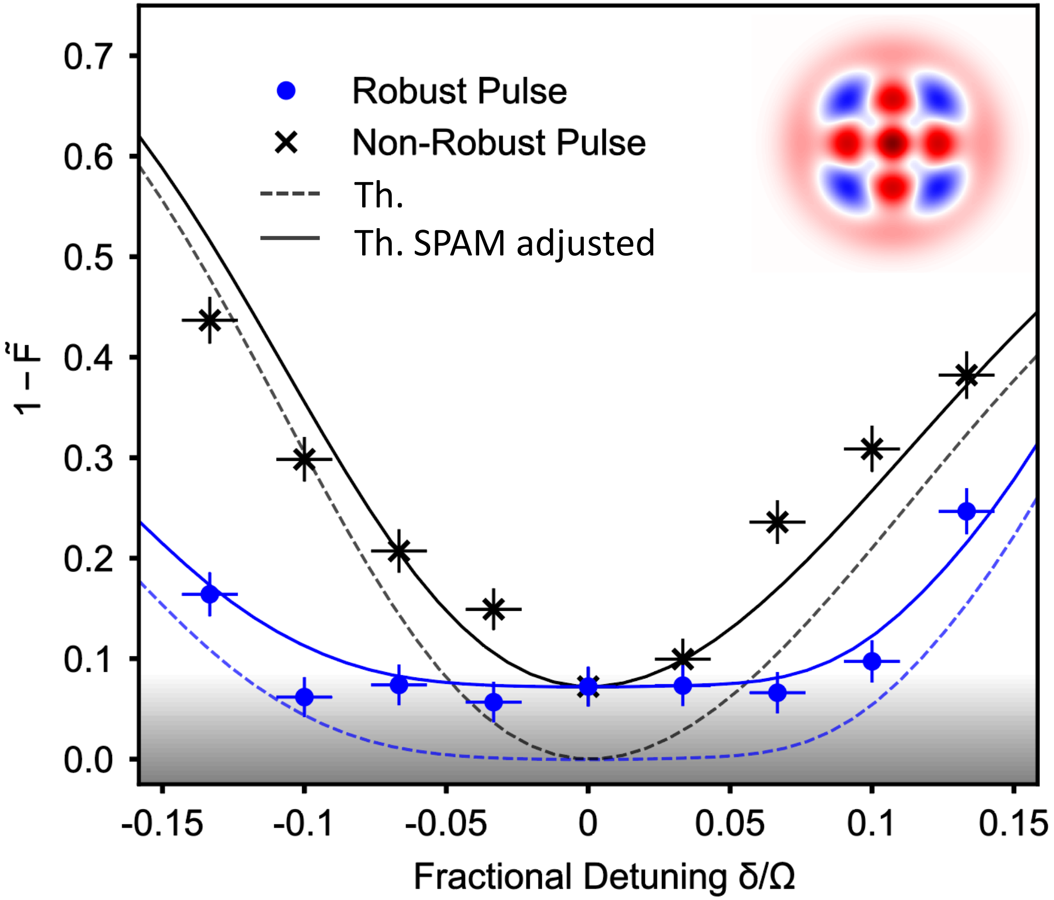


Binomial State Preparation

	Distance 2	Distance 3	
Target	$\lvert 0\rangle_L = (\lvert 0\rangle + \lvert 4\rangle)/\sqrt{2}$	$\lvert 0\rangle_L = (\lvert 0\rangle + \sqrt{3}\lvert 6\rangle)/2$	$\lvert 1\rangle_L = (\sqrt{3}\lvert 3\rangle + \lvert 9\rangle)/2$
Fidelity	0.889(9)	0.843(9)	0.77(1)

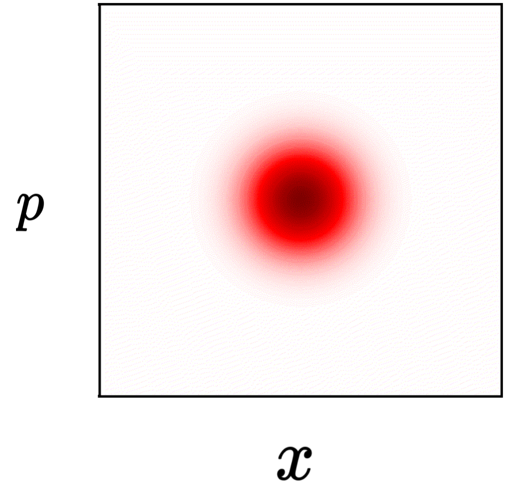


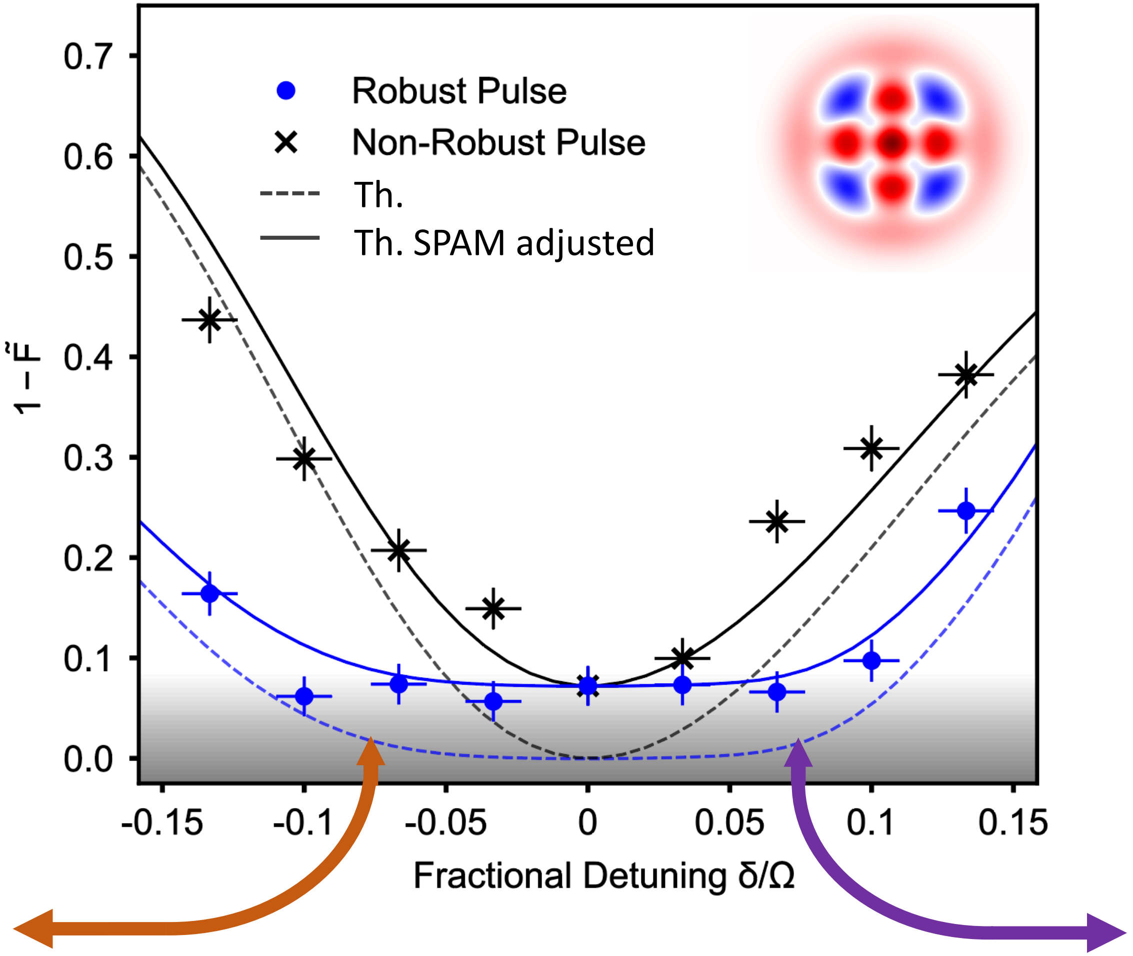
Demonstrating Noise-Robust Binomial State Preparation



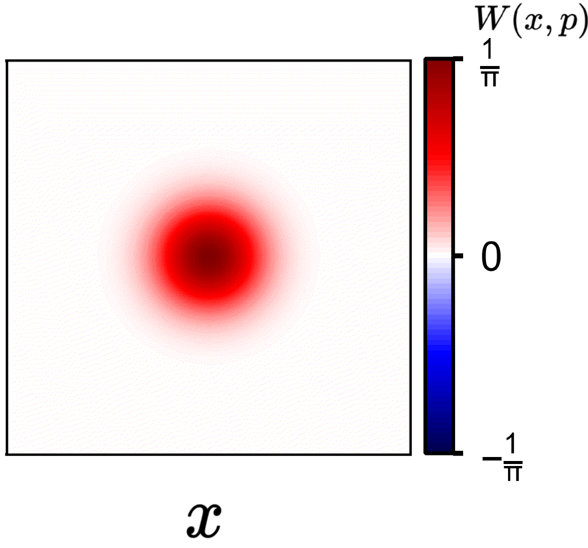
Demonstrating Noise-Robust Binomial State Preparation

$H_{k,\,\text{noise}} = -0.075\Omega a^\dagger a$

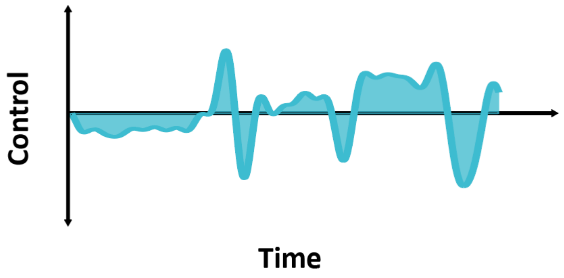




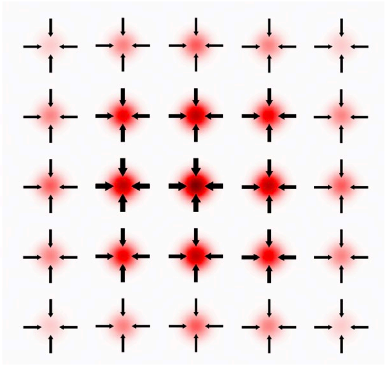
$H_{k,\,\text{noise}} = 0.075\Omega a^\dagger a$



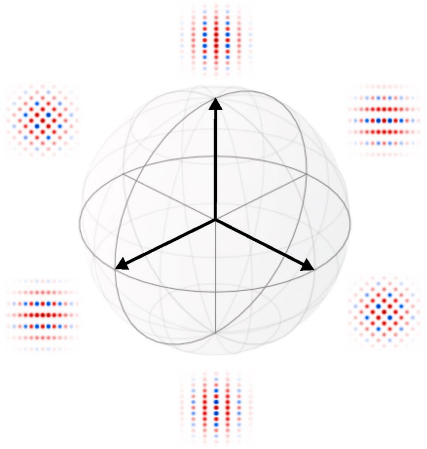
Future opportunities: beyond state preparation



State Preparation



Error Correction



Logical Operations

This Work:

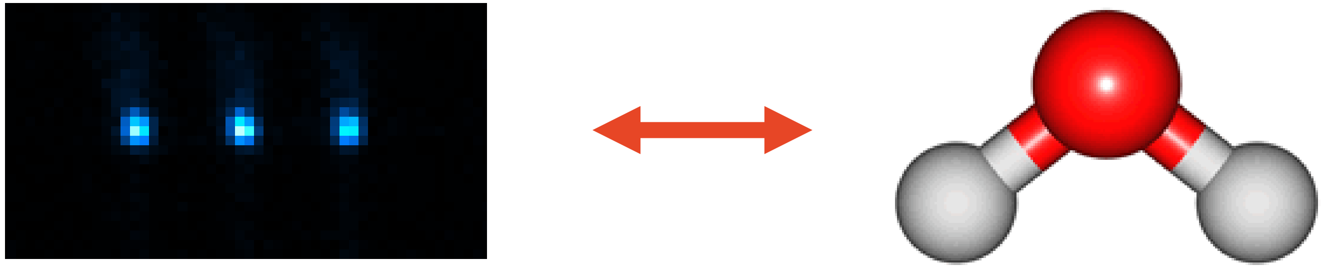
- Versatile
- Deterministic
- Noise Robust

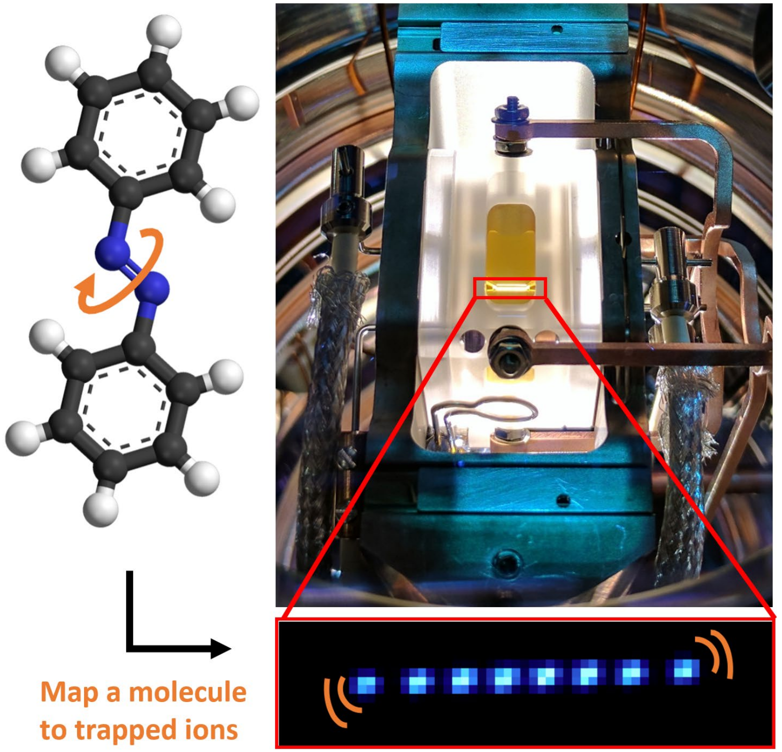
Future Work:

- State preparation and error correction of multi-mode bosonic states
- Single and two-qubit gates on GKP states

Simulating quantum chemistry with mechanical motions of trapped ions

Leverage bosonic modes that may otherwise go unused





Map a molecule to trapped ions

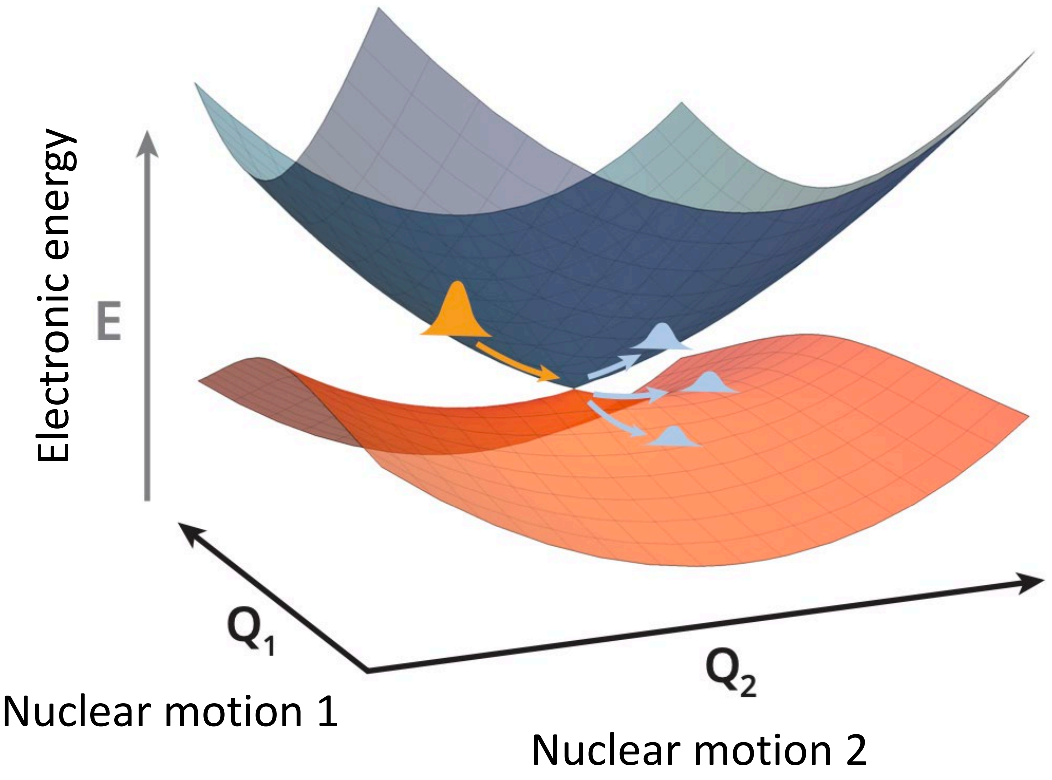
Key advantages:

- Incredible hardware efficiency
- Well-suited for dynamics problems (beyond static problems)
- Noise/dissipation is a feature, instead of a problem to simulate chemical dynamics in open quantum system
- Programmable

R. MacDonell, et al. "Analog quantum simulation of chemical dynamics," Chem. Sci **12**, 9794 (2021)

Our focus: Quantum chemistry beyond the Born-Oppenheimer approximation

Hardest to simulate with classical computers due to strong coupling between molecular electronic levels and nuclear vibrations



Conical Intersections: Electronic Structure, Dynamics & Spectroscopy (World Scientific, 2004).

- Conical intersection is a prime example of problems that are beyond the Born-Oppenheimer approximation: non-adiabatic dynamics
- Ultrafast photochemistry requires a dynamical, quantum treatment
- Exponentially expensive to simulate on classical computers

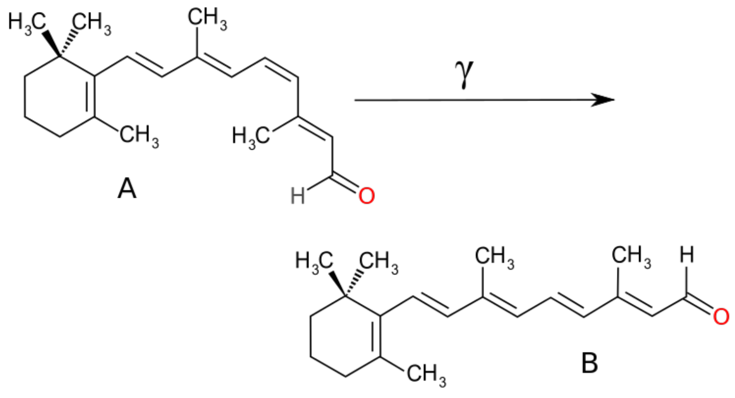
REVIEWS OF MODERN PHYSICS

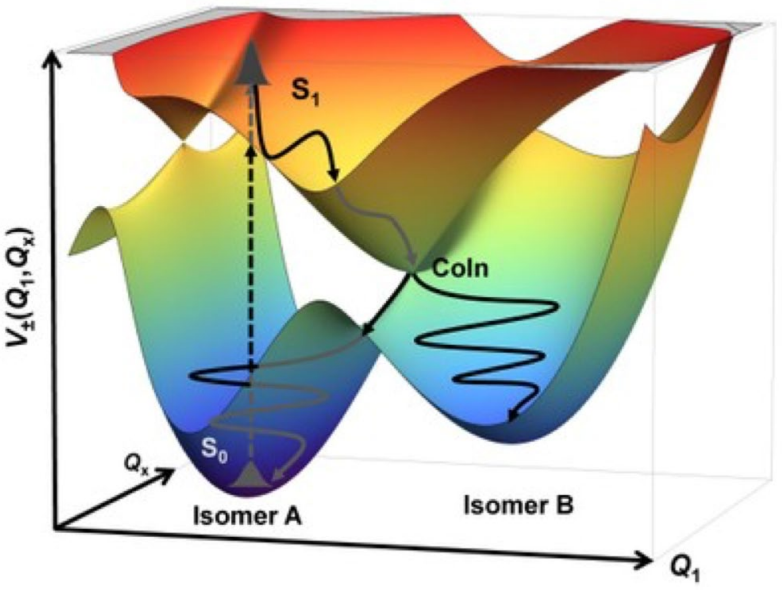
Diabolical conical intersections

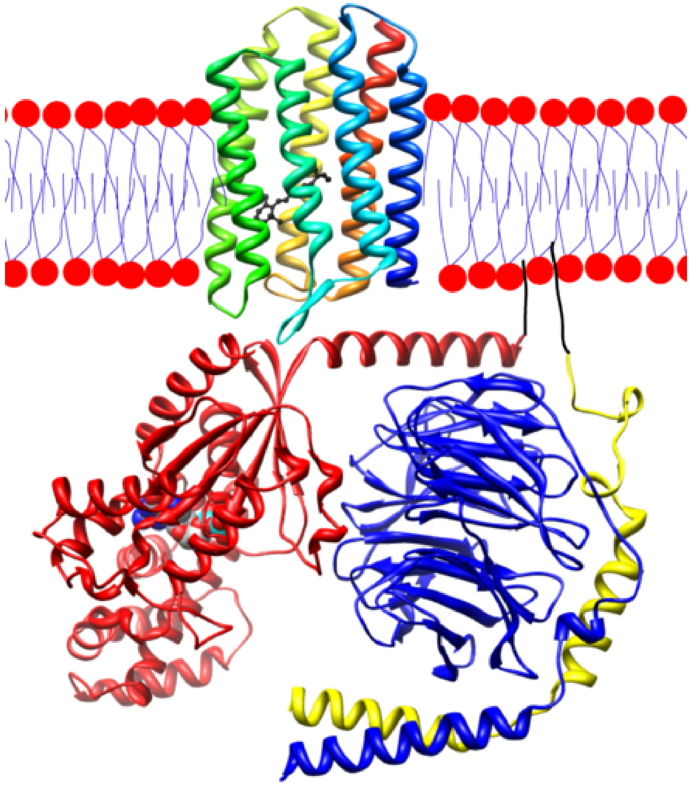
David R. Yarkony

Rev. Mod. Phys. **68**, 985 – Published 1 October 1996

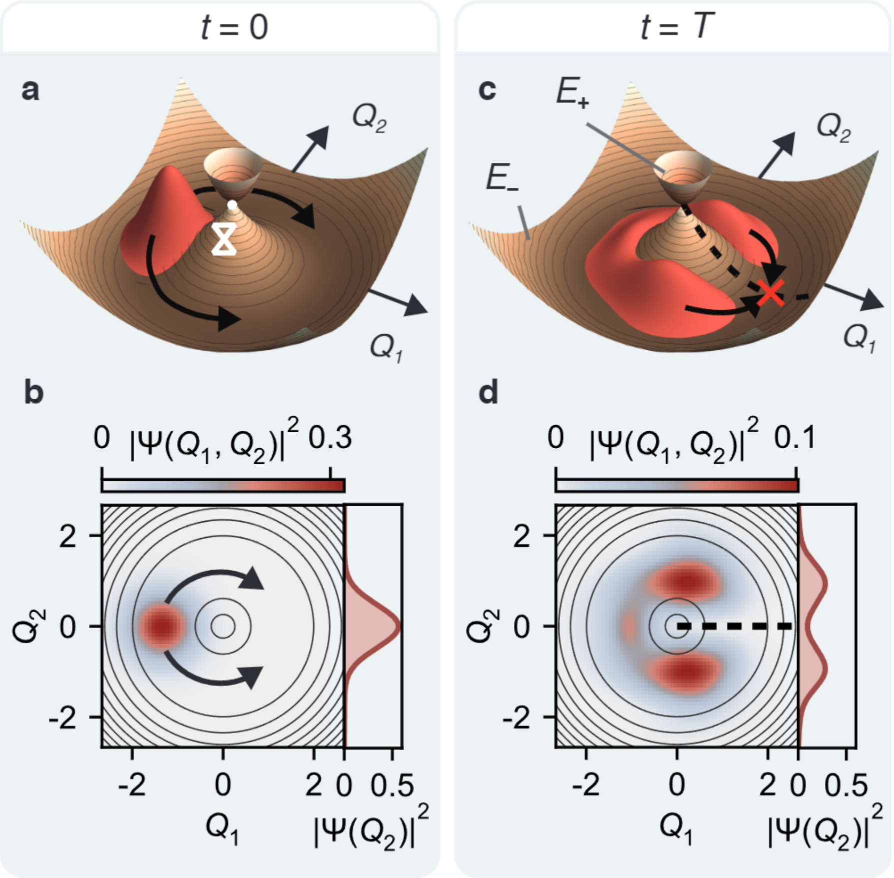
Conical intersection example: vision

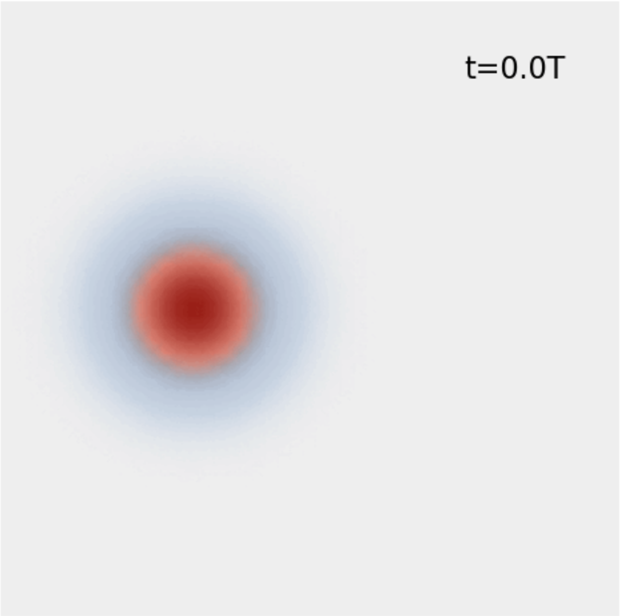






Conical intersection dynamics: geometric phase

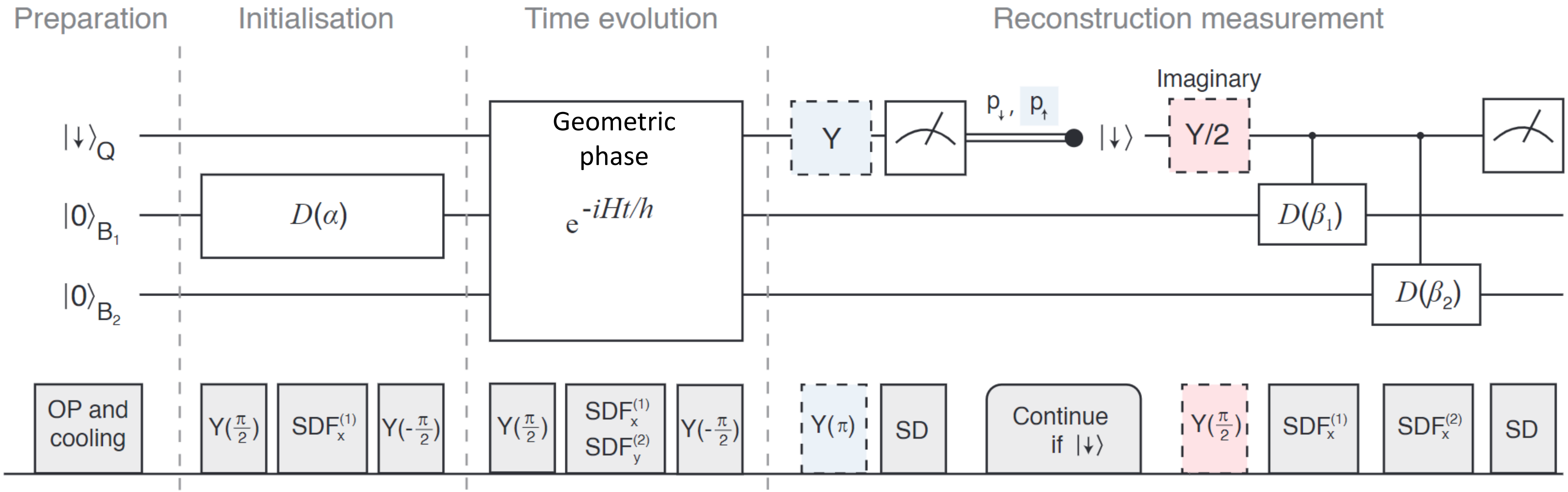




Jahn-Teller conical intersection:

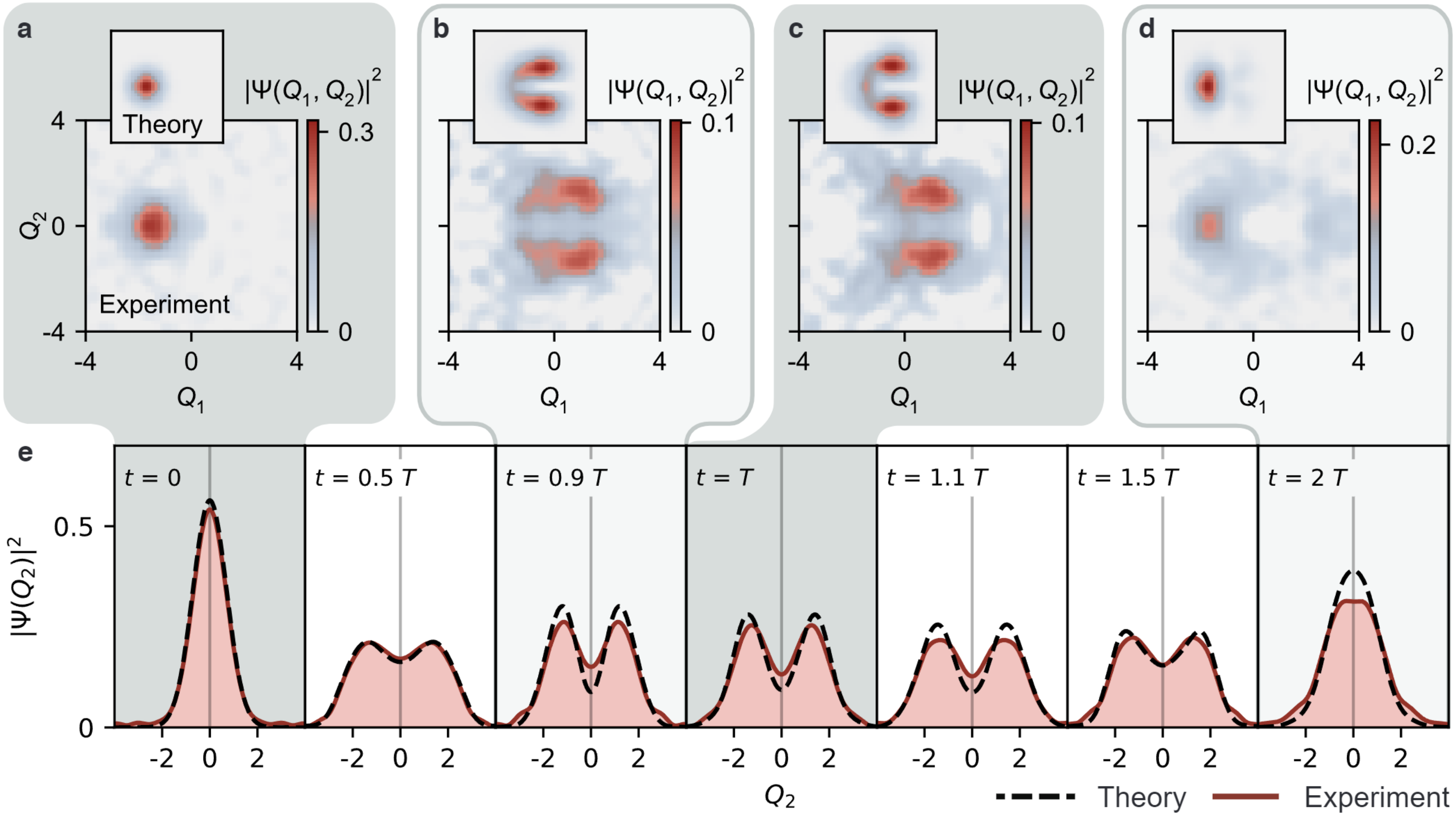
$$\hat{H}_{JT} = \kappa\hat{\sigma}_z\left(\hat{a}_1^\dagger e^{i\omega_1 t} + h.c.\right) + \kappa\hat{\sigma}_x\left(\hat{a}_2^\dagger e^{i\omega_1 t} + h.c.\right)$$

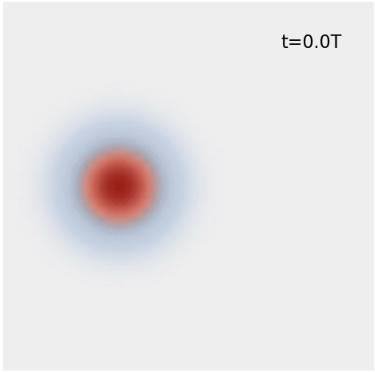
Simulating geometric phase dynamics with a trapped ion



"Direct observation of geometric phase in dynamics around a conical intersection," Nature Chemistry **15**, 1503 (2023)

Experiment data: direct observation of geometric phase interference



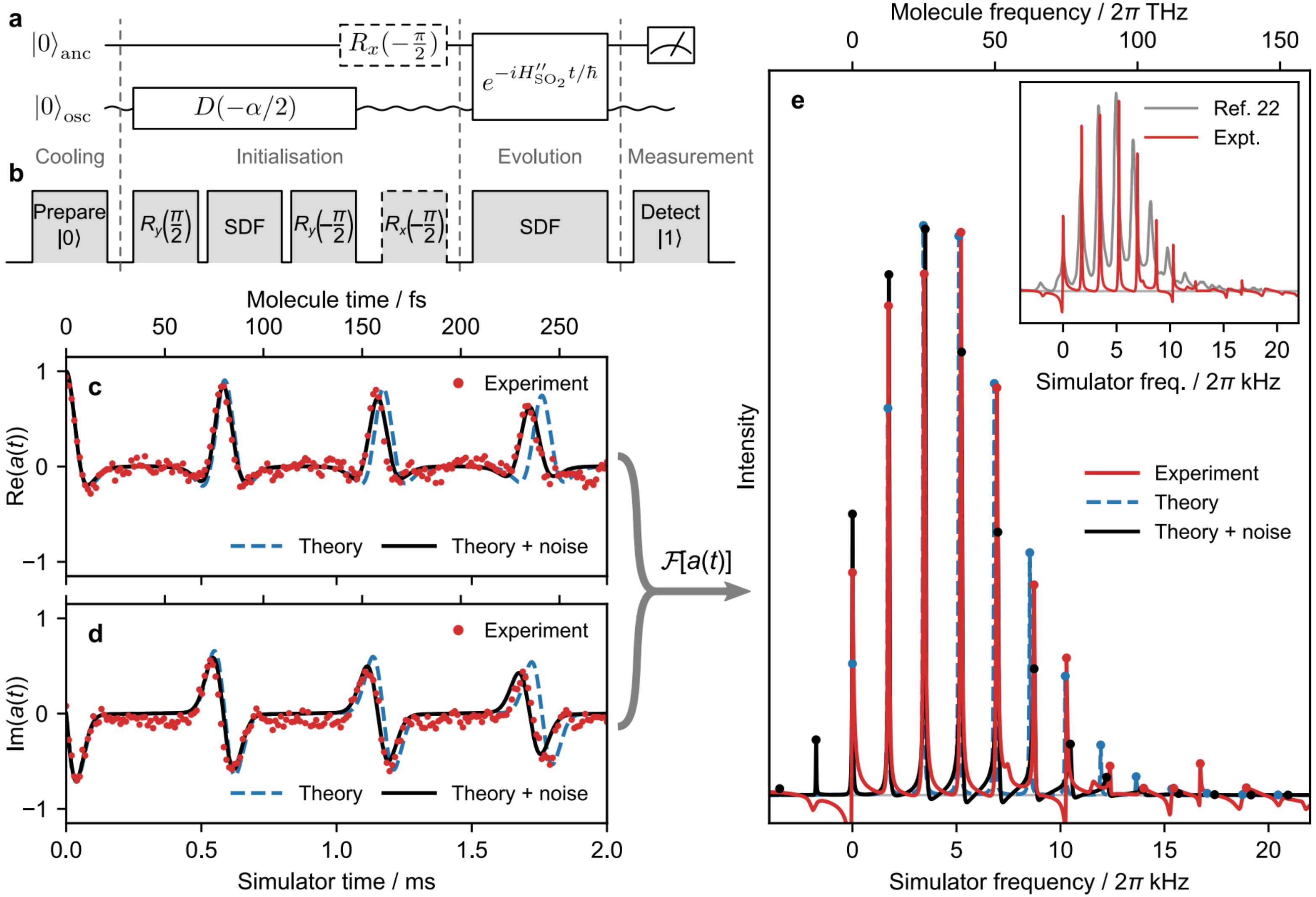


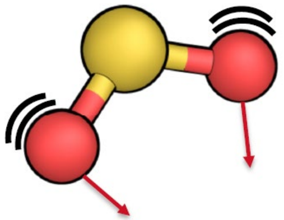
2023 Nov Issue

"Direct observation of geometric phase in dynamics around a conical intersection," Nature Chemistry **15**, 1503 (2023)

See also: "Simulating conical intersections with trapped ions," Nature Chemistry **15**, 1509 (2023) (by Ken Brown's group at Duke)

Experimental data: predicting SO_2 spectra with good agreement with real spectroscopy measurement

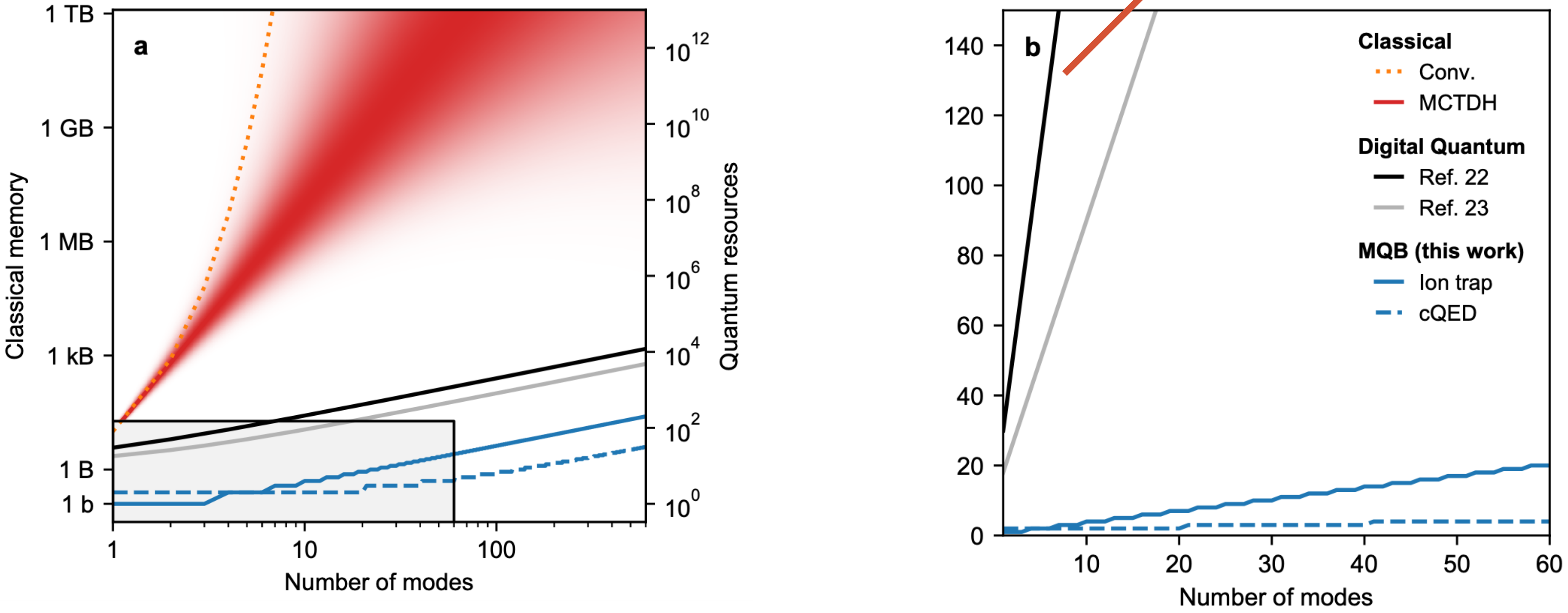




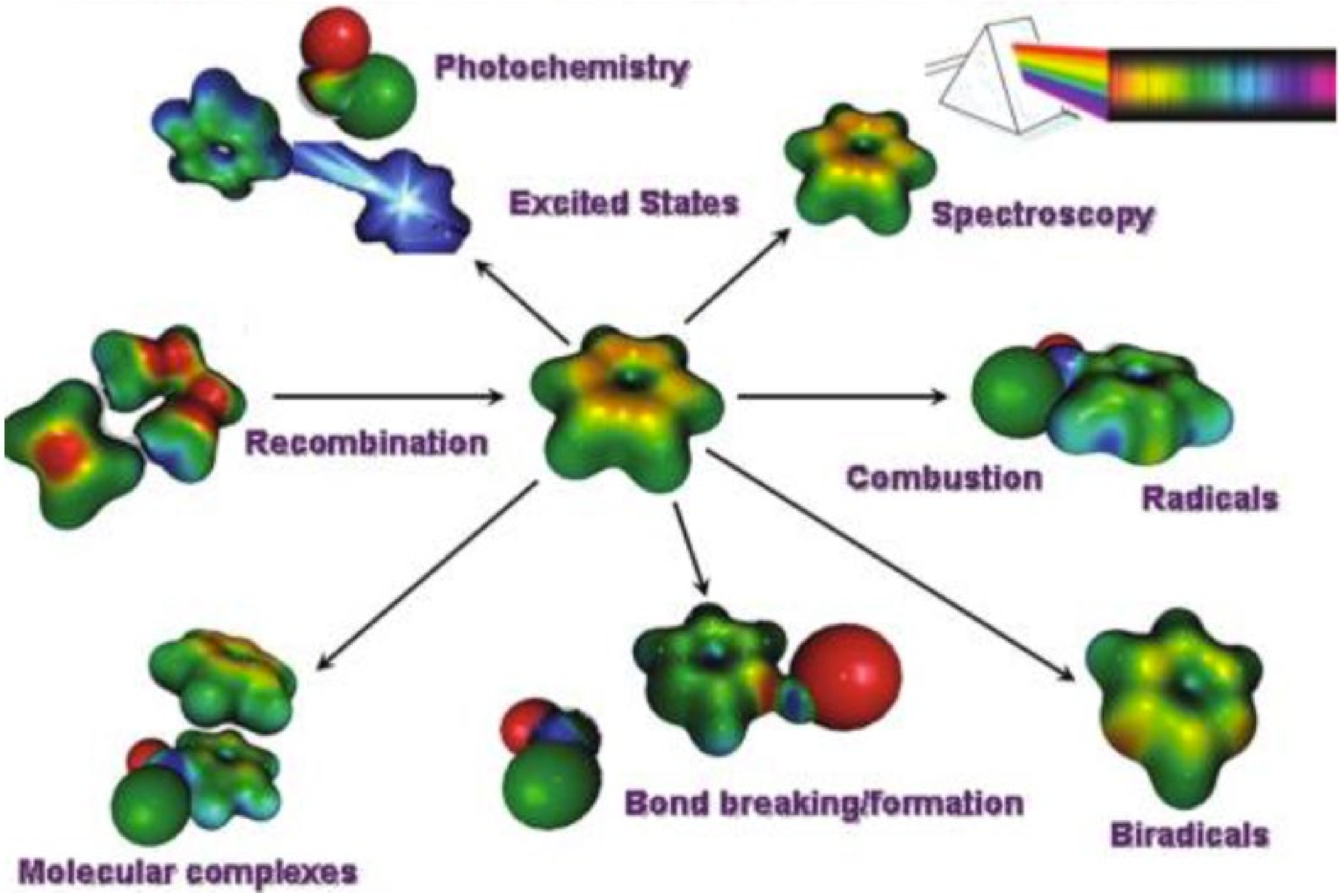
"Predicting molecular vibronic spectra using time-domain analog quantum simulation," Chem. Sci. **14,** 9439 (2023).

Scaling prospective of analog simulators for quantum chemical dynamics

Kassal et al., *PNAS* **105**, 18681 (2008).



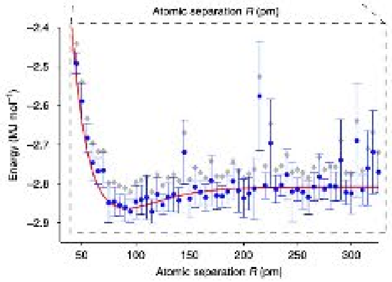
Future opportunities: simulating a large class of chemical *dynamics* difficult for conventional computers



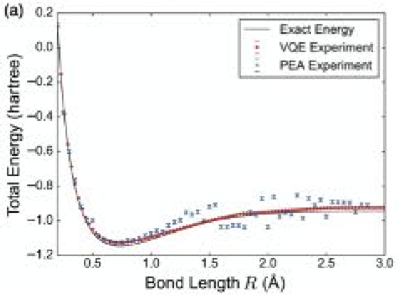
Extra Slides

Chemistry on quantum computer (static problems)

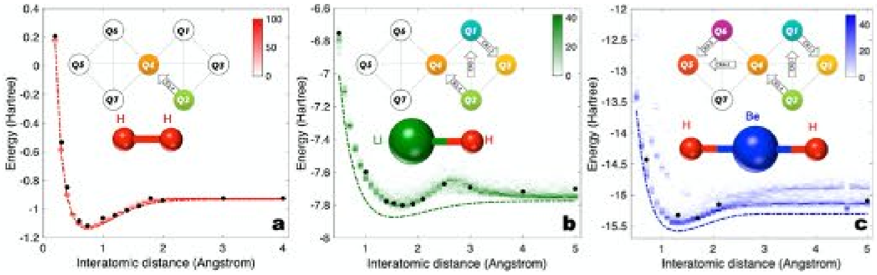
2014



Peruzzo, McClean, et al. (2014)

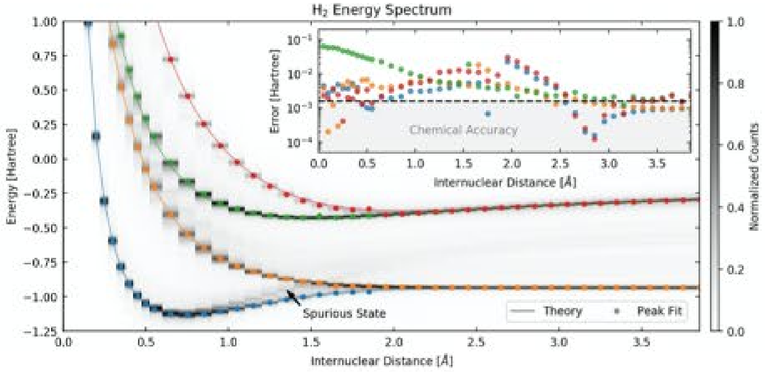


O'Malley, Babbush, et al. (2016)

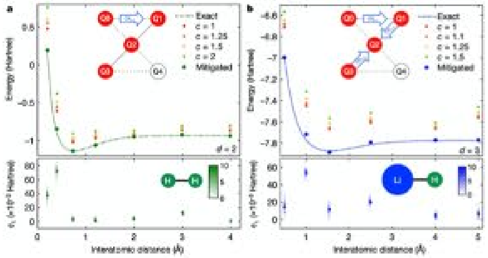


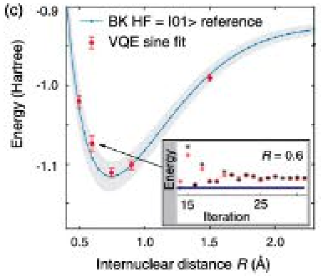
Kandala et al. (2017)

Colless et al. (2017)



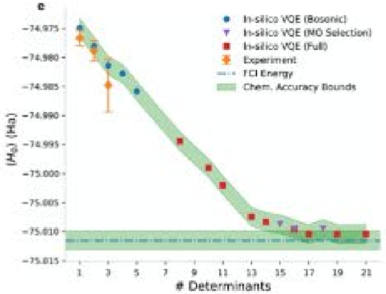
Hempel et al. (2018)





Kandala et al. (2019),

Nam et al. (2019)



Present

Google AI Quantum

Mapping conical intersection to a trapped ion

$$\hat{H}_{CI} = \frac{1}{2}\sum_{j}^{2} \omega_j(\hat{Q}_j^2 + \hat{P}_j^2) - \frac{1}{2}\Delta E\hat{\sigma}_z + \sum_{n}^{2} c_1|n\rangle\langle n|\hat{Q}_1 + c_2\hat{\sigma}_x\hat{Q}_2$$

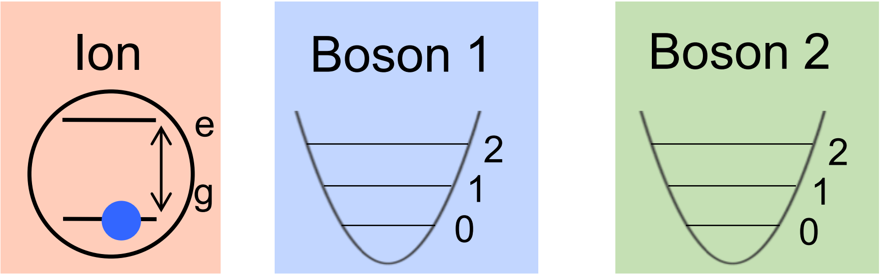
Nucleus motions

Electronic level

“tuning”

“coupling”

Encoding:



Qubit (spin)

Harmonic oscillators

$$\hat{H}_{ion} = \kappa_1\hat{\sigma}_z\left(\hat{a}_1^{\dagger}e^{i\omega_1 t} + h.c.\right) + \lambda_1\hat{\sigma}_x\left(\hat{a}_2^{\dagger}e^{i\omega_2 t} + h.c.\right)$$

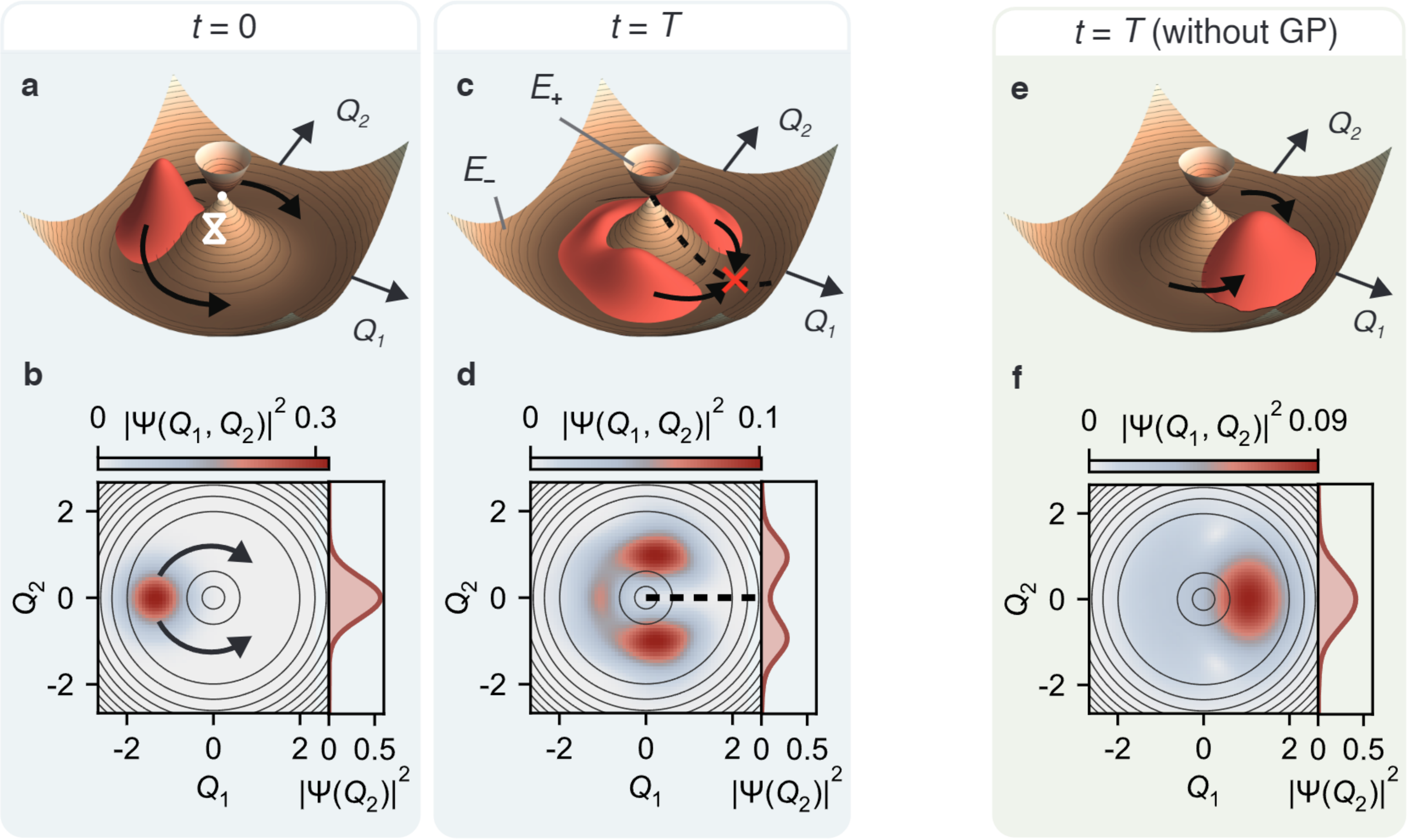
“Phase gate” interaction:

$$\hat{H}_Z = \frac{\eta\Omega_Z}{2}\hat{\sigma}_z\left(\hat{a}^{\dagger}e^{i\omega_1 t} + h.c.\right)$$

“Mølmer Sørensen” interaction:

$$\hat{H}_{MS} = \frac{\eta\Omega_{MS}}{2}\hat{\sigma}_x\left(\hat{a}^{\dagger}e^{i\omega_2 t} + h.c.\right)$$

Geometric phase (GP) around a conical intersection



Pulses

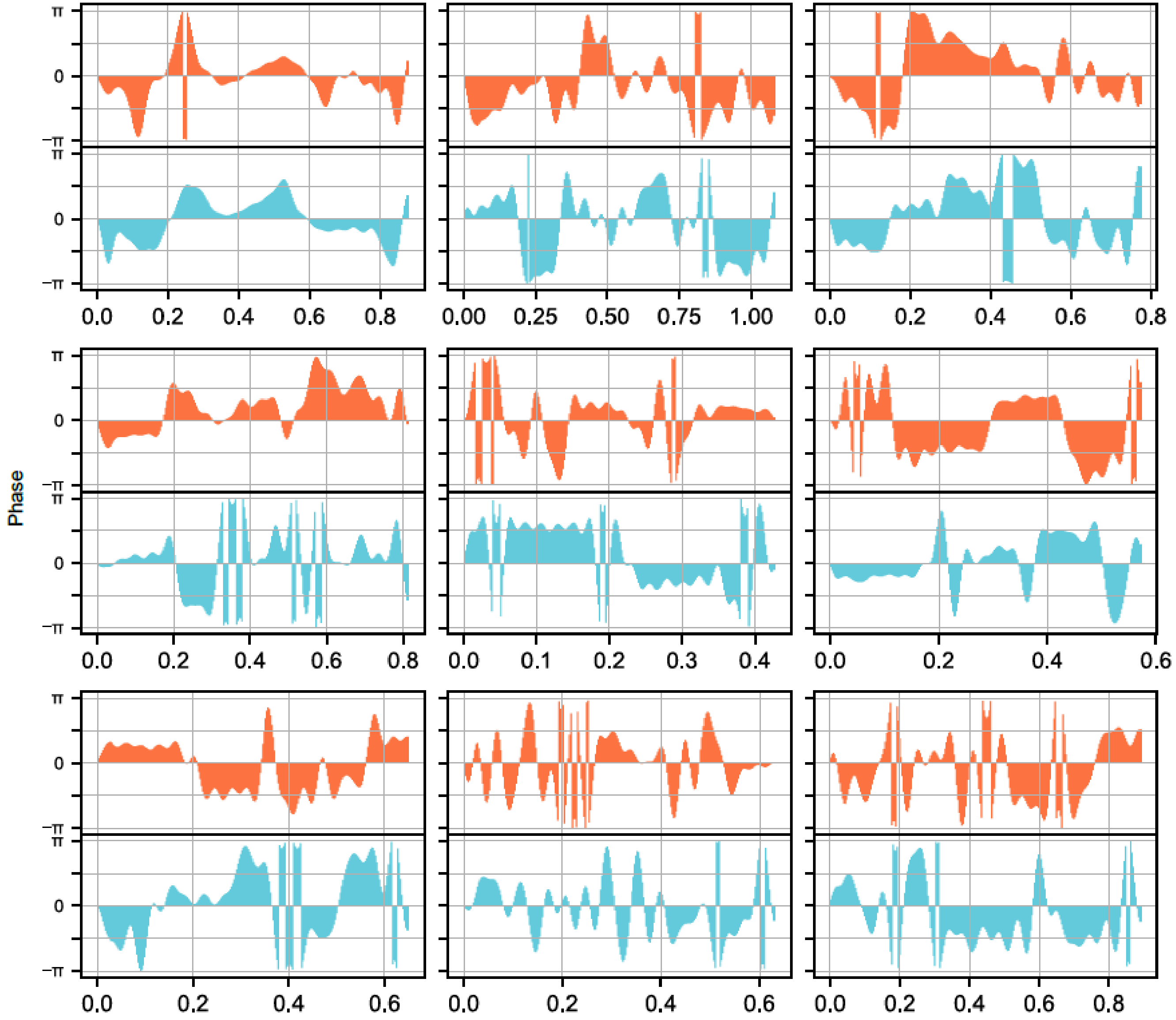
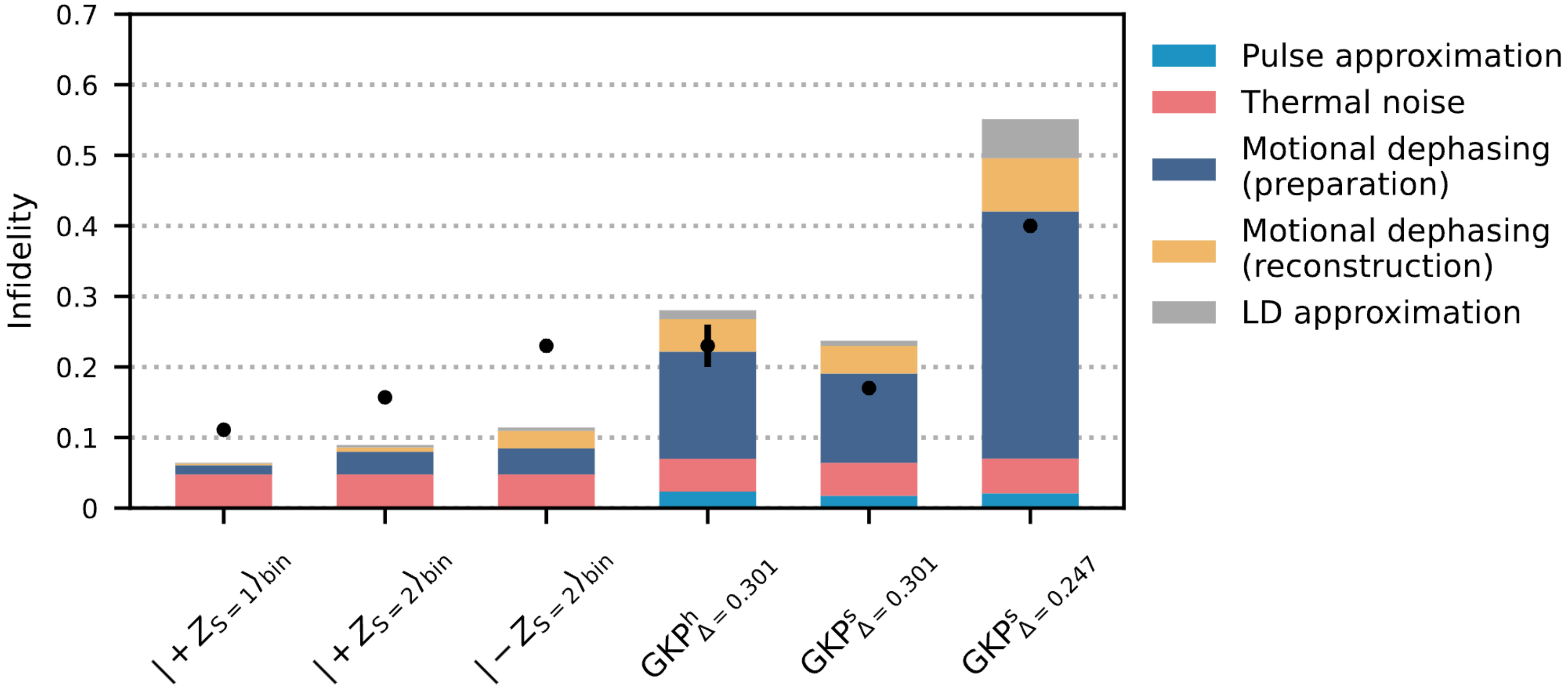
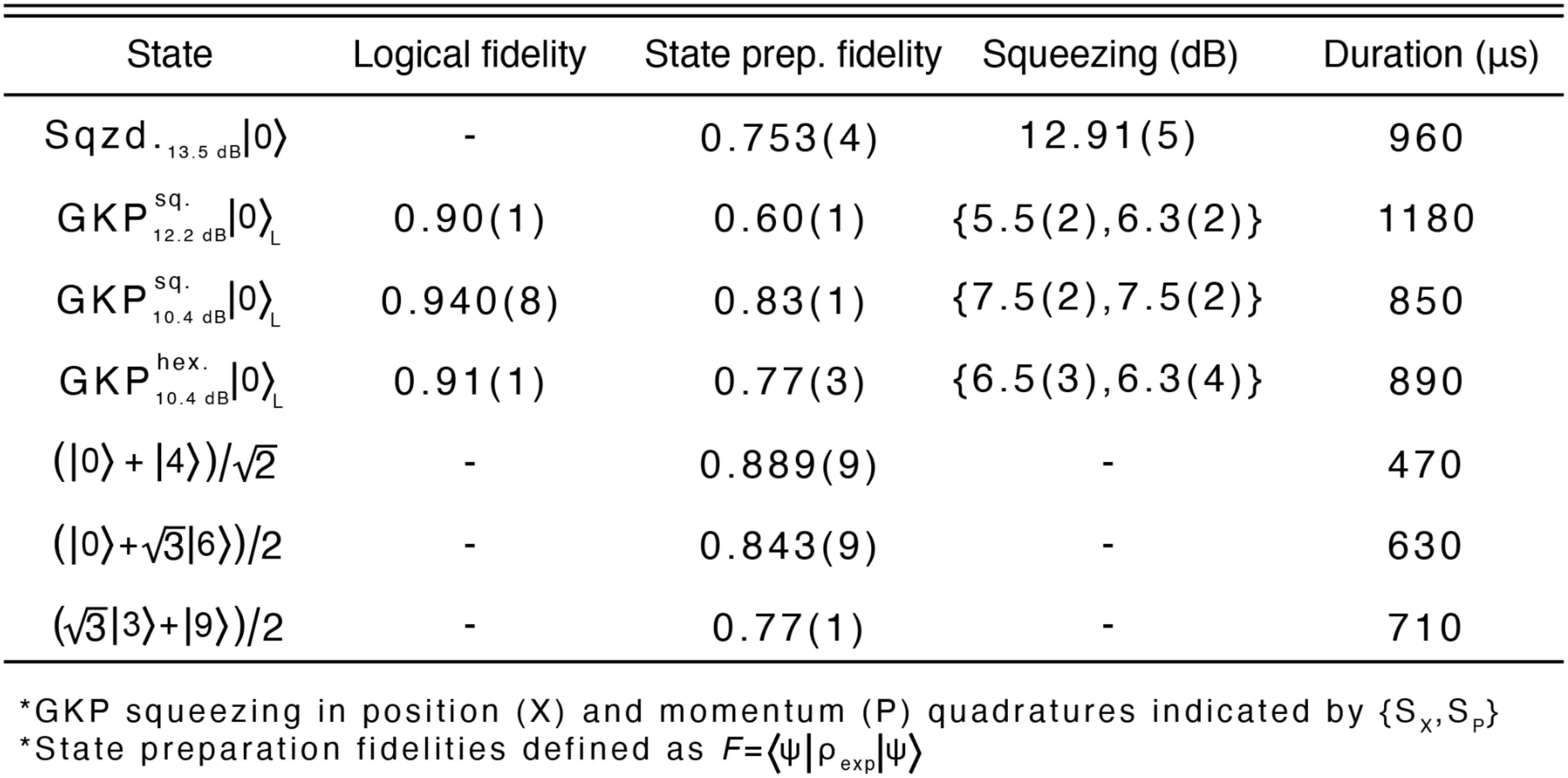


Figure S1. Pulses in order of their appearance in the main text: a) squeezed state, b) 1.4 GKP, c) 1.2 GKP, d) 1.2 GKP hex, e) 04 binomial, f) 06 binomial, g) 39 binomial, h) standard binomial, i) robust binomial

Appendix: Error Budget



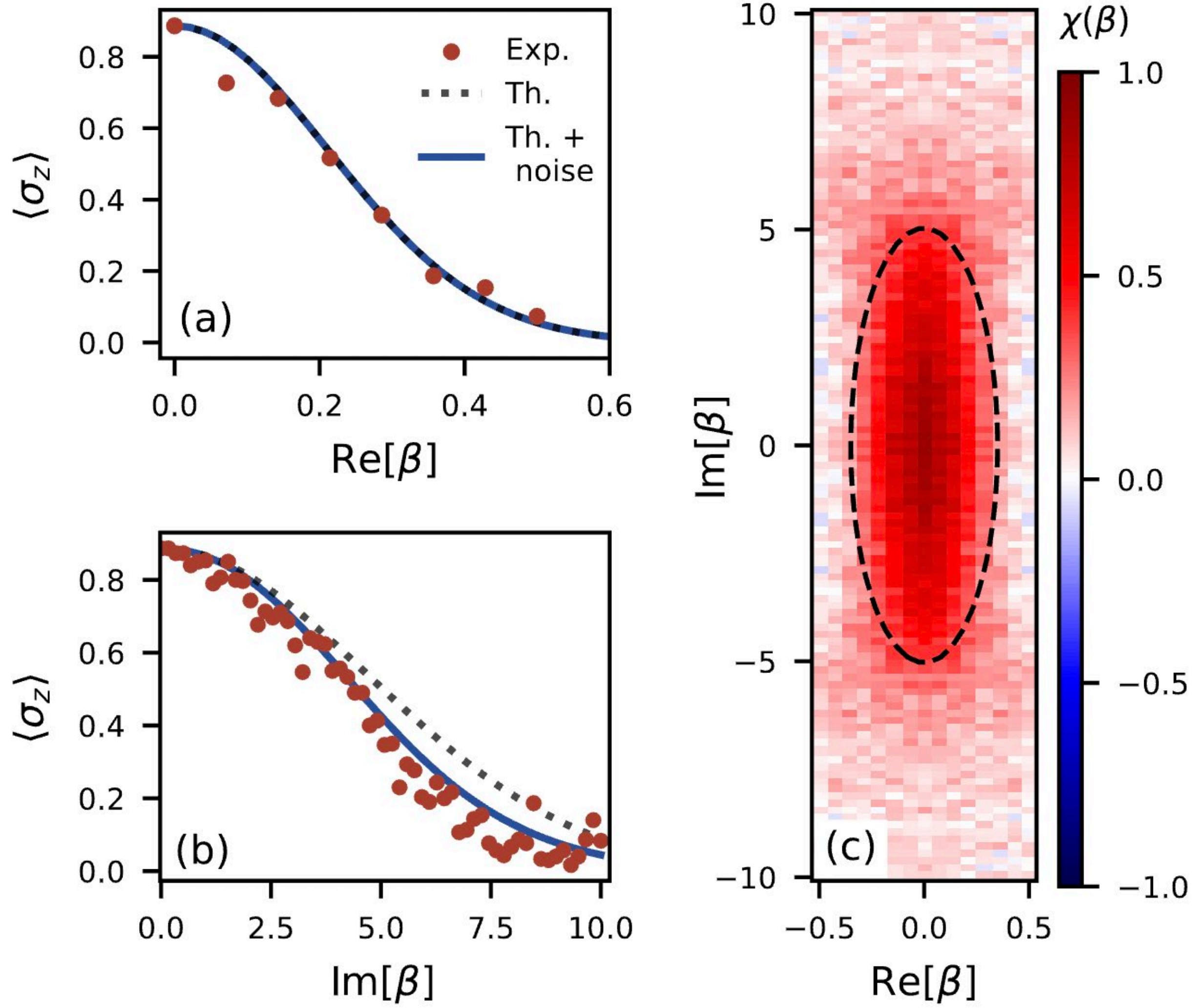
Appendix

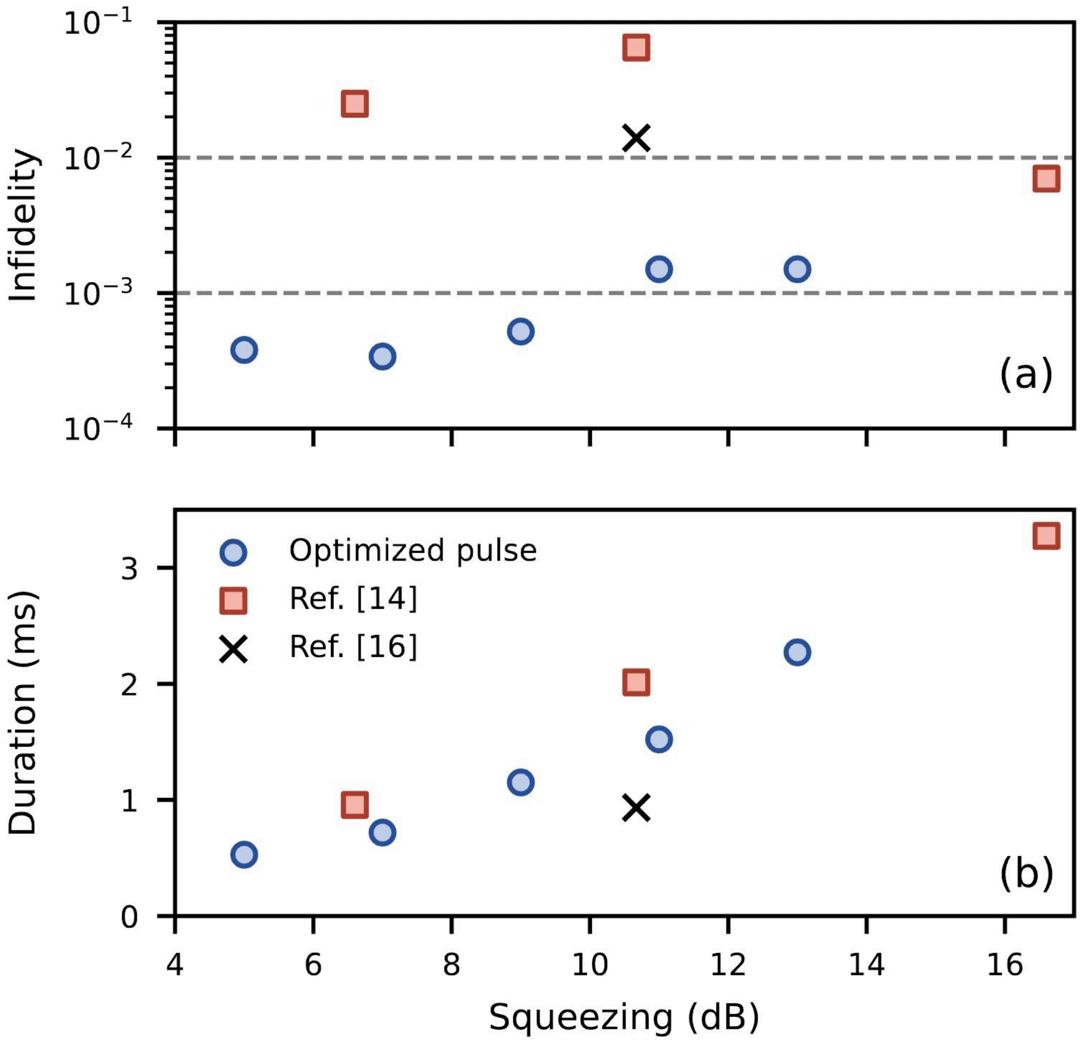


State	Logical fidelity	State prep. fidelity	Squeezing (dB)	Duration (μs)
$\text{Sqzd.}_{13.5\text{ dB}}\|0\rangle$	-	0.753(4)	12.91(5)	960
$\text{GKP}^{\text{sq.}}_{12.2\text{ dB}}\|0\rangle_L$	0.90(1)	0.60(1)	{5.5(2),6.3(2)}	1180
$\text{GKP}^{\text{sq.}}_{10.4\text{ dB}}\|0\rangle_L$	0.940(8)	0.83(1)	{7.5(2),7.5(2)}	850
$\text{GKP}^{\text{hex.}}_{10.4\text{ dB}}\|0\rangle_L$	0.91(1)	0.77(3)	{6.5(3),6.3(4)}	890
$(\|0\rangle + \|4\rangle)/\sqrt{2}$	-	0.889(9)	-	470
$(\|0\rangle+\sqrt{3}\|6\rangle)/2$	-	0.843(9)	-	630
$(\sqrt{3}\|3\rangle+\|9\rangle)/2$	-	0.77(1)	-	710

*GKP squeezing in position (X) and momentum (P) quadratures indicated by $\{S_X,S_P\}$
*State preparation fidelities defined as $F=\langle\psi|\rho_{exp}|\psi\rangle$

Appendix


(a)
⟨σ_z⟩
0.0
0.2
0.4
0.6
0.8
Re[β]
0.0
0.2
0.4
0.6
Exp.
Th.
Th. + noise
(b)
⟨σ_z⟩
Im[β]
0.0
2.5
5.0
7.5
10.0
(c)
Im[β]
10
5
0
−5
−10
Re[β]
−0.5
0.0
0.5
χ(β)
1.0
0.5
0.0
−0.5
−1.0


Infidelity
10^−1
10^−2
10^−3
10^−4
(a)
Duration (ms)
0
1
2
3
Optimized pulse
Ref. [14]
Ref. [16]
(b)
Squeezing (dB)
4
6
8
10
12
14
16

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MR. JOSH NUNN

CSO

ORCA Computing

Q4I

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Networking technologies for effective scaling of quantum computers

Josh Nunn

CSO

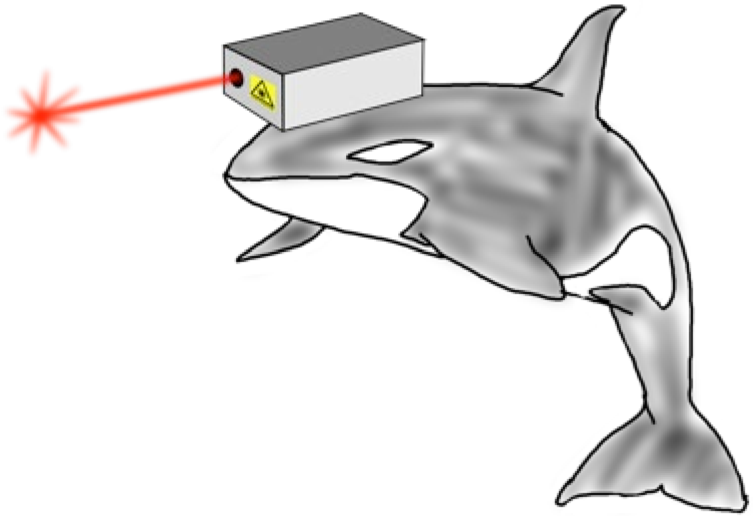
27th June 2024

About ORCA Computing

- Full stack photonic quantum computing (NISQ → FT)
- Incorporated in 2019, just before world ended
- Teams in London, Toronto, Austin
- Academic heritage:

group of Prof. Ian Walmsley while at U. Oxford

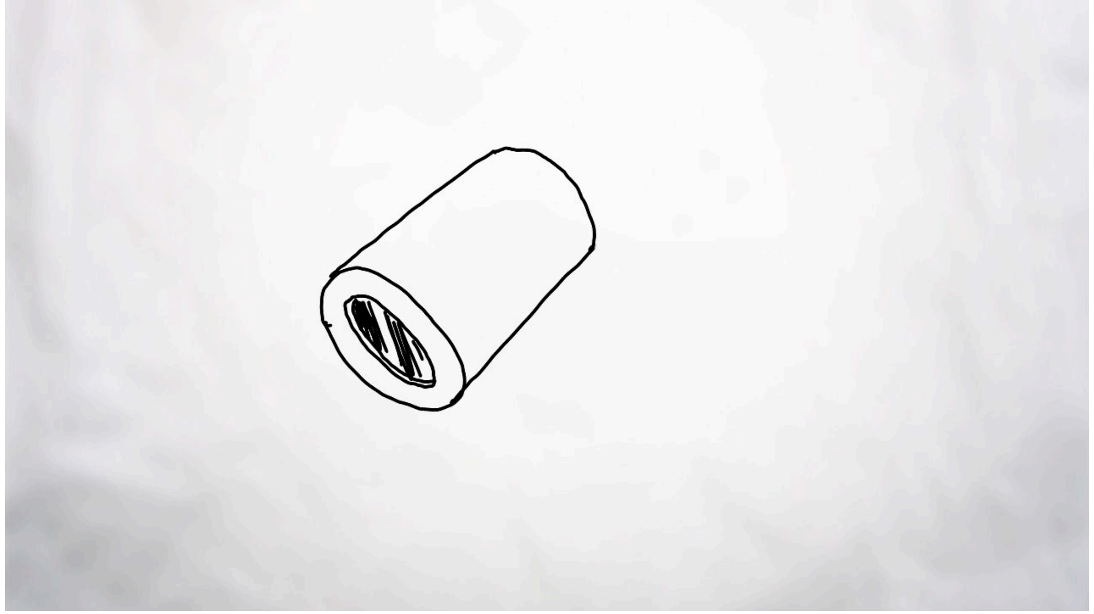
- 62 employees; growing

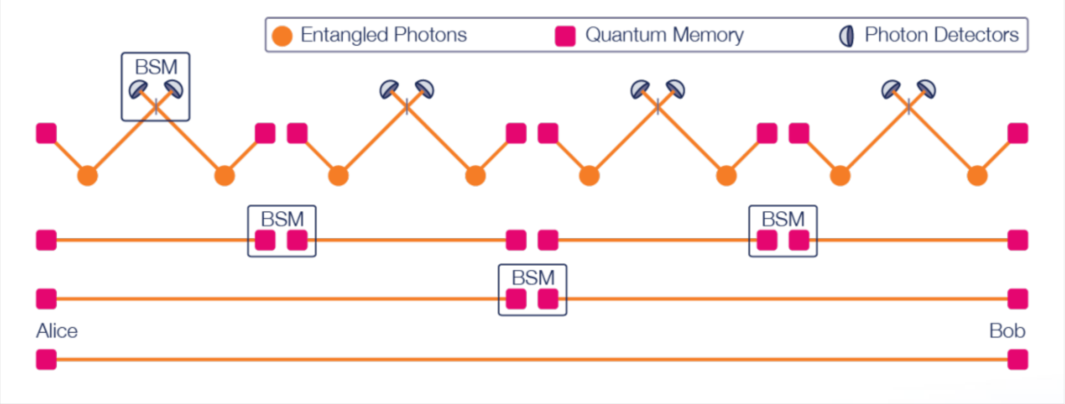


Single photons as qubits

- Noise-free at room temperature
  - No precision atom-trapping, high vacuum or EM shielding
  - Very high bandwidth
  - Optical fibre commercially mature:
    - Very low loss "quantum wiring" for modular systems

Research background

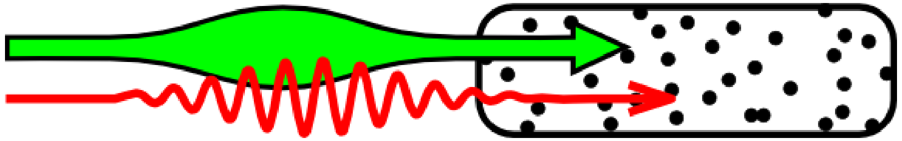




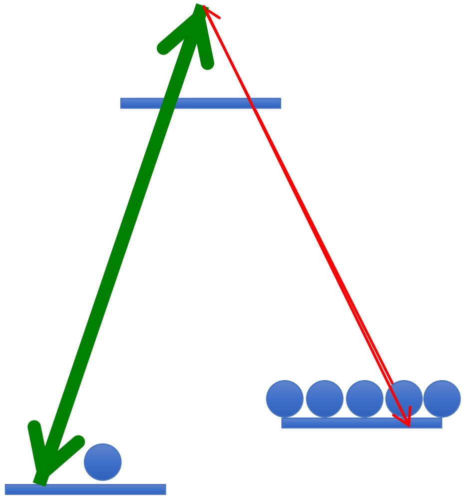
(Oxford 2012)

- Quantum memories for quantum repeaters
- Distribute entanglement by "repeat until success"

Raman memory



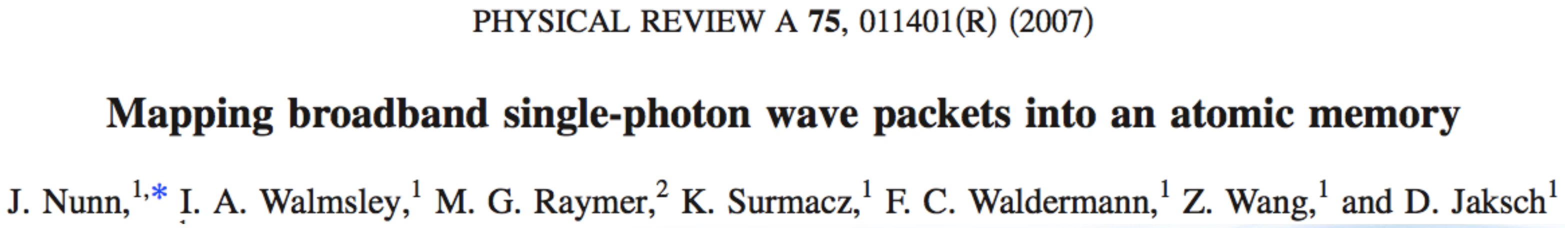
Atomic ensemble



Raman absorption

Off-resonant → Broadband

Control field → Mode-selection & shaping

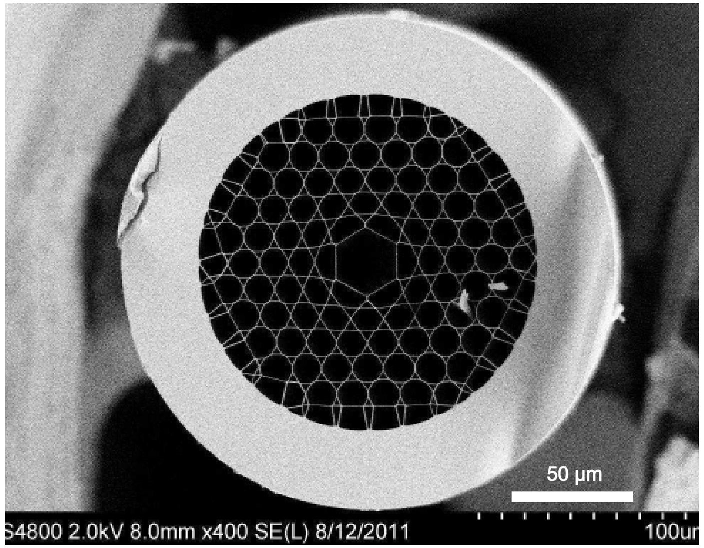


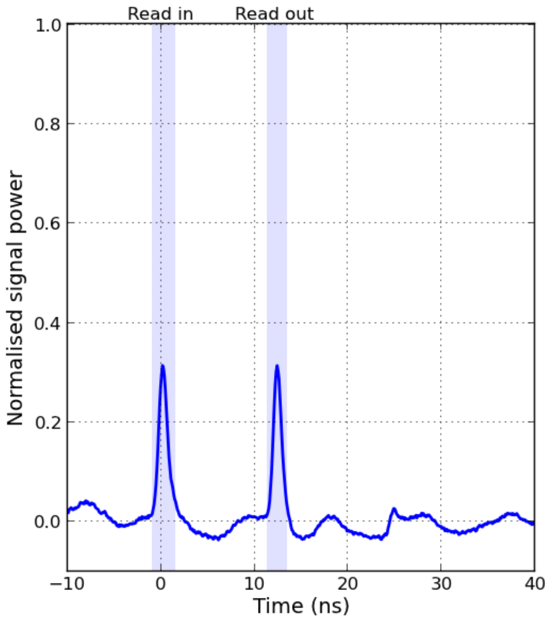
PHYSICAL REVIEW A **75**, 011401(R) (2007)

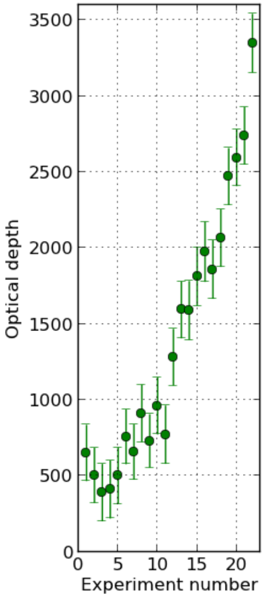
Mapping broadband single-photon wave packets into an atomic memory

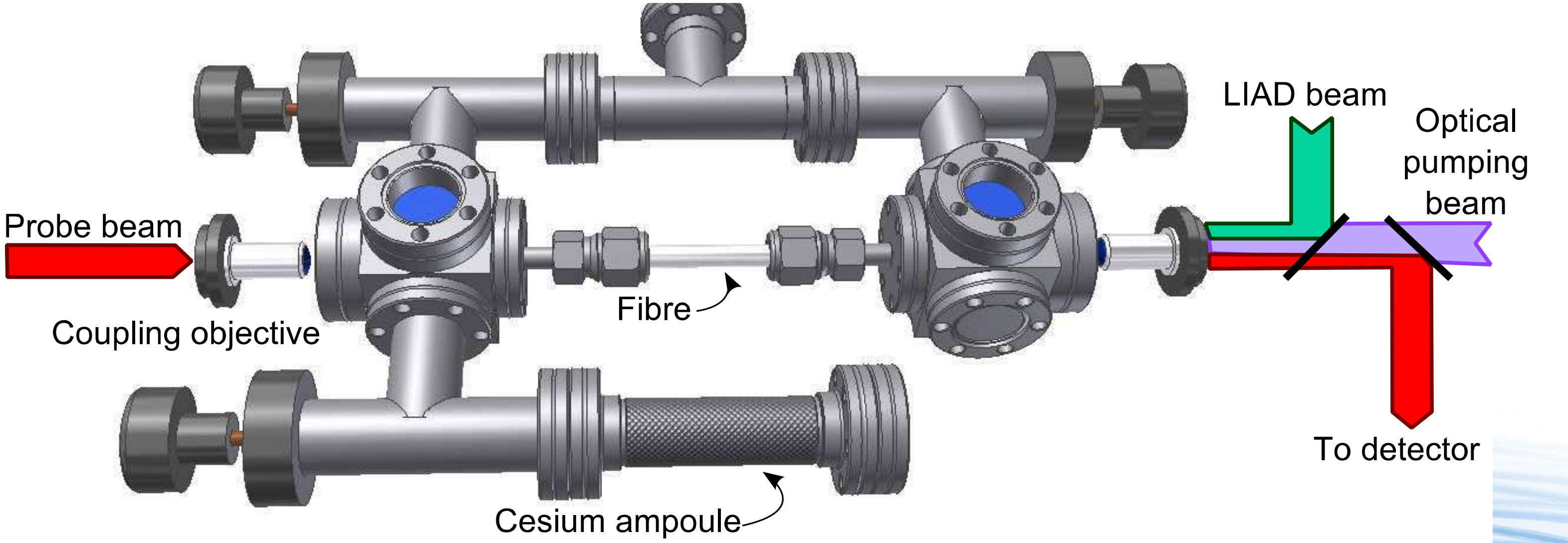
J. Nunn,[1,*] I. A. Walmsley,[1] M. G. Raymer,[2] K. Surmacz,[1] F. C. Waldermann,[1] Z. Wang,[1] and D. Jaksch[1]

Light storage in fibre

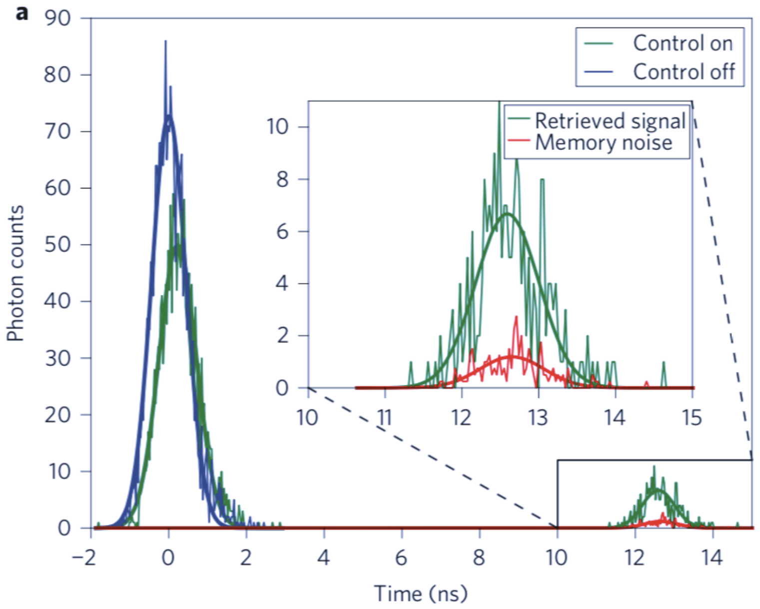


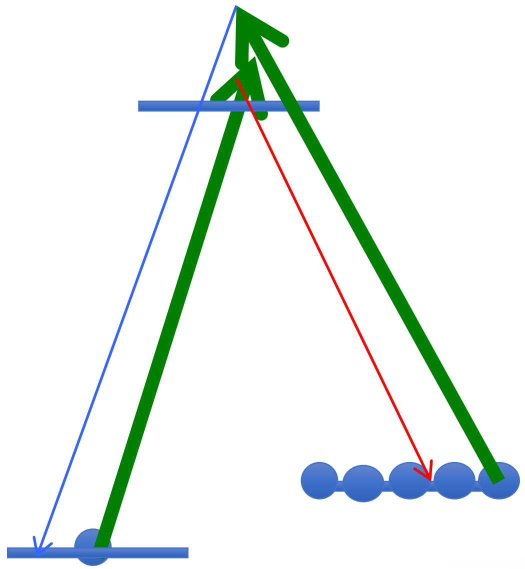




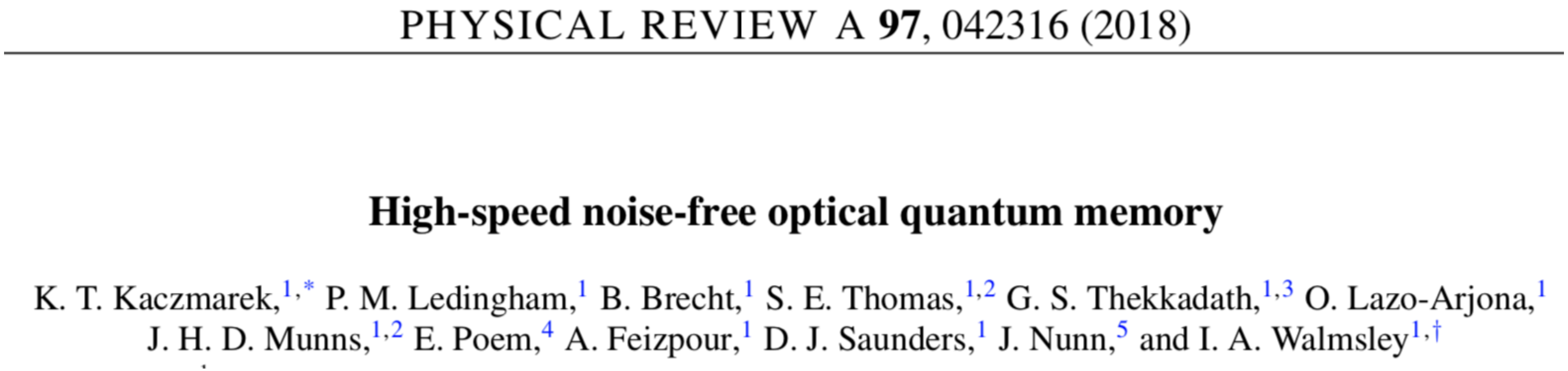


But: four-wave mixing noise





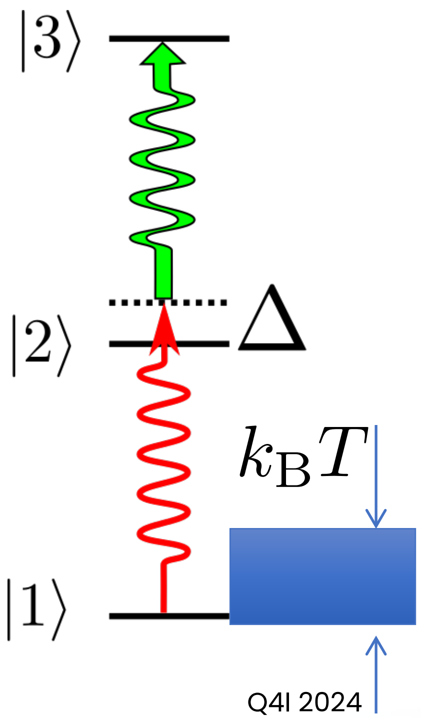
- Control couples to ground state
- Spontaneous anti-Stokes scattering produces spurious phonon
- Control pulse retrieves spurious phonon as noise



PHYSICAL REVIEW A **97**, 042316 (2018)

High-speed noise-free optical quantum memory

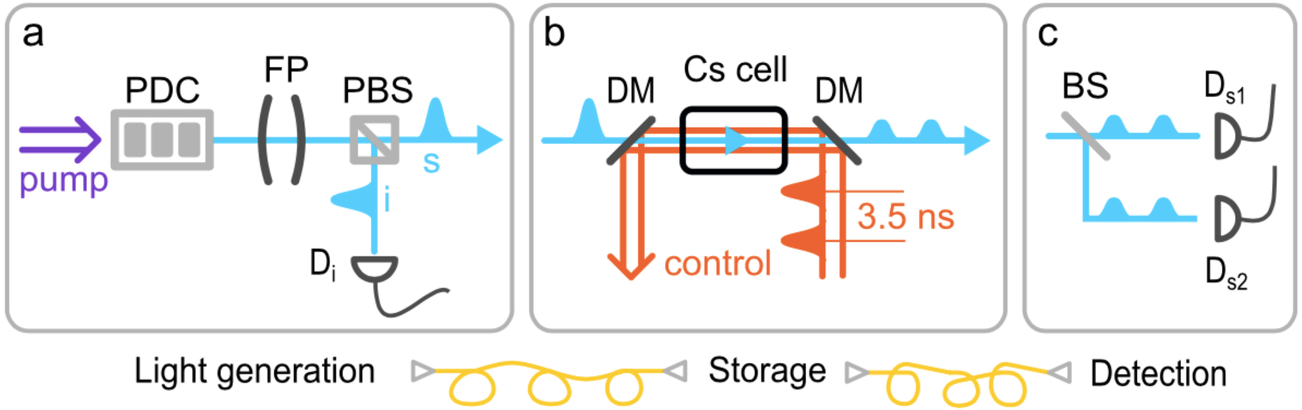
K. T. Kaczmarek,[1,*] P. M. Ledingham,[1] B. Brecht,[1] S. E. Thomas,[1,2] G. S. Thekkadath,[1,3] O. Lazo-Arjona,[1]
J. H. D. Munns,[1,2] E. Poem,[4] A. Feizpour,[1] D. J. Saunders,[1] J. Nunn,[5] and I. A. Walmsley[1,†]

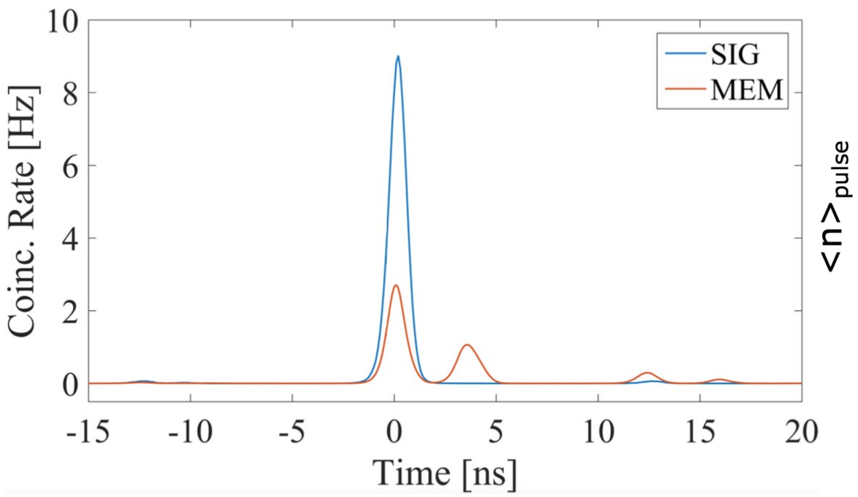


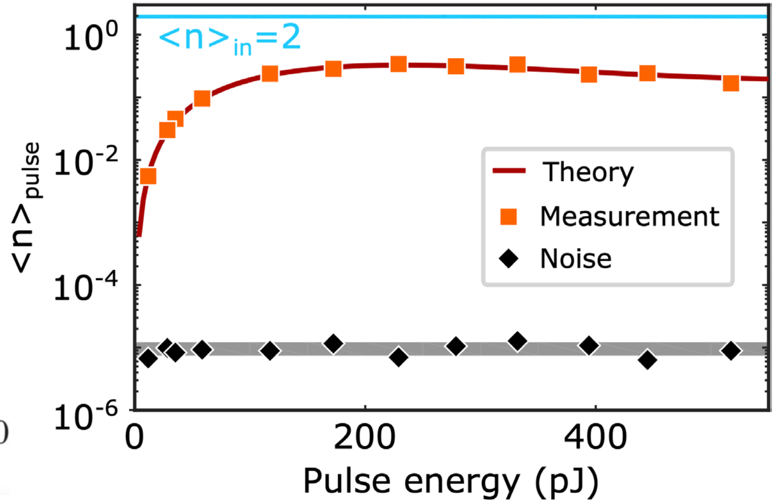
- Off-resonant cascaded absorption…

No four-wave
mixing noise

Storing photons in a Cs ladder



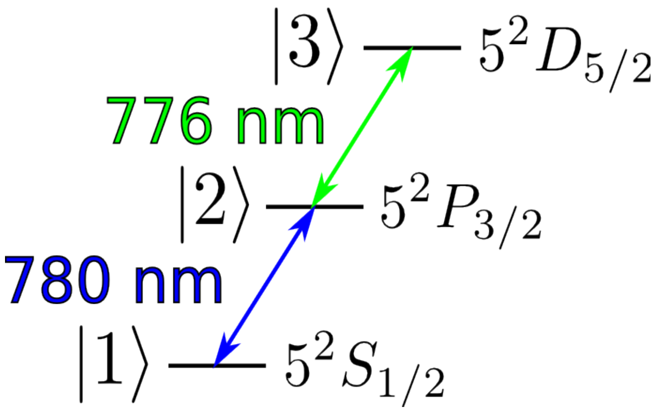


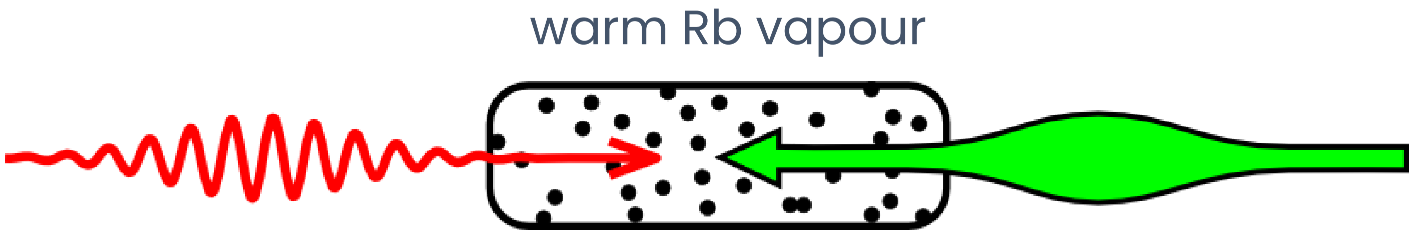


Rubidium is magic

- 5S→5P→5D: Fluorescence lifetime 240 ns

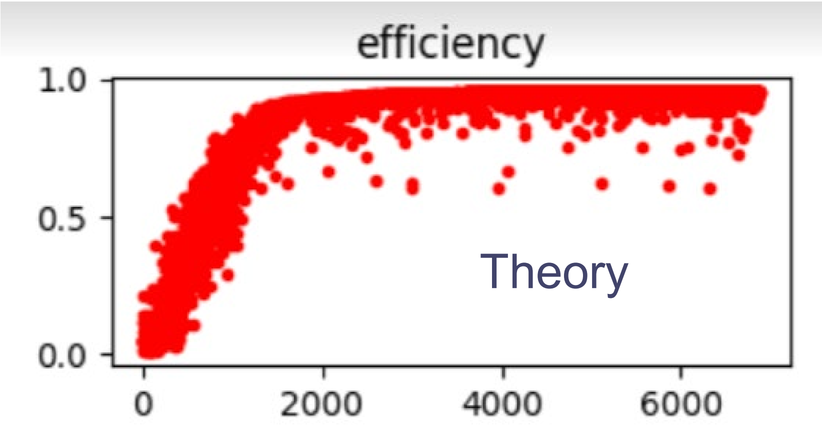
- Near-degenerate two-photon transition
  → Doppler cancelation, 100 ns lifetime



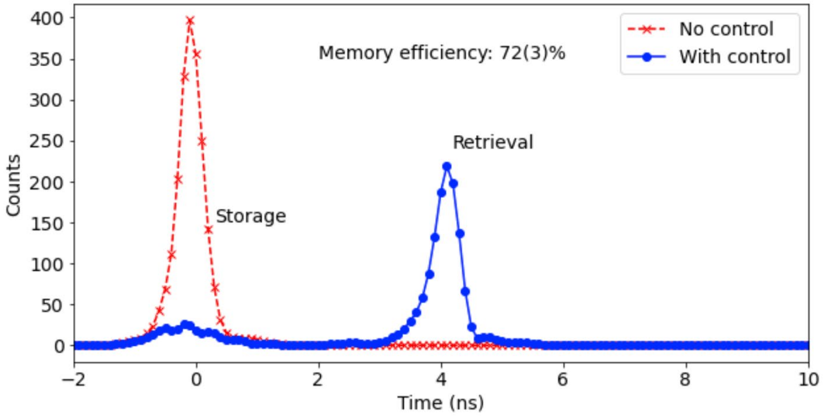


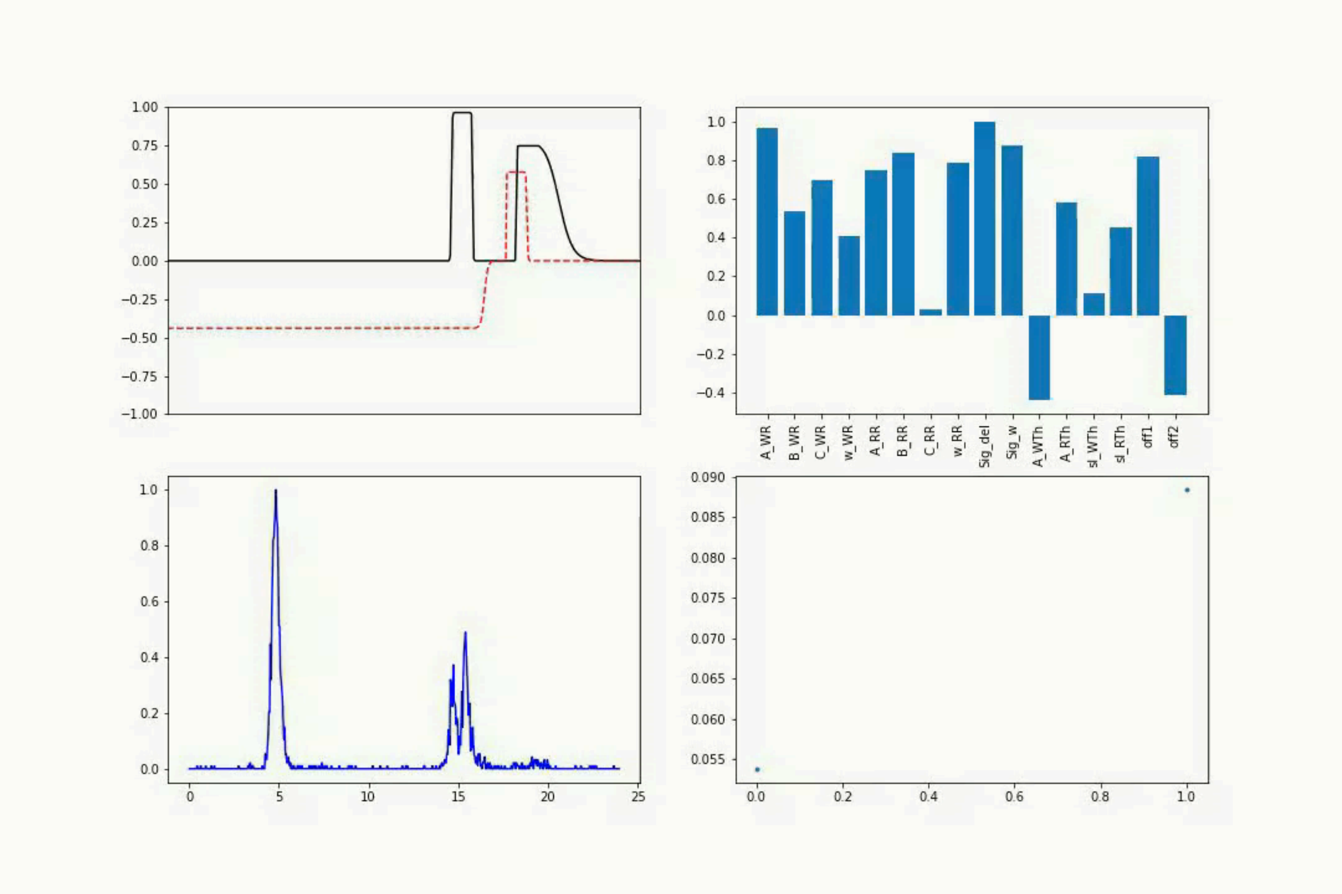
[Finkelstein *et al. Science advances* 4.1 (2018): eaap8598]

Optimizing the efficiency

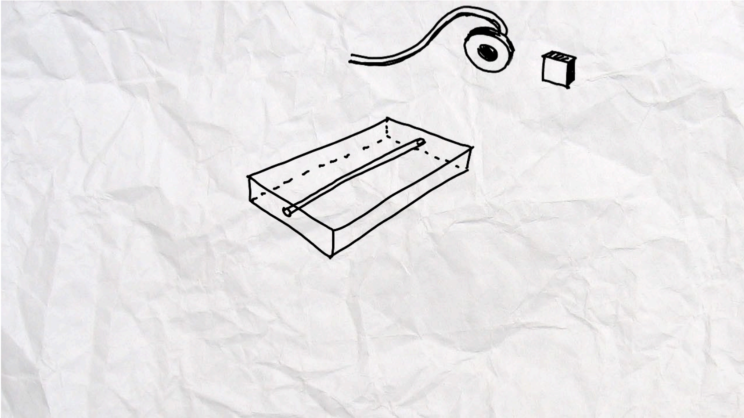


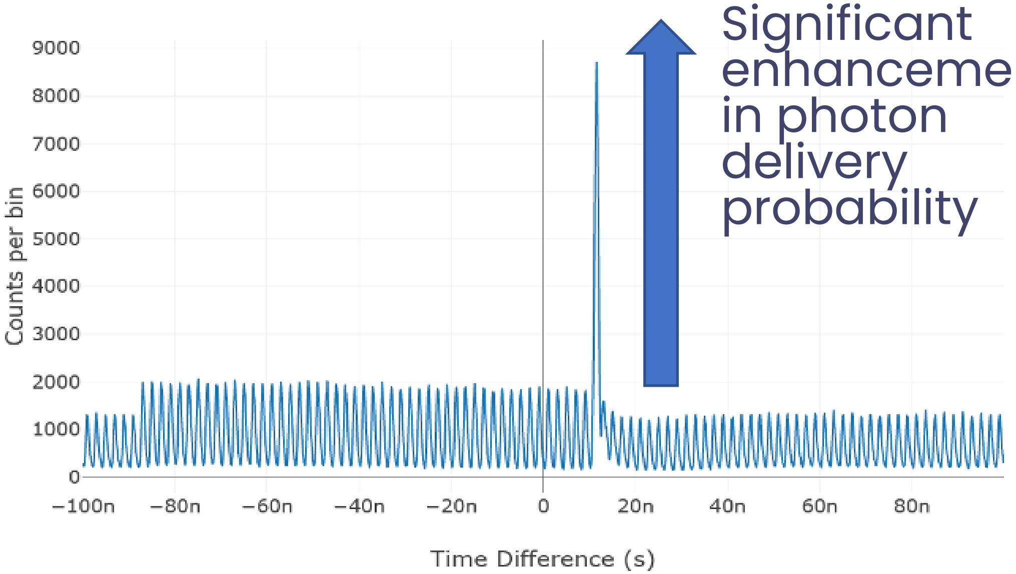
Measured (no optical pumping)





Application: photons on-demand using memory





Significant enhancement in photon delivery probability

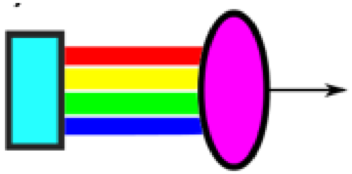
Simplest example: making a single photon

- Blue laser hits chi(2) crystal
- Sometimes produces pair of red photons
- Detecting one tells you the other is there (herald)
- Use quantum memory to capture photon and release on-demand

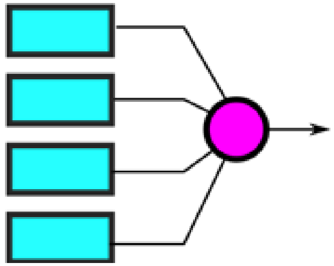
Multiplexing

TMUX

FMUX

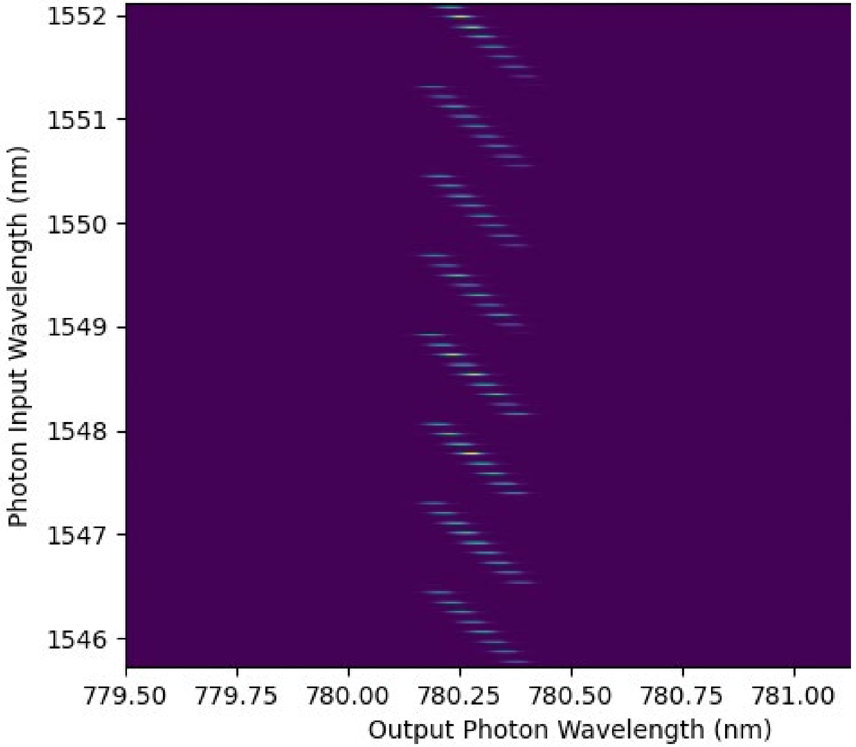


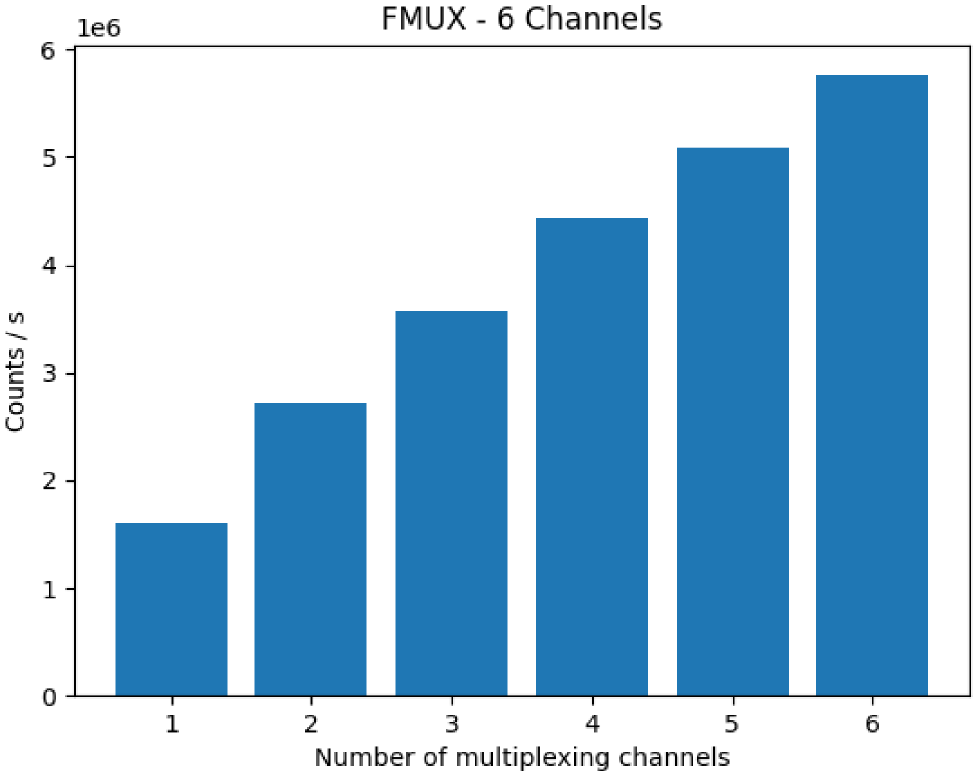
SMUX

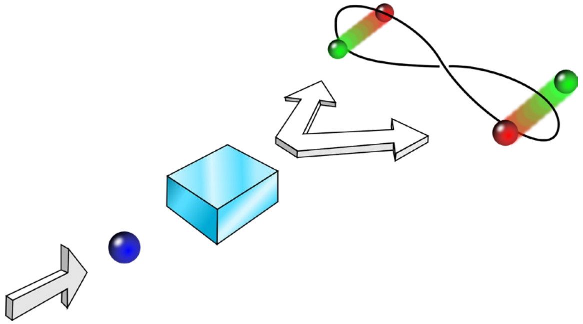


- One source has low chance of success
- Put enough sources together, and you are guaranteed success
- You need detection and fast feedforward to a memory / frequency converter / switch

FMUX

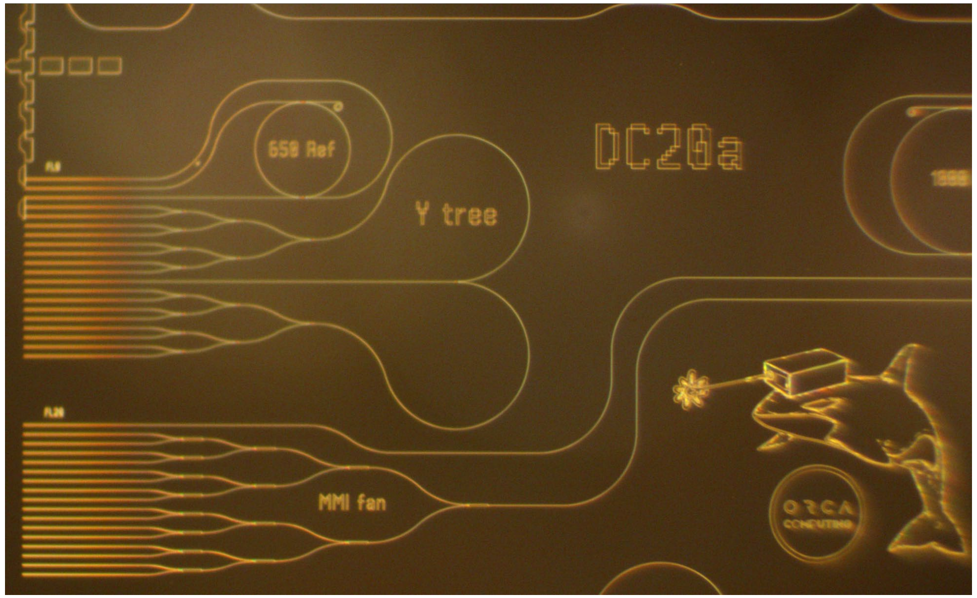


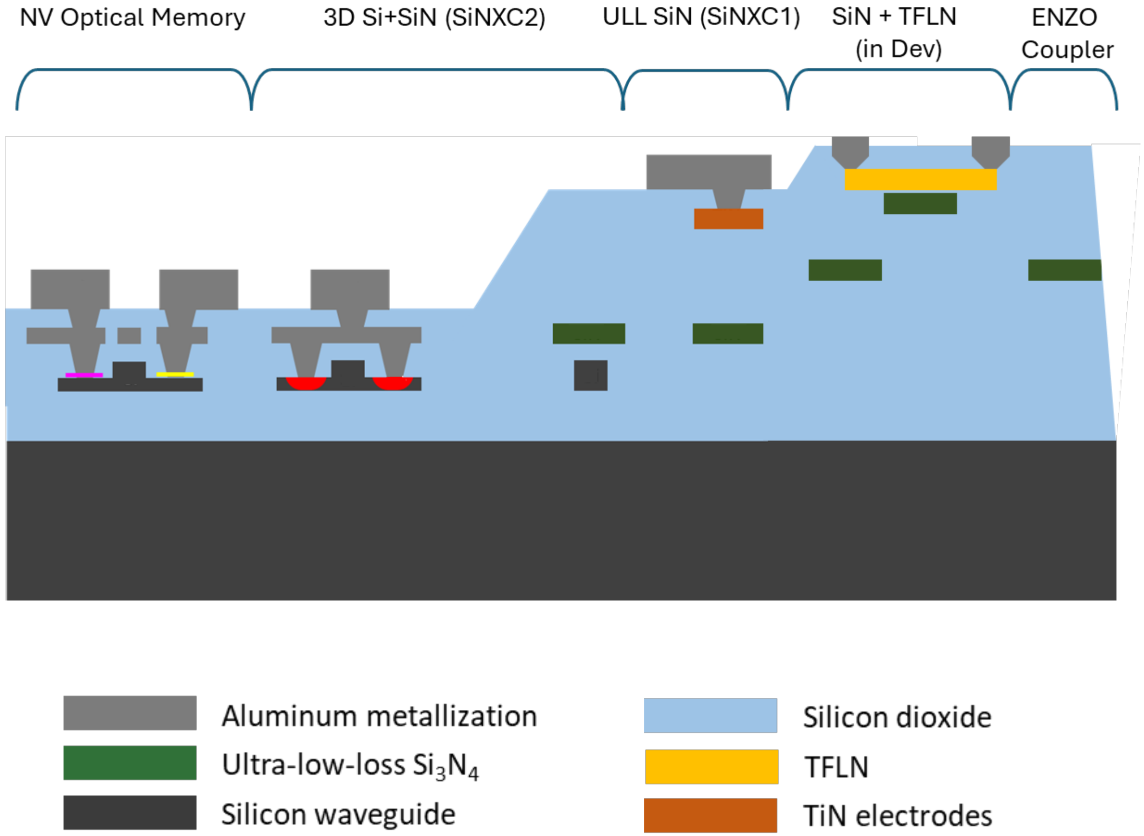




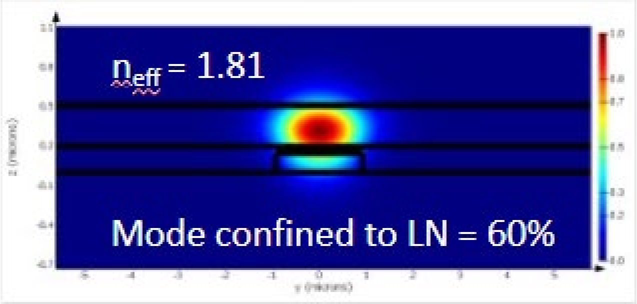
- Source emits across 100s of spectral modes
- Output wavelength interfaces with memory
- Ultra low-latency feed forward control – from detection to decision in 10ns

Towards SMUX: multi-port waveguide circuits

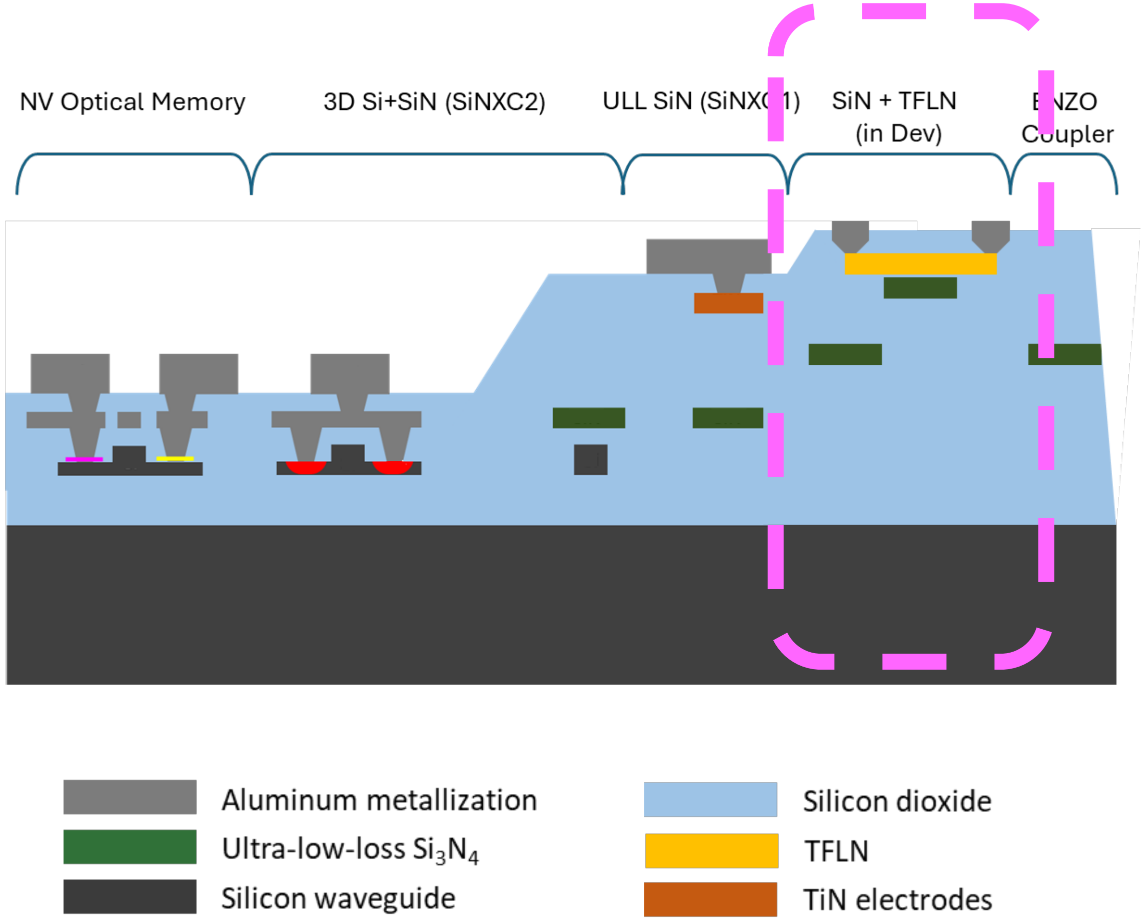




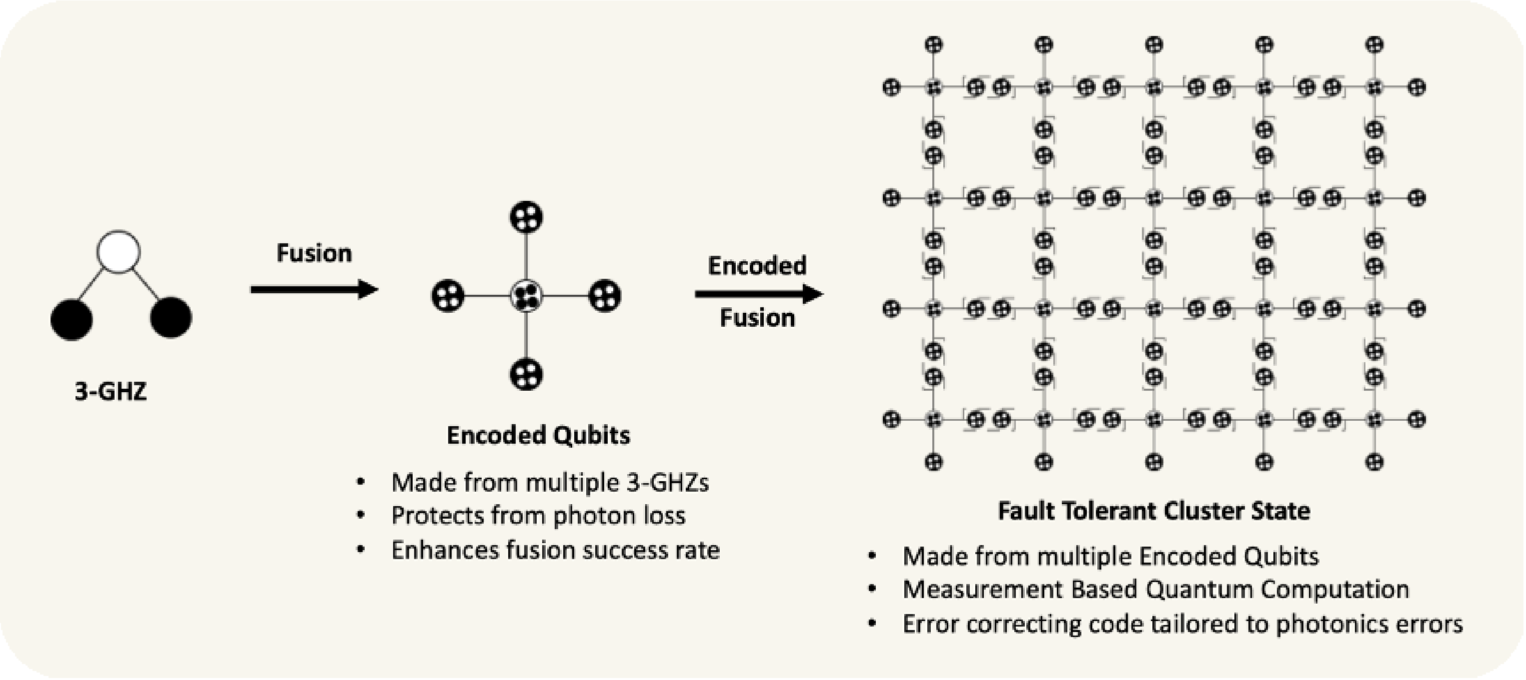
Towards SMUX: fast switching



- Integration of thin film lithium niobate (TFLN) on SiN waveguide
- Hybrid guidance enables low loss, fast switching fabrics
- Targeting < 0.5 dB, switching speed > 500 MHz, V_π < 2.5V



Towards fault tolerance



3-GHZ

Fusion

Encoded Qubits

- Made from multiple 3-GHZs
- Protects from photon loss
- Enhances fusion success rate

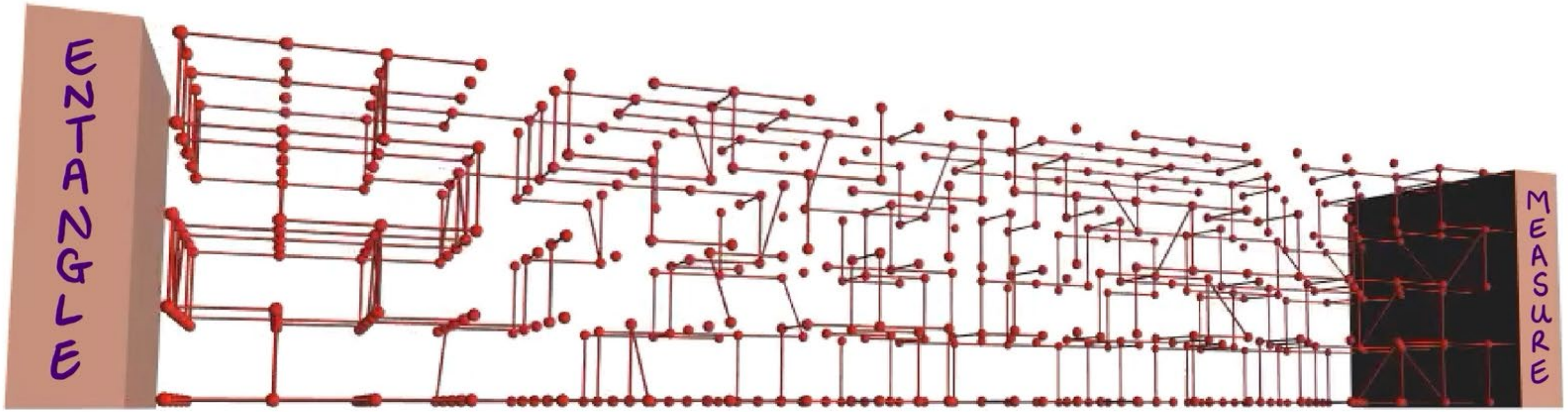
Encoded Fusion

Fault Tolerant Cluster State

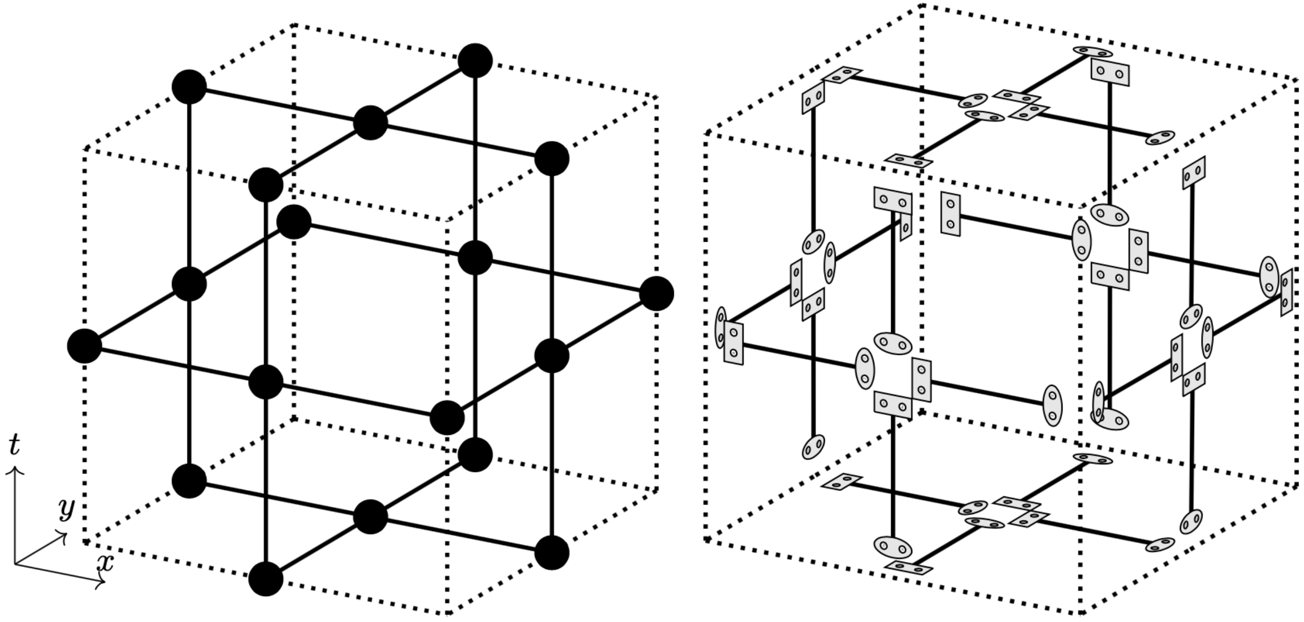
- Made from multiple Encoded Qubits
- Measurement Based Quantum Computation
- Error correcting code tailored to photonics errors

- Error correction needs large *cluster state*
- Create step-by-step: small clusters → entangled lattice

MBQC: lattice extended into 3D ("time direction")



Networking: forget the lattice; focus on the links

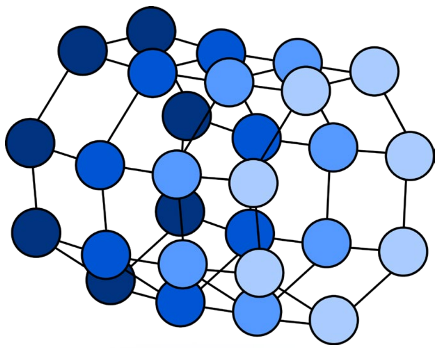


High photon-loss threshold quantum computing using GHZ-state measurements

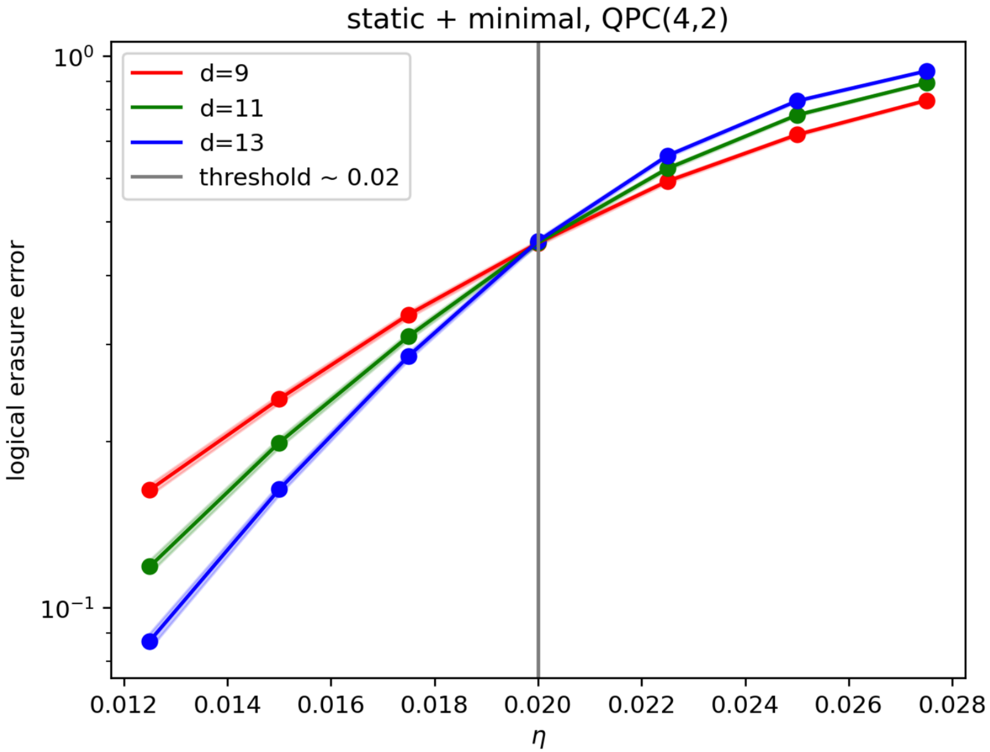
Brendan Pankovich, Angus Kan, Kwok Ho Wan, Maike Ostmann,
Alex Neville, Srikrishna Omkar, Adel Sohbi, and Kamil Brádler*
ORCA Computing

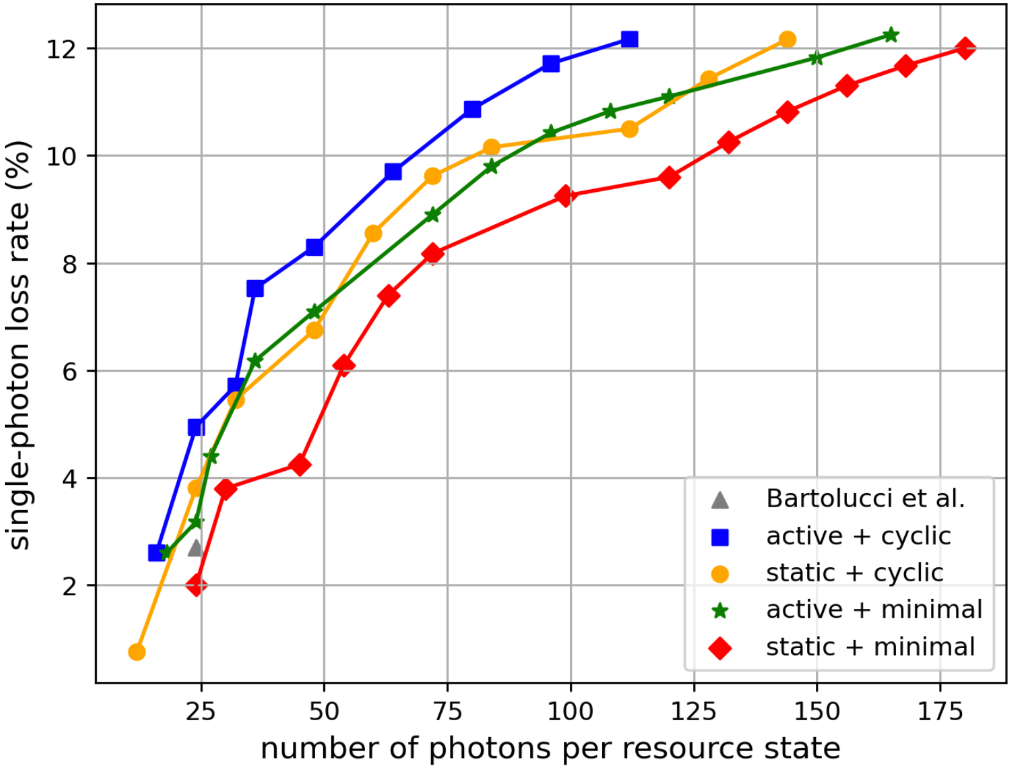
Simplest state possible: bi-partite link

Generalises to any topology

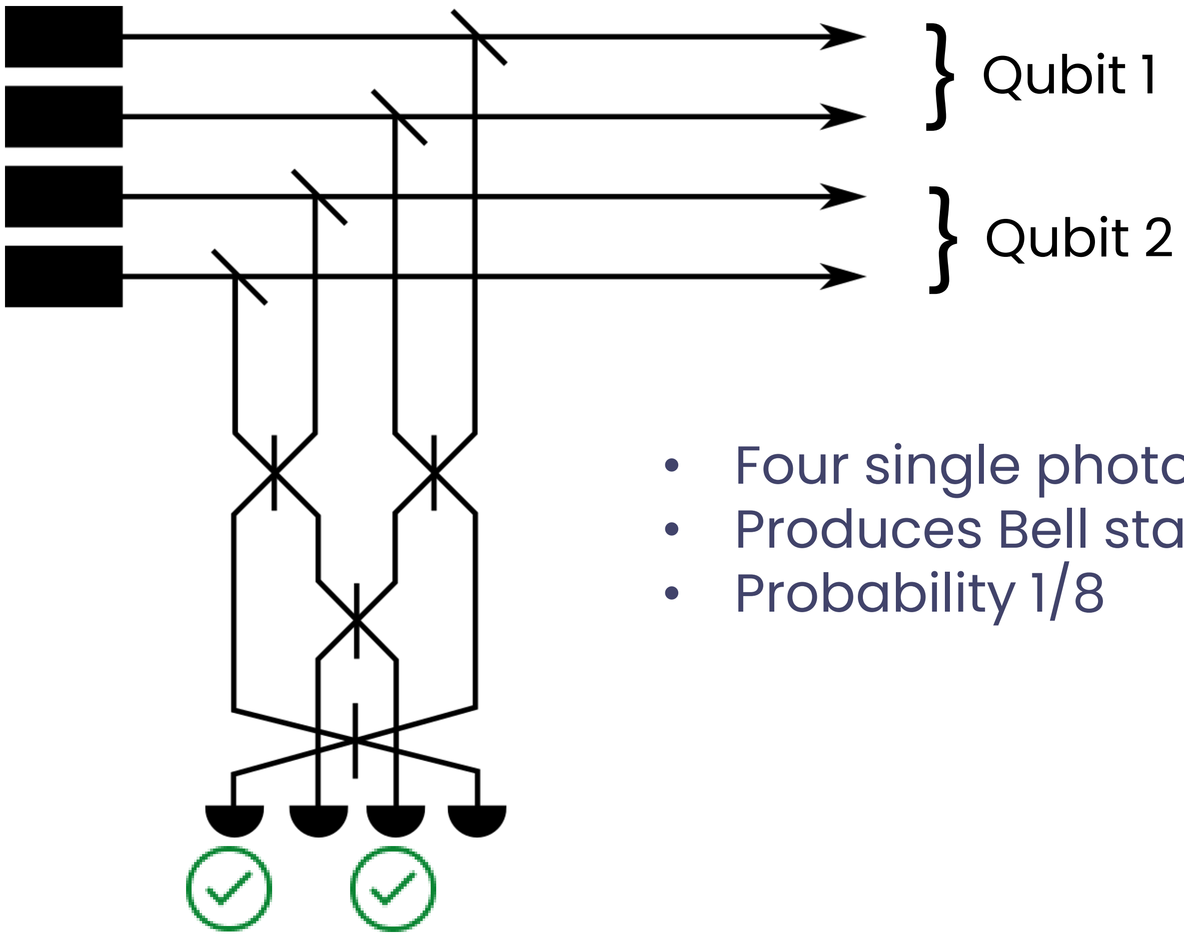


Loss thresholds



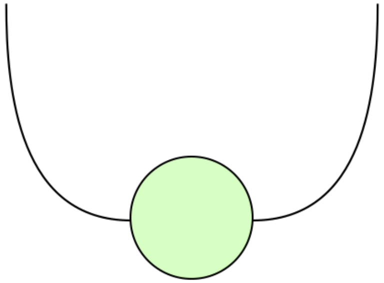


Bell state generator



$$|01\rangle + |10\rangle$$

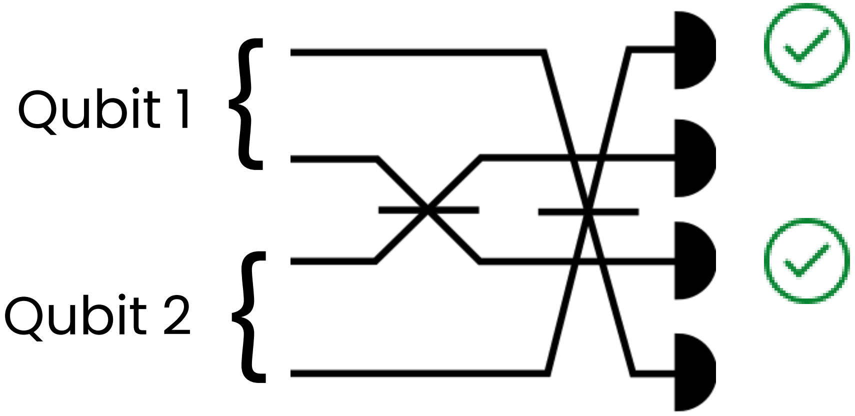
- Four single photons go in
- Produces Bell state when two photons are detected
- Probability 1/8

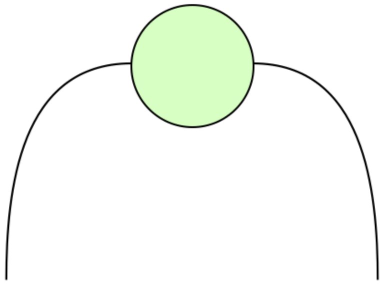


“ZX-diagram”

Zhang et al., Physical Review A **77** 062316 (2008)

Bell measurement (sometimes called “fusion”)

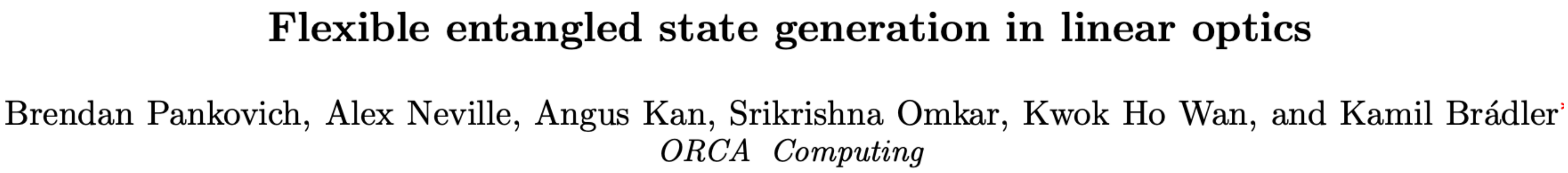




“ZX-diagram”

- Two qubits (i.e. two photons) go in
- Two clicks ”projects onto a Bell state” (i.e. tells you there was a Bell state)
- Probability 1/2

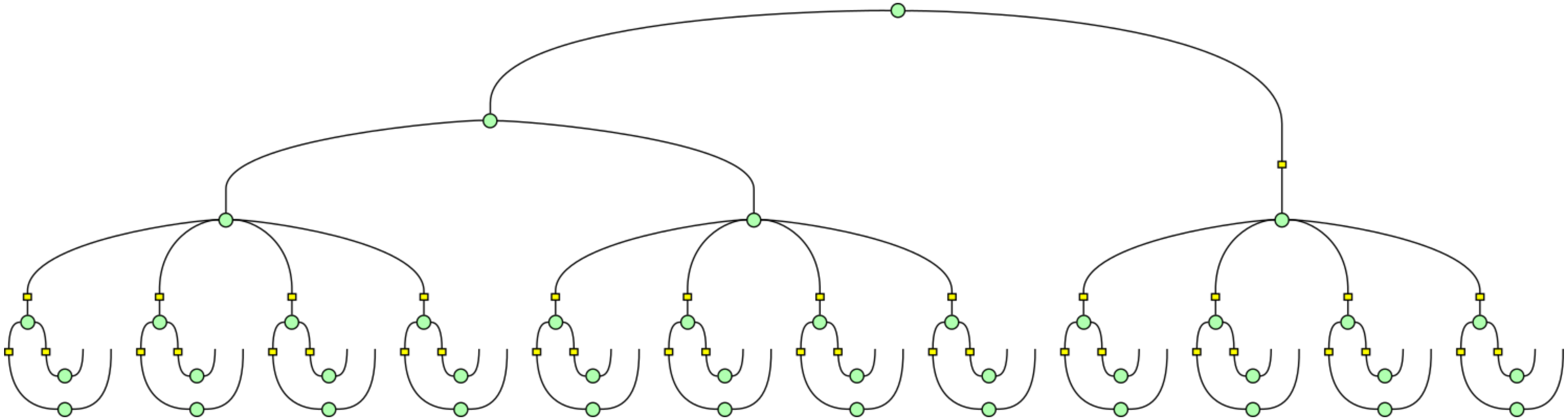
How to construct resource states



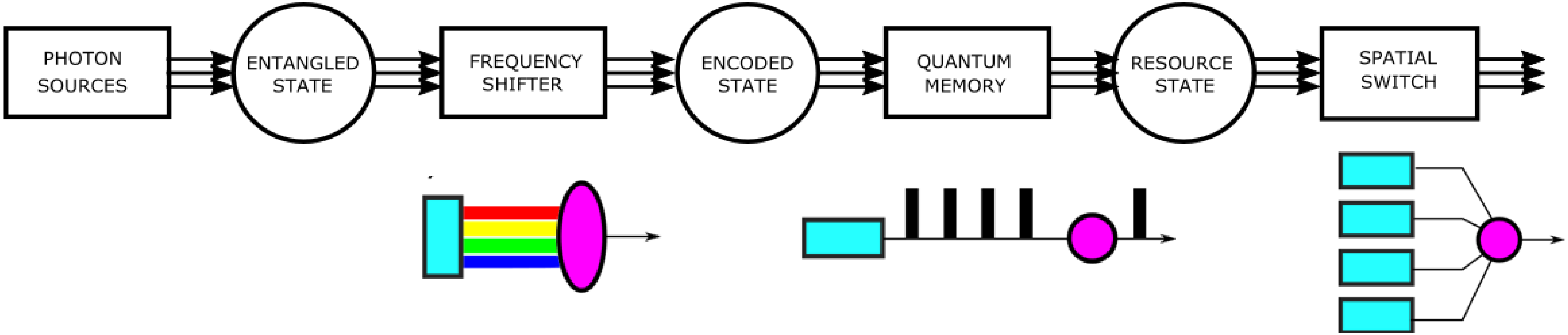
Flexible entangled state generation in linear optics

Brendan Pankovich, Alex Neville, Angus Kan, Srikrishna Omkar, Kwok Ho Wan, and Kamil Brádler
ORCA Computing

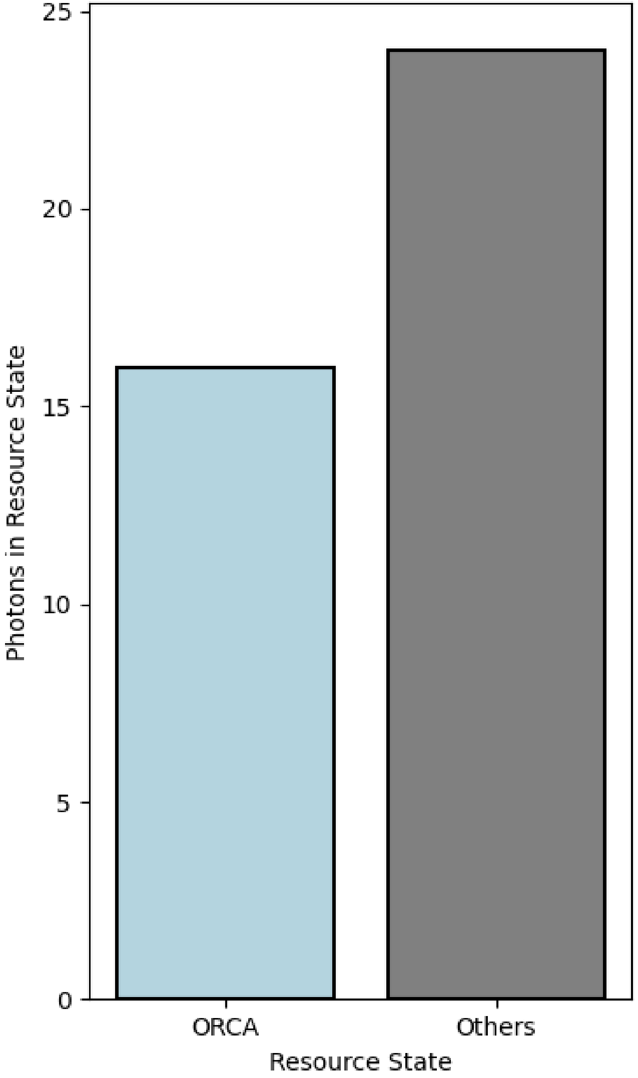
- Quantum parity check encoded Bell states
- Only two-photon Bell pairs required initially
- 3 patents; 2 papers



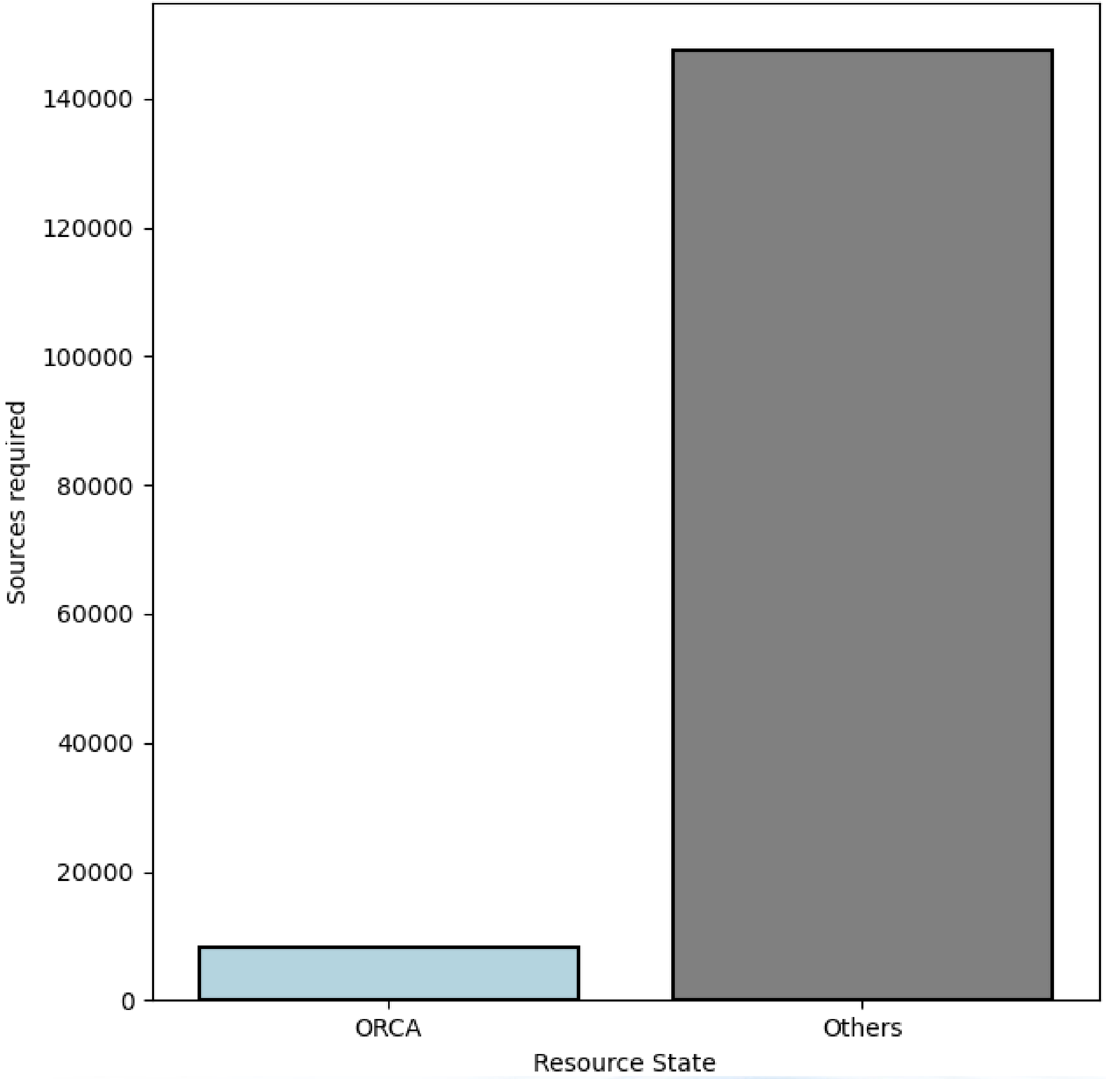
How to construct resource states



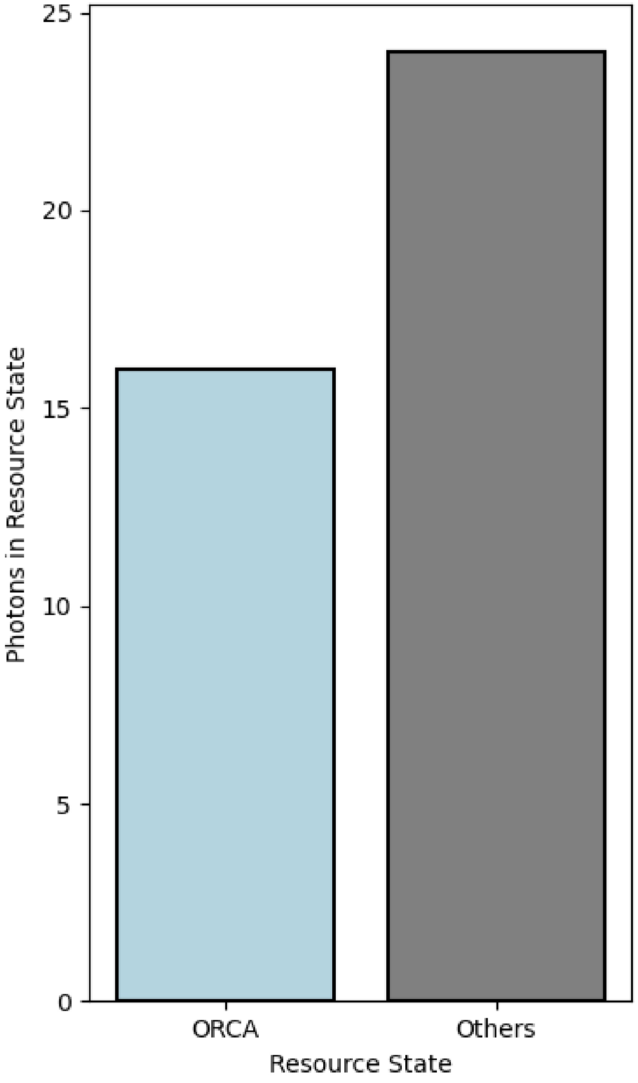
Comparison with other approaches



Construct with SMUX only



Comparison with other approaches



Using TMUX, FMUX and SMUX

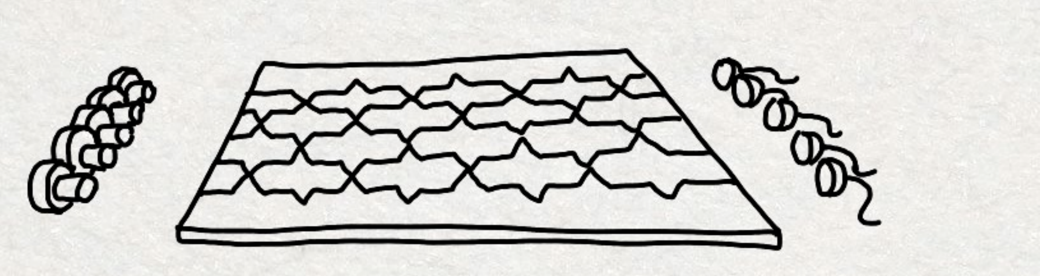
> 4 orders of magnitude

Aligned short- and long-term roadmap

- Identify applications with current technology; build towards fault tolerant systems
- Drives high quality component development and customer engagement/discovery

Photonic quantum samplers

Boson sampling: route to quantum advantage without universality

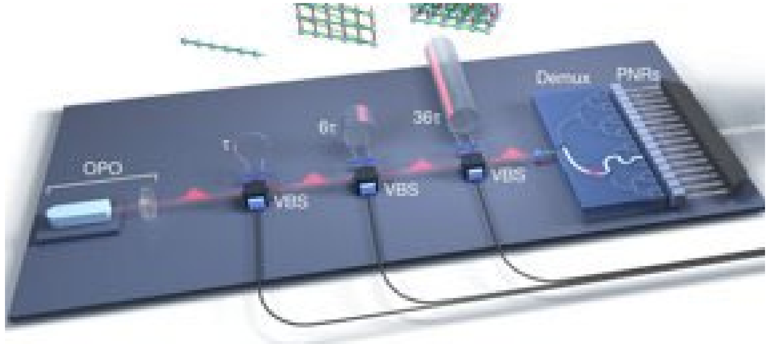


hard to simulate on a laptop beyond 30 photons, and hard for HPC beyond 40 photons

spatial; Gaussian

Jiuzhang, 2020

time-bin; Gaussian



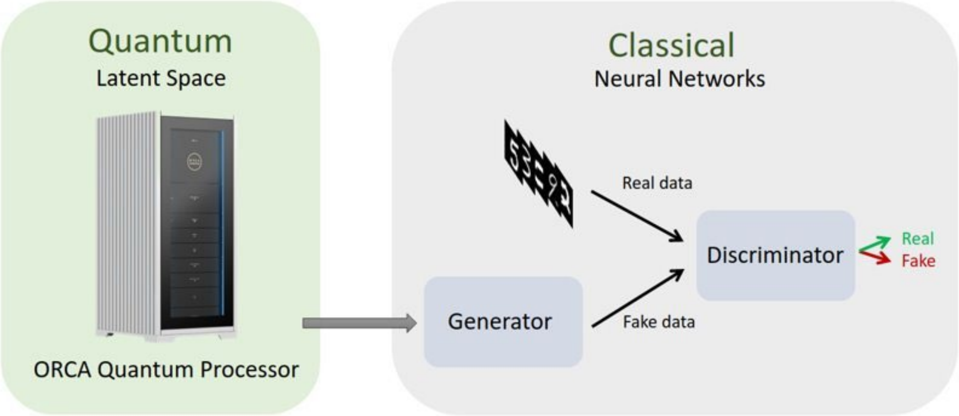
Borealis, 2022

time-bin; non-Gaussian

ORCA PT-Series

Hybrid GANs

Generative adversarial networks convert a small-scale latent vector to potentially large data.



In recent work[1], we show that using a photonic quantum processor to produce the latent space in a GAN can allow a model to:

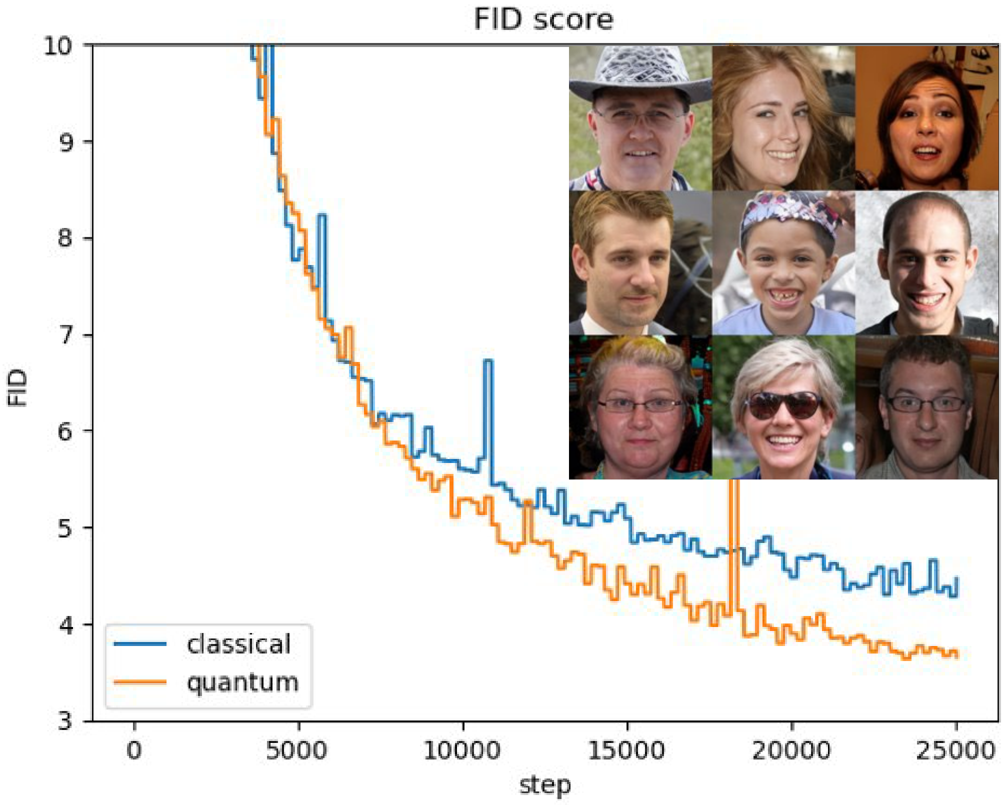
- Generate a broader range of distributions
- Produce higher-quality results for some models and datasets

This approach is scalable and suitable for near-term photonic quantum processors

[1] Wallner, Hugo, and William R. Clements. "Towards an inductive bias for quantum statistics in GANs." ICLR 2023 Workshop on Physics for Machine Learning. 2023.

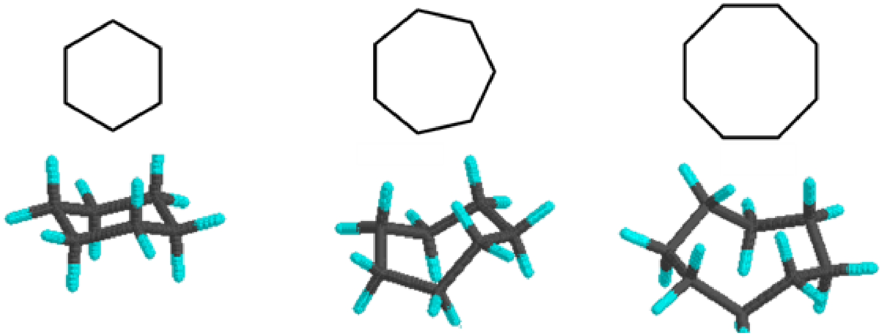
Initial results (simulated)

Images



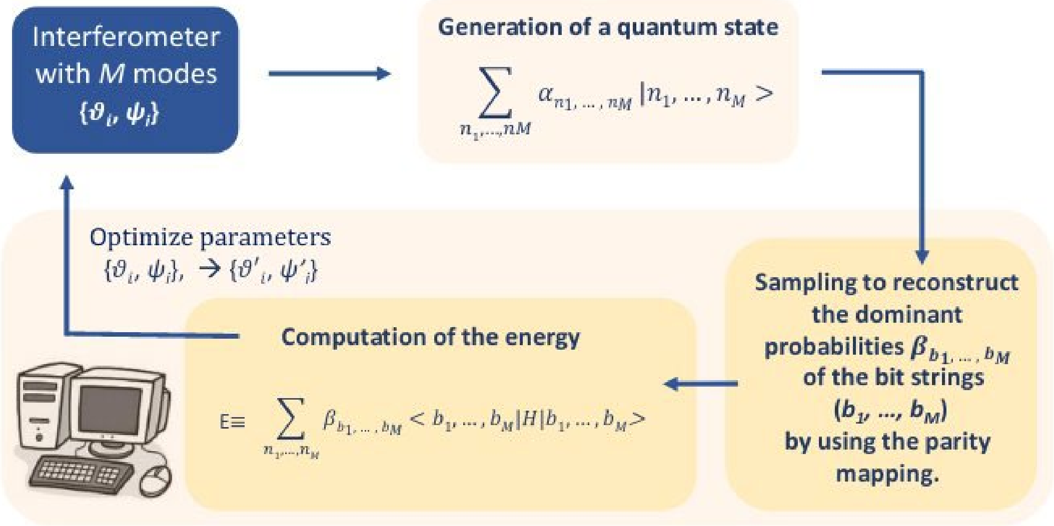
Chemistry

Molecules can take many different conformations, which determine their chemical properties



Up to 20% improvement in the generated conformation angles on the test set than the classical latent space

Binary bosonic solver



Interferometer with *M* modes $\{\vartheta_i, \psi_i\}$

Generation of a quantum state

$$\sum_{n_1,\dots,nM} \alpha_{n1,\dots,nM} |n_1,\dots,n_M >$$

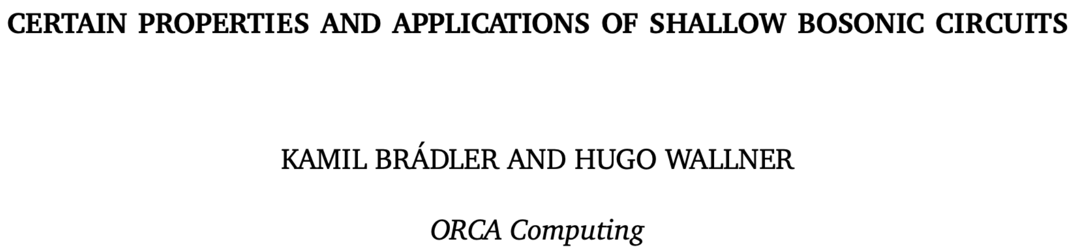
Sampling to reconstruct the dominant probabilities $\beta_{b_1,\dots,b_M}$ of the bit strings $(b_1, \dots, b_M)$ by using the parity mapping.

Computation of the energy

$$E \equiv \sum_{n_1,\dots,n_M} \beta_{b_1,\dots,b_M} < b_1,\dots,b_M|H|b_1,\dots,b_M>$$

Optimize parameters $\{\vartheta_i, \psi_i\}, \rightarrow \{\vartheta'_i, \psi'_i\}$

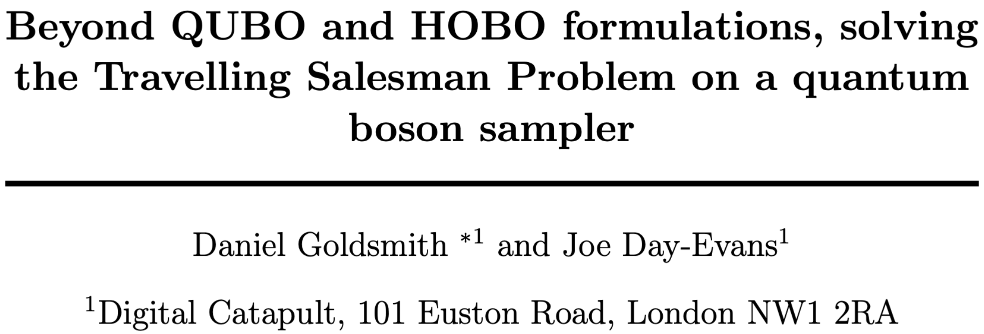
- Map output photon number to binary string
- Train photonic circuit to minimise cost function (challenge to train efficiently)
- Explores solution space non-classically
- Problem size limited by photon number



CERTAIN PROPERTIES AND APPLICATIONS OF SHALLOW BOSONIC CIRCUITS

KAMIL BRÁDLER AND HUGO WALLNER

ORCA Computing

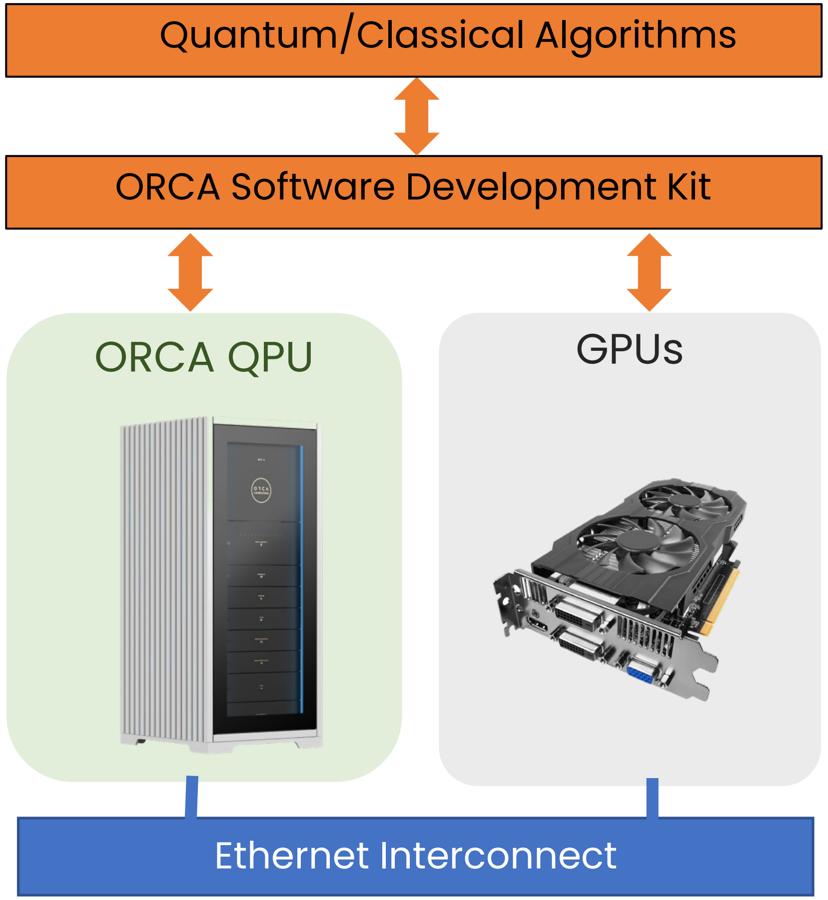


Beyond QUBO and HOBO formulations, solving the Travelling Salesman Problem on a quantum boson sampler

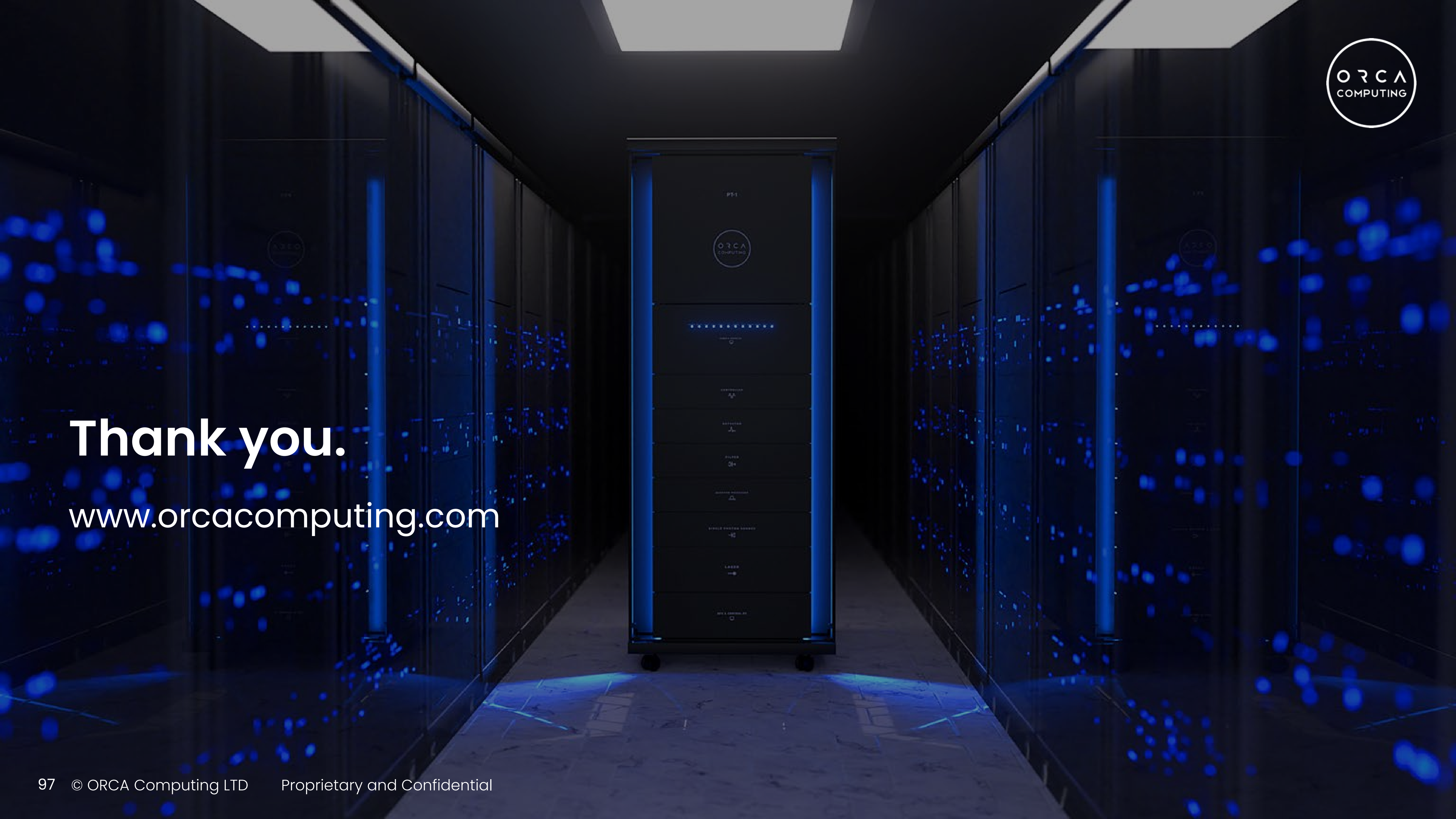
Daniel Goldsmith *[1] and Joe Day-Evans[1]

[1]Digital Catapult, 101 Euston Road, London NW1 2RA

Integration with HPC



- PT-Series quantum processor connected to NVIDIA GPU cluster
- ORCA SDK coordinating neural networks in PyTorch and the PT-Series for hybrid ML applications
- Integration with CUDA Quantum and HPC environments



Thank you.

www.orcacomputing.com

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MS. REBECCA MILLS

Senior International Focal Point

Air Force Research Lab (AFRL)
Information Directorate (RI)

Rome, New York

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AFRL

AFRL INTERNATIONAL COLLABORATION MECHANISMS

REBECCA MILLS,
SENIOR INTERNATIONAL FOCAL POINT
AFRL INFORMATION DIRECTORATE
27 JUN 2024

INTERNATIONAL ARMAMENTS COOPERATION (IAC) INSTRUCTION

- AIR FORCE INSTRUCTION (AFI) 16-110
    - Explains USAF participation in International Armaments Cooperation (IAC) programs
    - Seeks to achieve the goals and objectives
        - National Security Strategy (NSS), National Defense Strategy (NDS), National Military Strategy (NMS)
        - USAF Strategic Master Plan (SMP)
        - Secretary of the Air Force (SECAF) science and technology (S&T) priorities
        - And a few others

- AIR FORCE RESEARCH LABORATORY INSTRUCTION 16-110, dtd 19 Jun 2017
    - Establishes responsibilities for the AFRL International Program
    - Enhance ability for AFRL to meet its mission and strategic goals
        - Harness global critical technologies and talent
        - Increases effectiveness, reduces duplication, and improves compatibility and performance
        - Promotes interoperability and improves political-military relationships

International Agreement Types (Gov’t-to-non Gov’t) (Academic or Industry)

AFRL (Gov't) International Collaboration with Industry or Academia

- **International Cooperative Research And Development Agreement (iCRADA)**
  - Enable sharing and collaborative research with an international company or academic institution
  - No funds are exchanged
  - Time, equipment, facilities, knowledge are committed
  - Each side must benefit equitably from the effort
  - These are new for AFRL/RI, but new understanding in how to proceed and accomplish the paperwork
- **AFOSR Grants** – Partner with AFOSR to provide grants to key universities/professors for specific research to complement Tech Directorate portfolios.
  - 6.2 funds are allowed to be added to AFOSR 6.1 funded research
  - Strive for 50:50 co-funding
- **Cooperative Agreements (CAs)**
  - The CA is a contractual document/vehicle with funding
  - Although funding is provided (like a grant), a dual work plan is developed with both nations for a collaborative project
    - Army Research Lab frequently uses this approach in
    - AFRL/RI has small experience

International Agreement Types (Gov’t-to-Gov’t)

Master Memorandums of Understanding (MOUs)

- **Master Research, Development, Test and Evaluation (RDT&E) MOUs**
  - **Provides the construct or framework for the type of collaboration allowed with a nation**
  - DoD establishes with various countries to allows parties to legally interact in some capacity
    - Bilateral or Multilateral
  - Can be up to 25-year length
  - Can be classified
- **Under Master MOUs - specific activity agreements are written**
  - Project Agreements (PAs) – Bi- or Multi-lateral
  - Information Exchange Agreements (IEAs) or Data Exchange Agreements (DEAs)
    - *These are synonymous* – Dependent on Master MOU verbiage
  - Equipment and Material Transfer Agreement (E&MTA) (Loan Agreements)
  - Working Group – Defines Terms of Reference (TOR)
    - Exploratory purposes
- **Engineering and Science Exchange Program (ESEP)**

Primary MOU Mechanisms

PROJECT ARRANGEMENT (PA) UNDER A *MASTER* RDT&E_MOU

- Gov't-to-Gov't agreement with detailed provisions on specific collaborative projects
- Equitability for programmed resources ($$$)
- Requires an overarching RDT&E MOU to be in place

DATA/INFO EXCHANGE AGREEMENT (D/IEA) UNDER A *MASTER* D/IEA MOU

- Basic gov't –gov't agreement in specified technical areas
- *No* material or personnel exchanged; *No* resources programmed; Quid-pro-quo basis of sharing
- Requires an overarching Master D/IEA MOU to be in place

ENGINEER & SCIENTIST EXCHANGE PROGRAM (ESEP) MASTER MOU

- Full-time placement of AFRL S&Es in foreign government lab, or vice-versa – 16 Nations
- Maximum 2-year time limit
- Selections boarded at SAF/IA
- Language training provided
- Flexible use of ESEP is available

• OTHER COLLABORATION AVENUES

- The Technical Cooperative Program (TTCP), NATO Science & Technology Office (STO)

International Personnel Exchange Agreements

Personnel Exchange Summary

Government

Traditional ESEP
Competitive Program Selection

→ Require Master Engineering and Science Exchange Program (**ESEP) MOU Agreement with Nation**

- **Minimum of 3 years RDT&E experience**
- **UNCLASS Level Work Only – Public Domain**
- **Requires position descriptions & full package and approvals**

CPP
Cooperative Program Placement

→ Requires RDT&E MOU AND Project Agreement (PA)

Academic

WOS
Windows on Science

→ AFOSR support for short visit (< ~14 days) for ACADEMICS via seminar/presentation

WOW
Windows on the World

→ Provides opportunity for AF researcher at a foreign university
(21 days to 179 days TDY)

Current Nations with Established ESEP (Gov't) MOU

Australia	Japan
Canada	Korea
Chile	Norway
Czech Republic	Poland
France	Singapore
Germany	Spain
Israel	The Netherlands
Italy	United Kingdom

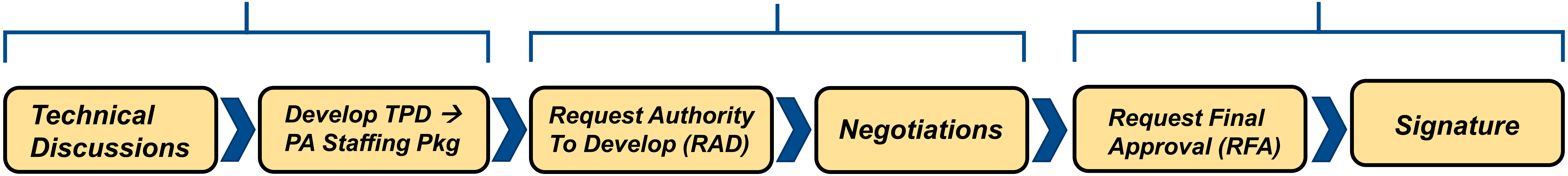
Agreement Process

Project Agreement (PA) Process Timeline

Initiation&Development (1-18 months-TPO dependent)

Staffing&Negotiation (6-12 months)

Final Review &Approval (3-6 months)



Technical Discussions
- TD Proponent with AFRL/SPI and SAF/IAPC guidance

Develop TPD → PA Staffing Pkg
- TD Proponent with AFRL/SPI and SAF/IAPC guidance

Request Authority To Develop (RAD)
- USD(AT&L) for MOUs
- HQ USAF for Project Arrangements (PAs)

Negotiations
- SAF/IAPC with TD Proponent's Support

Request Final Approval (RFA)
- HQ USAF (as required)
- USD(AT&L)
- OSD
- Interagency
- Congress (if necessary)

Signature
- SAF/IA

Dependent on the partner, sensitivity of the tech, other dept/agency involvement, etc…

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(Domestic and Int’l CRADAs)

QUESTIONS?

Backup

FIRST Steps for Agreement Creation

- US AFRL HQ International Office (XPPI) will engage Senior International Focal Point (SIFP) or Alternate: International Point of Contact (IPOC) at appropriate AFRL tech directorate
    - Meet to discuss plans/desires for collaboration
    - Determine correct Master RDT&E PA/IEA MOU
- Create the Technical Planning Document (TPD)
    - Template based
        - Shared with partner cohort to draft and refine – often in working groups or via email, phone
        - Define objective, scope and tasks and funding needs
    - Once both sides agree on content, TPD serves the basis of technical information for the PA
- Iterative process

Agreement Execution

- Agreement becomes effective the date that the last final signature is obtained
  - Behind the scenes while waiting, work occurs to prepare necessary contracts, equipment research, etc. to enable immediate start
  - No technical work is allowed to get a head start – defeats nature of collaboration
- Partners usually have a kickoff meeting
  - Regrouping of all teams
  - Detailed project plan and schedule, milestones, etc are created
  - Logistics for actual sharing and experimenting are discussed/planned
- Yearly reports are often required
- Final reports are always required and must be finished with all edits before the end of the PA
  - Usually plan for draft final report to be ready 6 months before the end date to allow refinement and approval processes for each nation.
- Agreements can be amended as needed for extra time, extra tasks, additional funding, etc.
  - Plan for amendment one year before the end date

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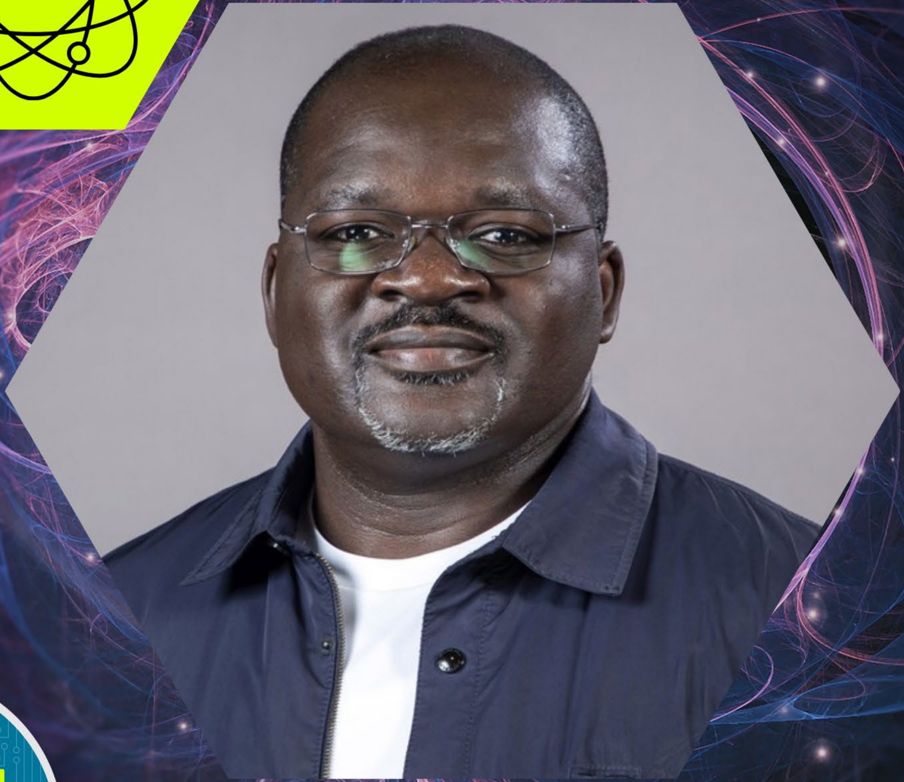

PROF. HERBERT FOTSO

Associate Professor
Department of Physics
University at Buffalo

Q4I

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Enabling Efficient Qubit-Photon Interfaces for Scalable Quantum Information Processing Platforms

Herbert F. Fotso

Department of Physics
University at Buffalo, SUNY

University at Buffalo
The State University of New York

Outline

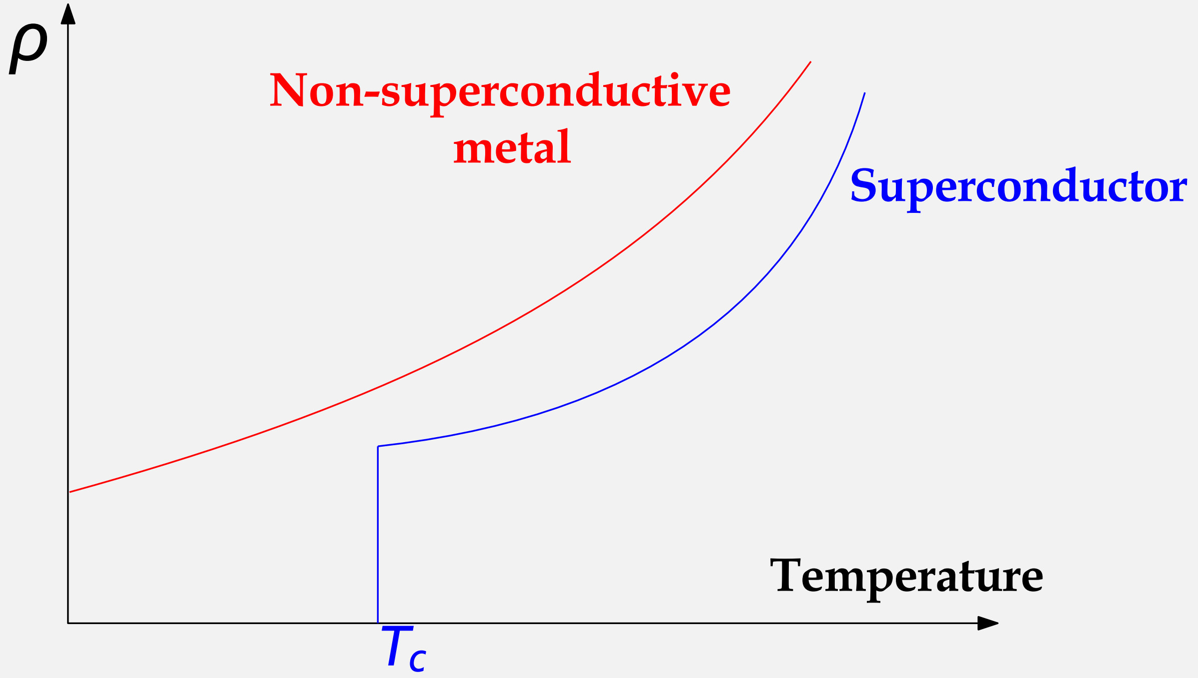
- Qubits/QIP, why do we care?
  Technologically promising materials and their challenge
- Limits of classical computation
- Challenges at the interface of quantum optics and QIP
- Spectral diffusion, restoring photon indistinguishability
- Experimentally achievable external fields protocols
  VFRP and Collaboration with AFRL Quantum Group

Electric current and dissipation

Metallic conductor ⇒ heat, dissipation
US Power Grid, Loss ∼ 14 New York City's

Superconductivity

Superconductivity, What is it?



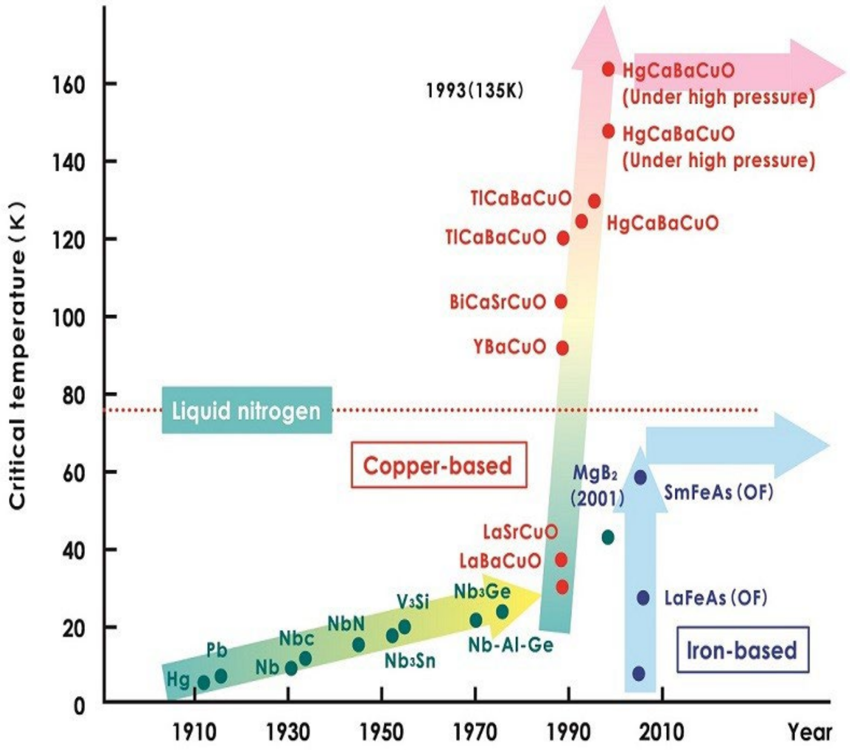
No dissipation/loss below a certain (critical) temperature (T_c)

Ideally, we want T_c to be room temperature.

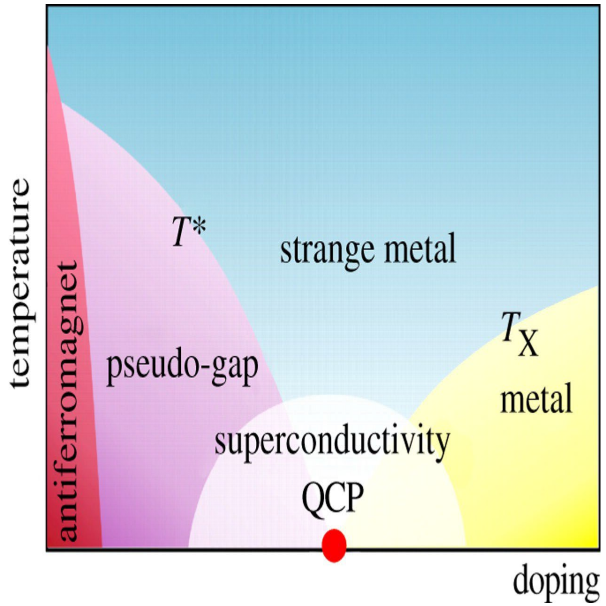
Superconductivity ...

High temperature superconductivity.

The T_c timeline:



Cuprates, phase diagram



Many competing phases
High complexity

Developing Novel Materials: High T_c Superconductivity

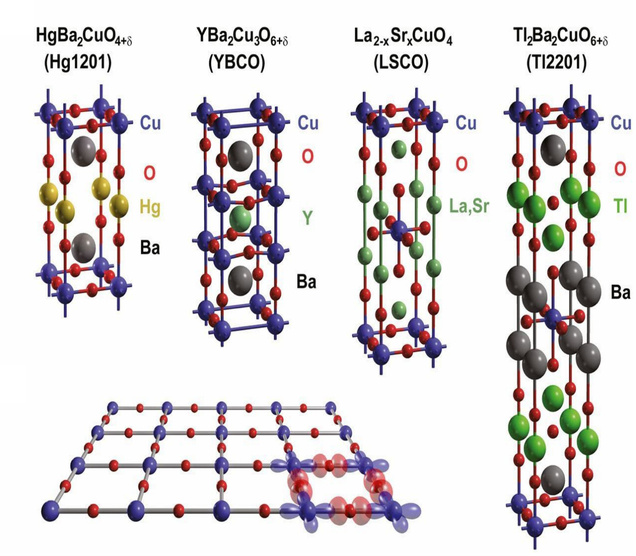
Technological challenges

Metallic conductor ⇒ heat, dissipation
US Power Grid, Loss ~ 14 New York City's

Levitating trains, top speed ~ 300*mph*

Better electromagnets, liquid Nitrogen ~ *77K*
Liquid Helium ~ *4K*

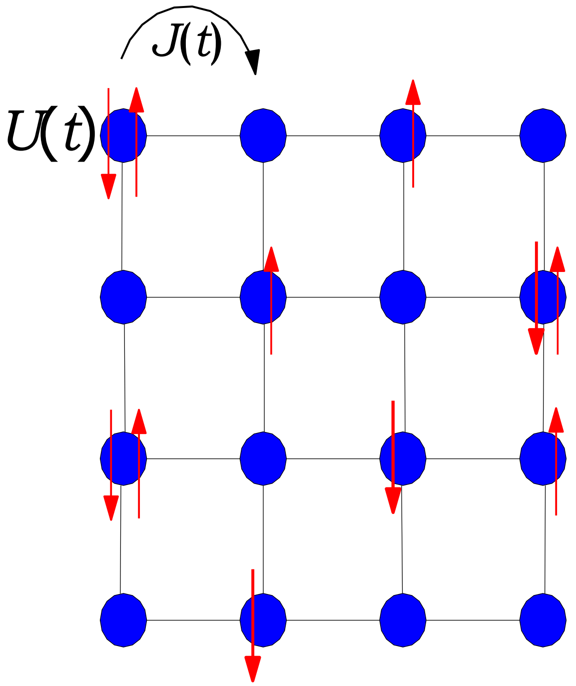
Promising Materials



Neven Barišić et al. PNAS 2013;110:12235-12240

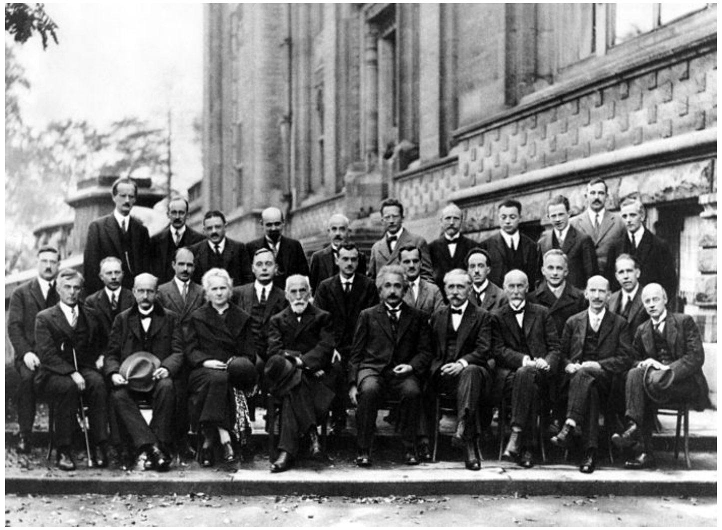
Cuprates
High T_c superconductors
Crystal structure

Challenging Theory



Hubbard model
Deceptively simple

Computational Methods. Why?



"Theory of everything"

- Quantum Mechanics:
  Solvay conference 1927
- Only a handful of problems are solvable EXACTLY
- Progress relies on well understood approximations
- May also solve small systems numerically

Many interacting particles

- "More is Different"

  P.W. Anderson, Science **177**, 4047 (1972).
- Many emergent phenomena

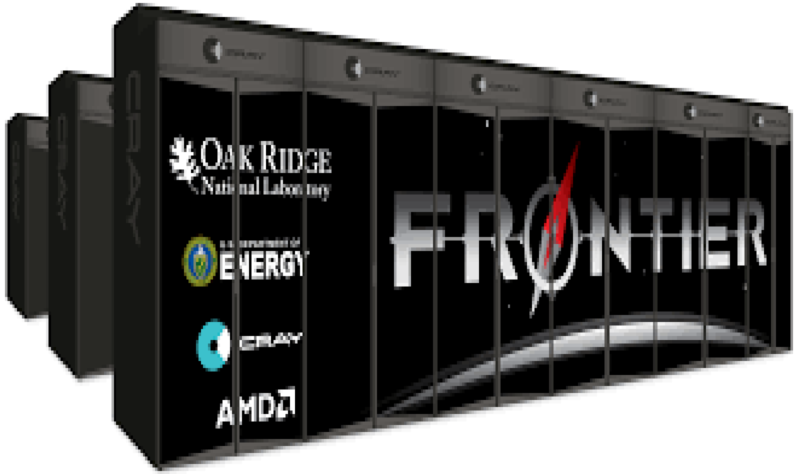
Computational Methods

- New insights
- Guide experiments
- Suggest new materials
- Explore possible mechanisms

⋮

- Ongoing efforts
- **Challenge: Quantum problem on Classical computers**

The limits of classical computation



State of the art classical computer
$\sim$ **50 electrons**

Double the capacity $\Rightarrow$ 1 more electron

Computer power alone will not be enough

1 Petaflop $\rightarrow$ $\sim$ 2 MW of power
(1 MW powers $\sim$ 1000 homes)

→ **Better algorithms are essential**

Fundamental limits!

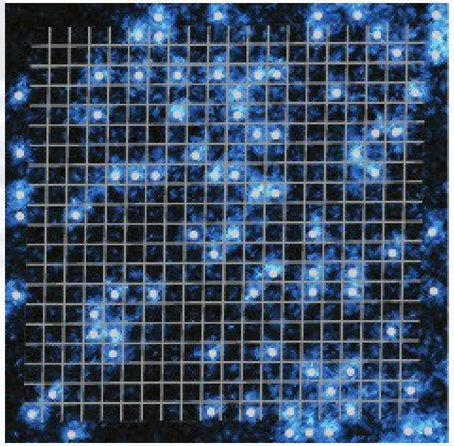
A Path Forward: Quantum Computation

Quantum computation for quantum systems.

Richard Feynman, 1982.

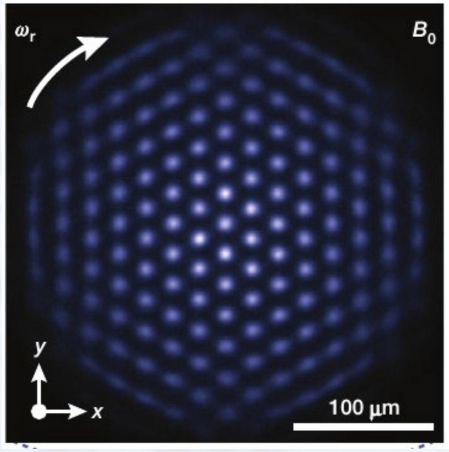
Match the exponential growth of the problem.

Quantum Simulators



M.F. Parsons et al. PRL **114**, 213002 (2015)

Quantum Computing



J.W.Britton et al. Nature **484**, 489 (2012)

The Future: Quantum Computation?

Linear VS Exponential Scaling

Classical bit, **on/off**

- 1 bit: 1 or 0
- 2 bits: 00,10, 01, 11
  system is completely
  defined by
  2 independent numbers

  :
- N bits:
  ⋯ N numbers

Quantum bits, **qubit**, spin-1/2

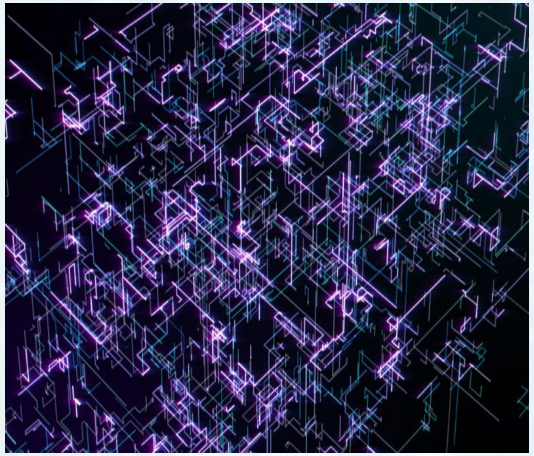
- 1 spin $|\uparrow\rangle$ or, $|\downarrow\rangle$
- 2 spins: **a**$|\uparrow\uparrow\rangle$
  b$|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$ **c**$|\uparrow\downarrow\rangle - |$
  $\downarrow\uparrow\rangle$ **d**$|\downarrow\downarrow\rangle$
  4 numbers needed (2^2)
- 3 spins:
  8 numbers needed (2^3)

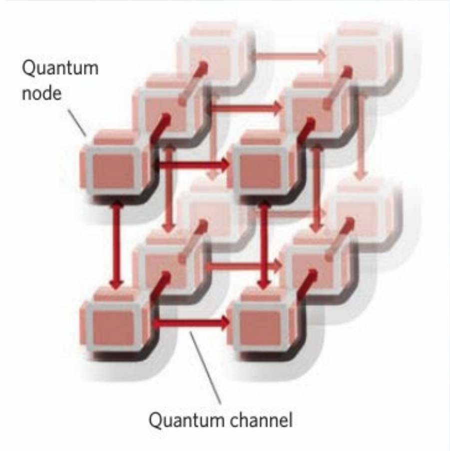
  :
- N spins: 2^N numbers

300 qubits ⇒ 2^{300} numbers/states
Number of particles in the Universe!!!
As long as they are fully entangled.

Beyond novel materials: ...

- Quantum Communication/Networking

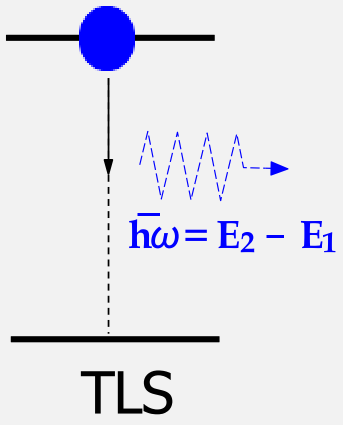




J. Kimble, Nature **453**, 1023 (2008).

- Encryption
- Quantum Chemistry
- Quantum Sensing
  Detect/measure increasingly weak signals with high resolution
- What else? The future will tell...

QIP The Building Blocks: Quantum Bits

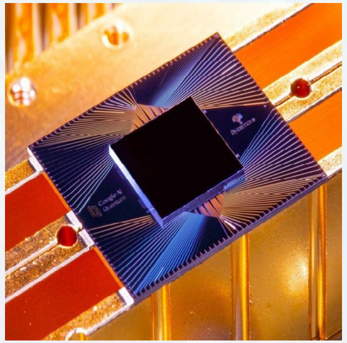


Loss - DiVincenzo criteria:

- * State initialization of the qubits
- * Long-lived coherences
- * Universal set quantum gates
- * Efficient qubit measurement
- * Scalable to large numbers of qubits

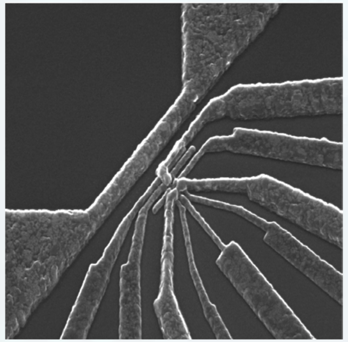
Different promising implementations:

Superconducting qubits



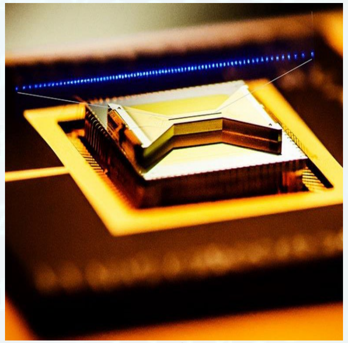
Google

QDots



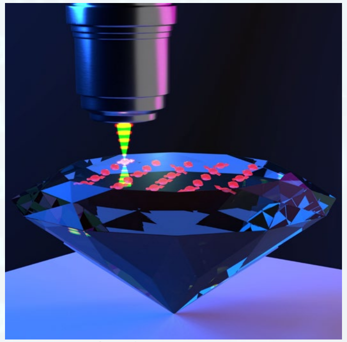
A. Dzurak

Trapped ions



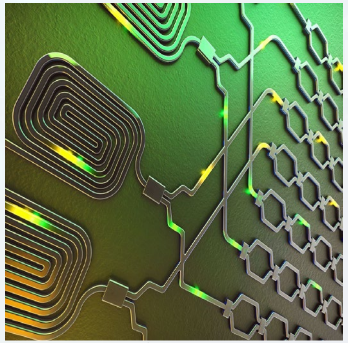
IonQ

Electron/nuclear spins



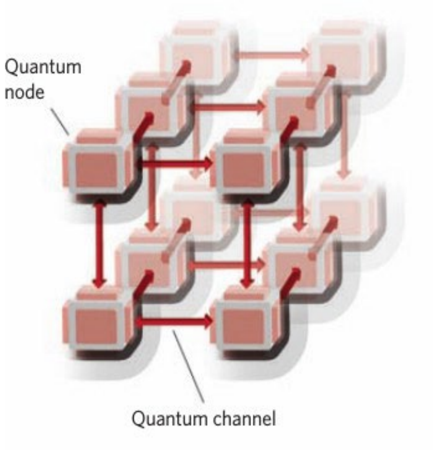
Oxford Univ.

Photons ...



X Qiang

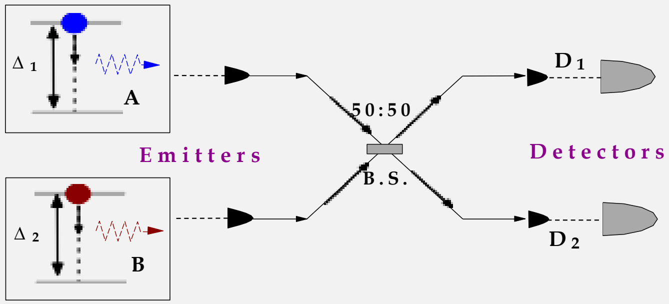
Hybrid Platforms, The Future?



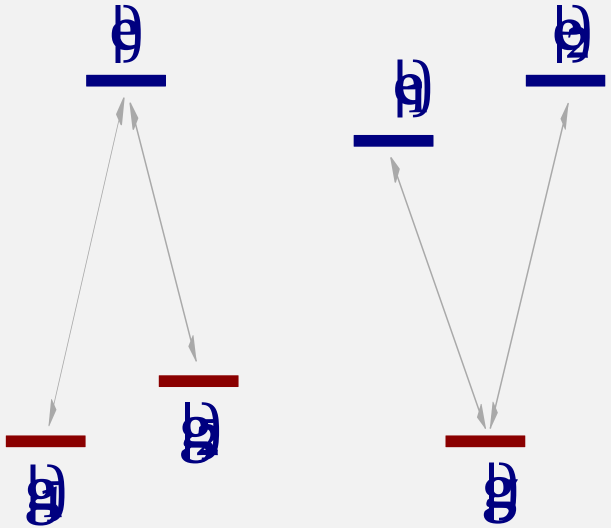
J. Kimble, Nature **453**, 1023 (2008).

- Use different systems for their optimal properties:
  - Superconductors for computation
  - Electron/nuclear spins for networking
  - Atomic clouds for memories ...
- Establish efficient interfaces between platforms
- **Optimal light-matter interfaces are essential!**

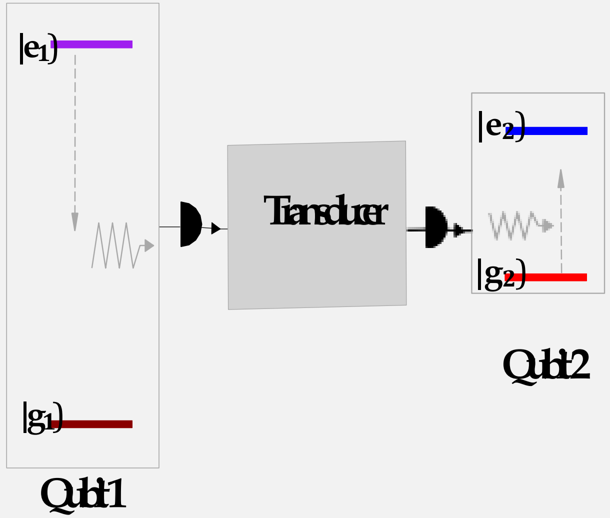
Photon-mediated processes for QIP challenges



Two-Photon Interference, Entanglement Generation



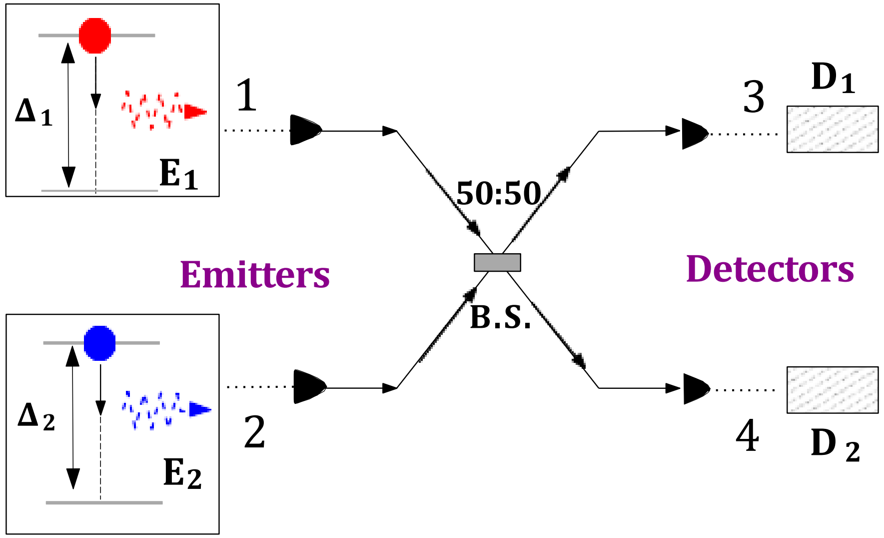
No-Clone Theorem, Quantum Memories

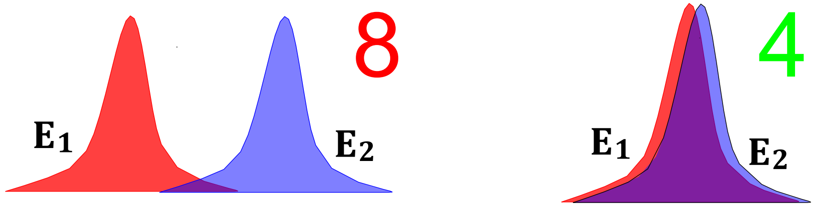


Different Frequencies, Quantum Transduction

Photon-mediated processes for QIP challenges ...

Hong-Ou-Mandel Two-Photon Interference and Distinguishable Photons

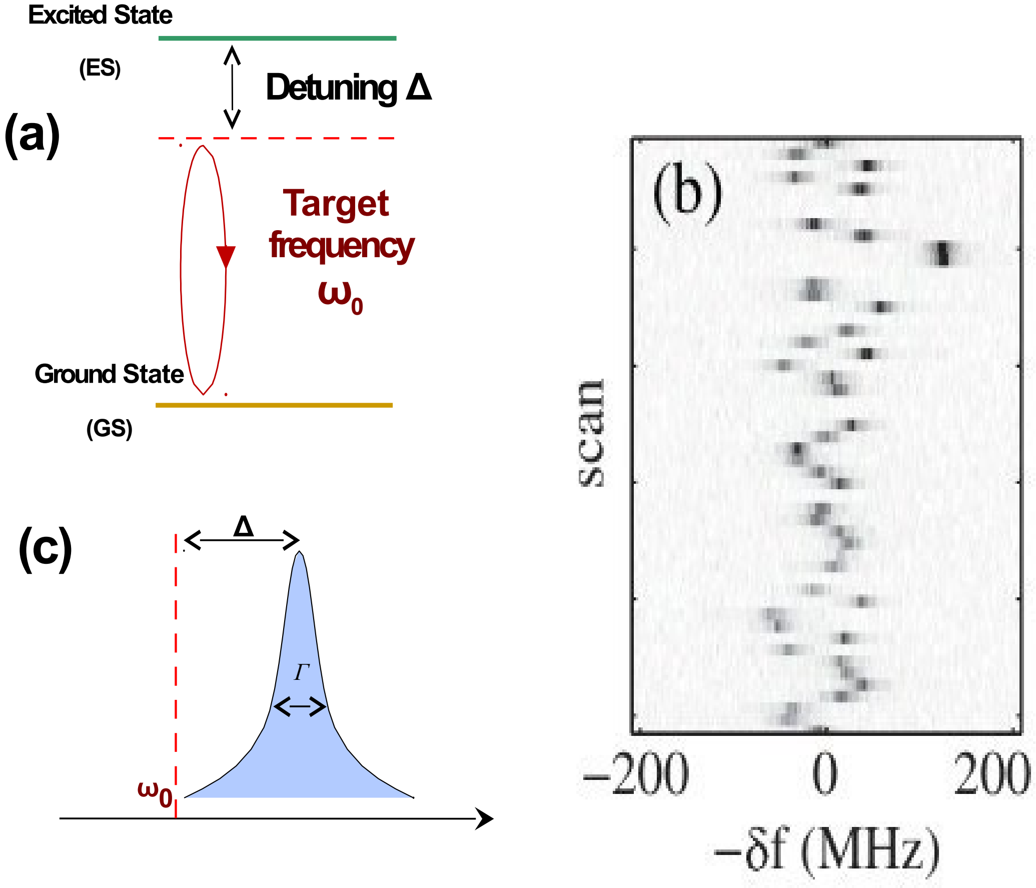




Can the spectra be adjusted as needed?
Can we overcome spectral diffusion?

Can we restore TPI with external controls?

The challenge of spectral diffusion



K. M. Fu et al. PRL **103**, 256404 (2009)

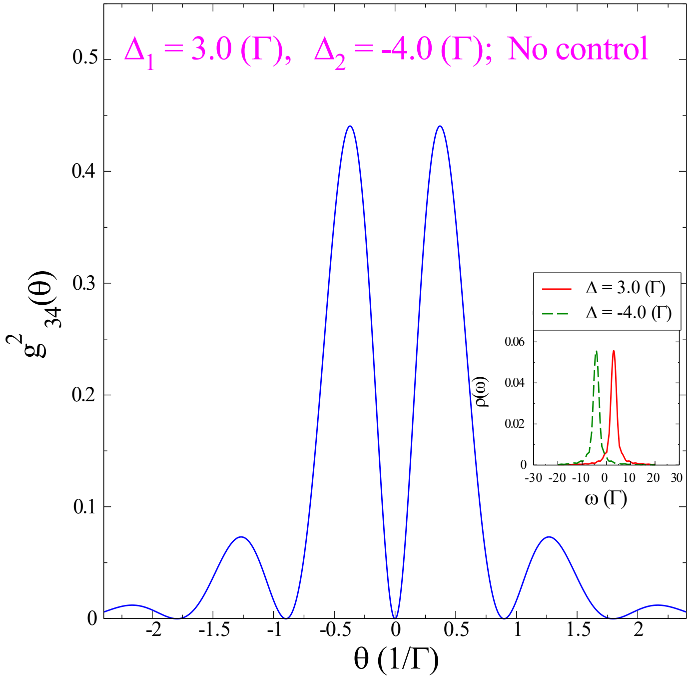
Can we use pulse sequences to suppress spectral diffusion?

Two-Photon Interference

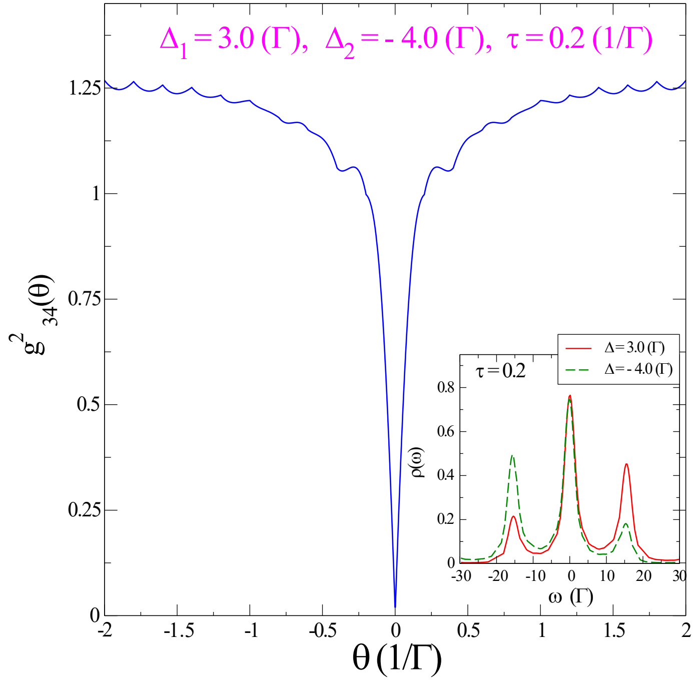
HOM with pulse-driven quantum emitters:

Intensity correlation function: $G^{(2)}_{34}(t,\theta) = \langle a^{\dagger}_{3}(t)a^{\dagger}_{4}(t+\theta)a_4(t+\theta)a_3(t)\rangle$

INtegrated cross-correlation function: $g^{(2)}_{34}(\theta) = \lim_{T\to\infty} \int_0^T G^{(2)}_{34}(t,\theta)dt$



No control



Periodic pulse sequence

Minimal dependence on the detuning/environment:

up to $|\Delta_2 - \Delta_1| \sim 10\Gamma$

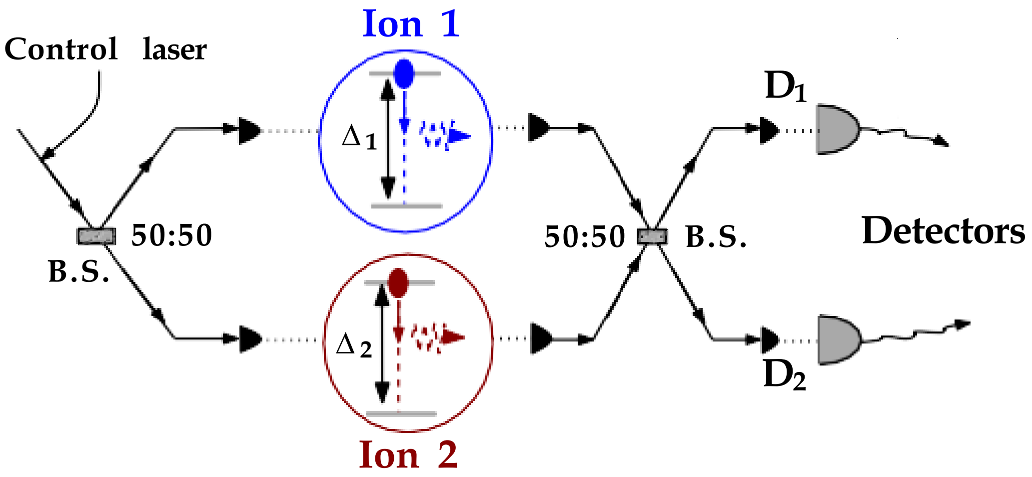
HFF, Phys. Rev B 100, 094309 (2019).

Collaboration with AFRL

- Innovare Advancement Center
  - Multiple qubit modalities:
    Trapped Ion, Photon, Superconducting qubits
  - Theory - Experiment connection
  - Exploration of new frontiers

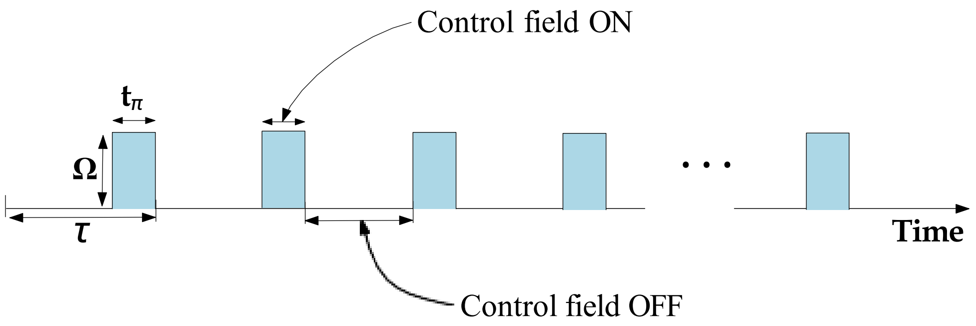
- Realistic protocols for spectral modulation and TPI

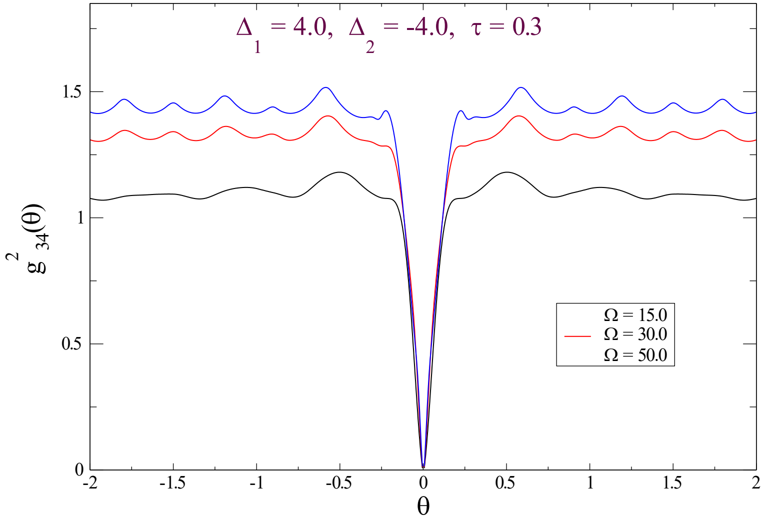
Scheme for TPI with spectrally different ions:

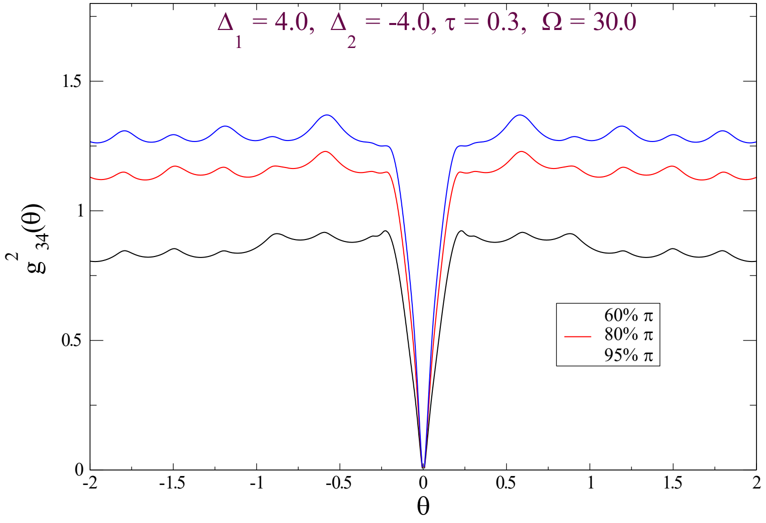


Collaboration with AFRL ...

Imperfect Pulses: finite width, incomplete rotations





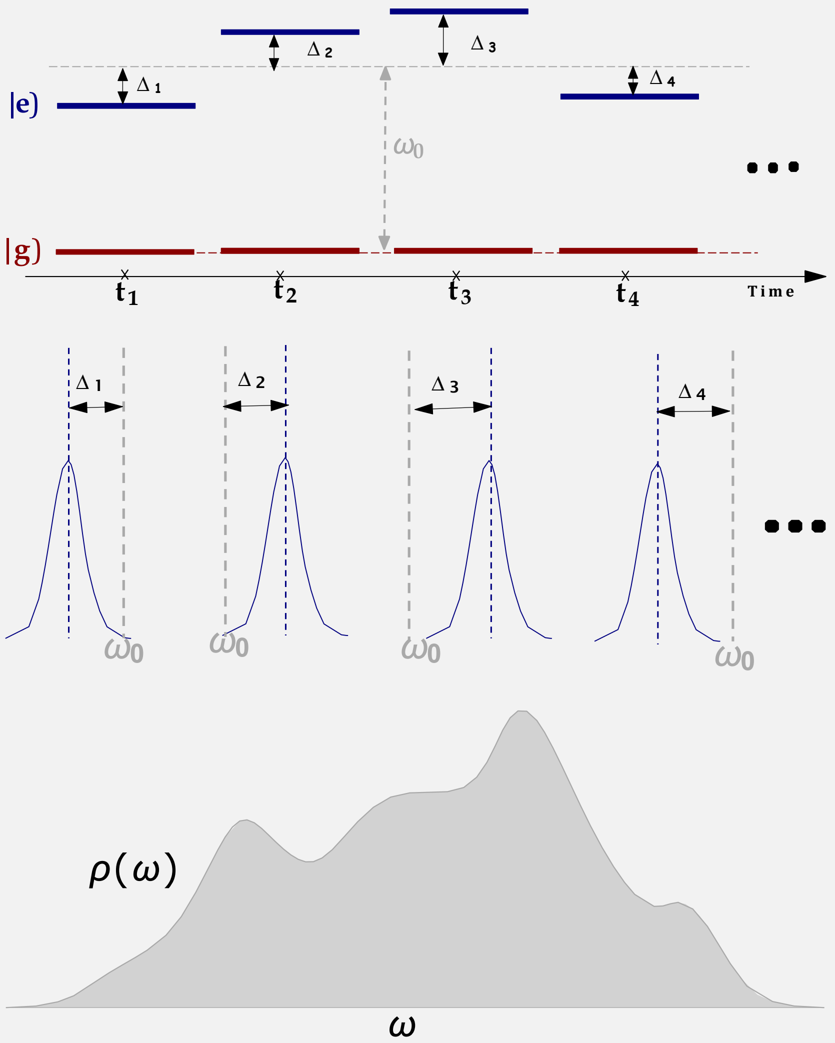


Pulse sequence effective even when highly non-ideal:

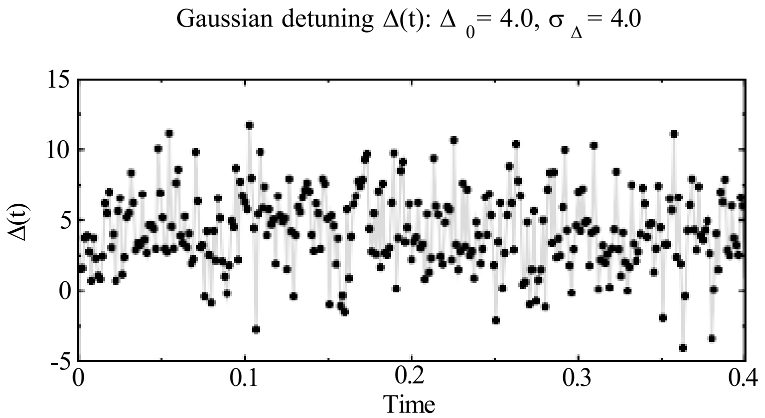
Finite width, Imperfect rotations

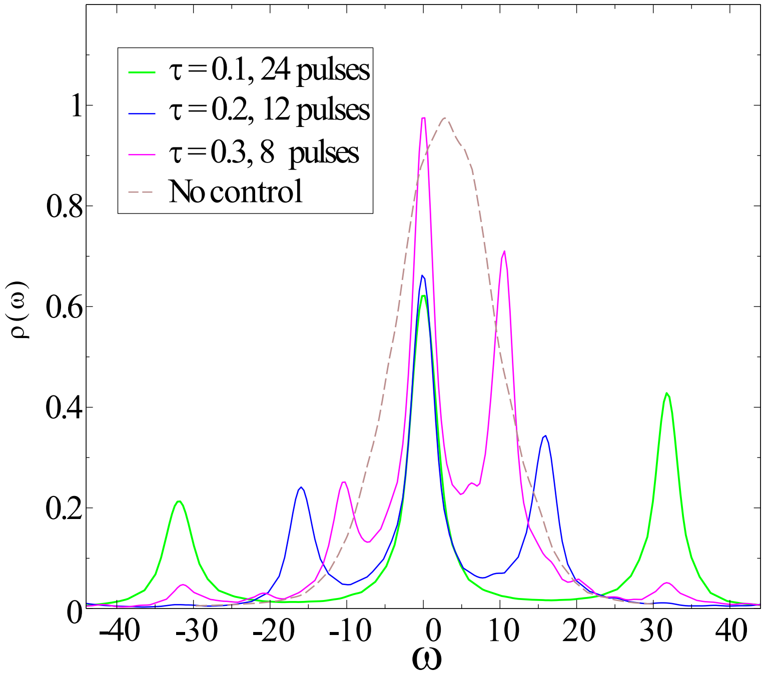
Explicitly Noisy Quantum Emitters

Spectral Diffusion: Explicit Noise

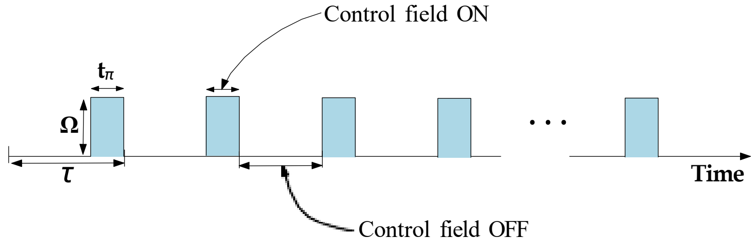


Emitter in Noisy Environment, Finite Width Pulses





Finite width pulses



Well defined refocused spectrum:

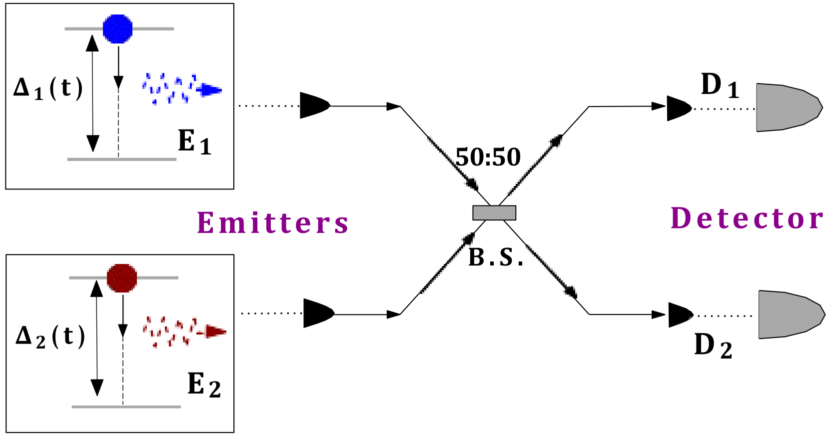
- Narrow central peak at pulse carrier frequency

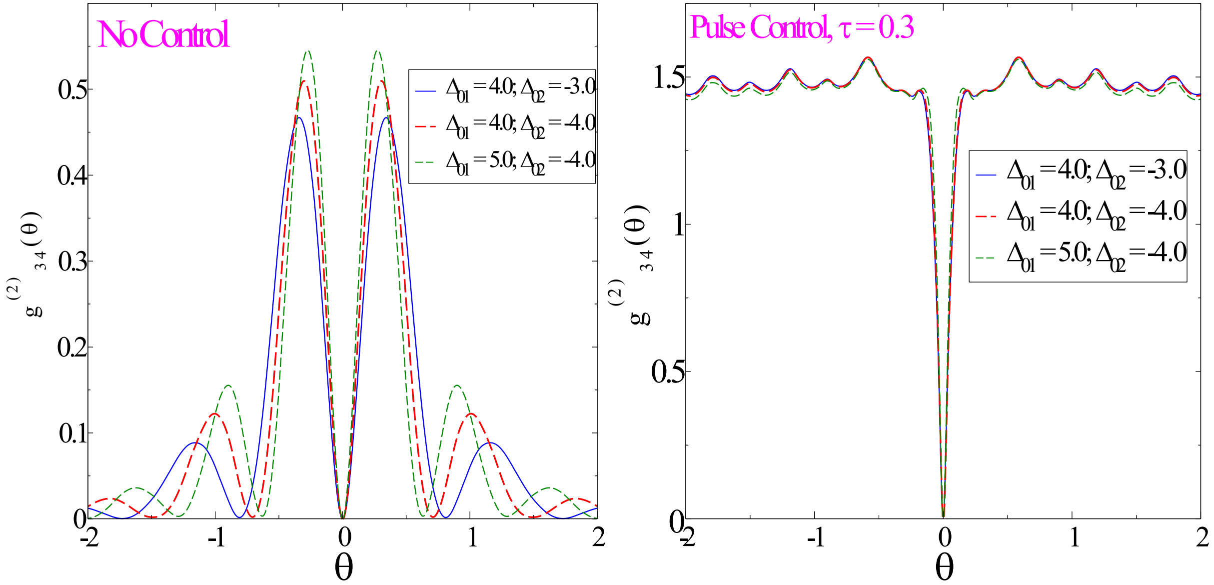
  With ∼ 50% of spectral weight and width ∼ Γ

- satellite peaks at $\pm\pi/\tau$

HFF, Phys. Rev. A 107, 023719 (2023)

Two-Photon Interference: Two Distant Noisy Emitters





Two random Gaussian detunings: $\sigma_{\Delta 1} = \sigma_{\Delta 2} = 6.0$

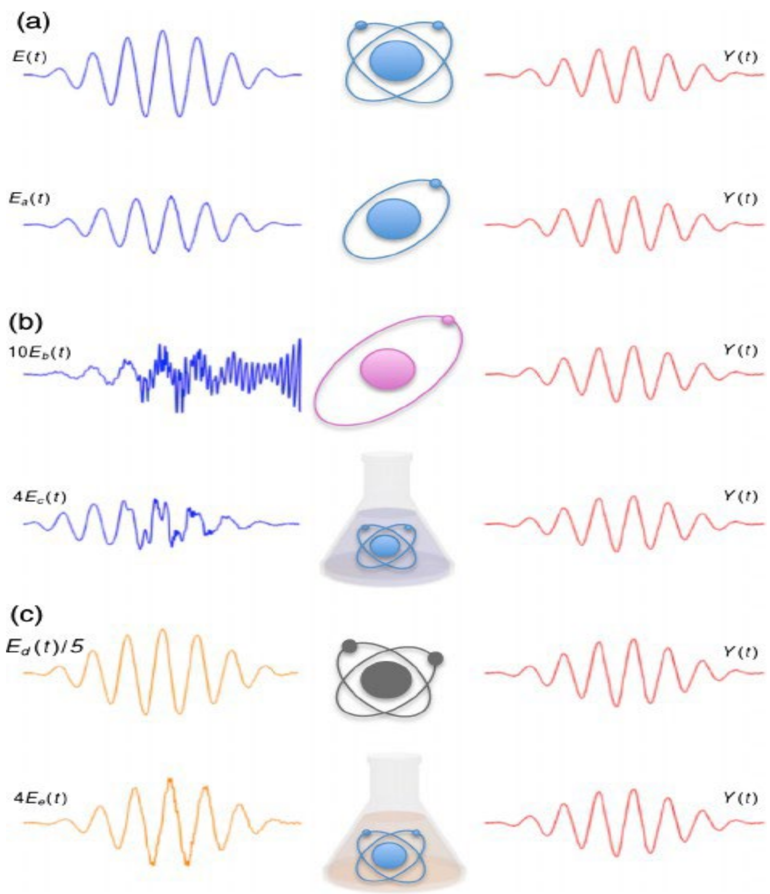
Enhancement of Two-Photon Interference from noisy emitters

HFF, Phys. Rev. A 107, 023719 (2023)

Other similar efforts

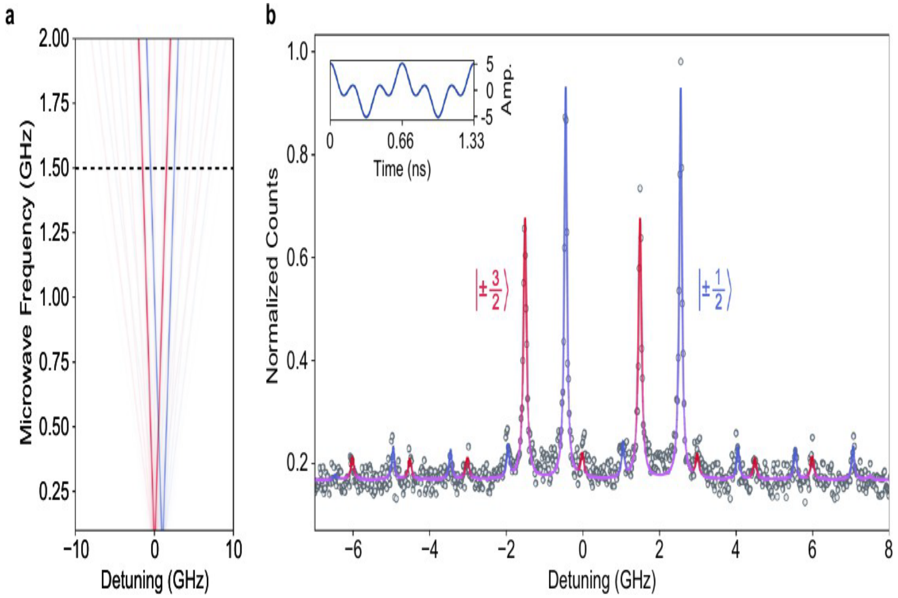
Quantum Mimicry

Can we make multiple different systems behave in the same way?



A. G. Campos et al. PRL 118, 083201 (2017).

Experiment-Theory on SiC

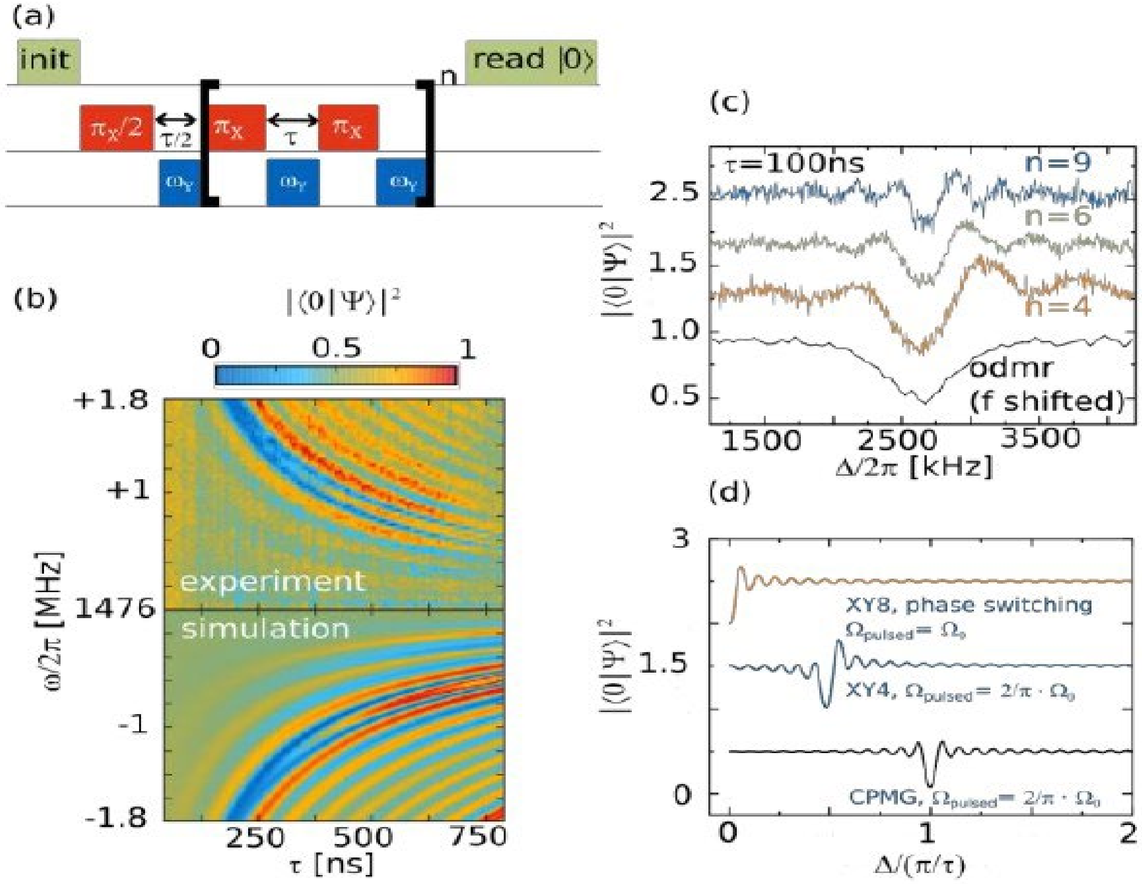


Lukin et al., npj Quantum Information **6**, 80 (2020).

Use of RF sideband for QDots or NVs two-qubit gates ...

Sensing with absorption spectrum of pulse-driven emitters

Sensing of weak E&M signals: $1/T_2$ instead of $1/T_2^*$



T. Joas et al, Nat. Comm., **8**, 964 (2017)

Conclusion and Outlook

- The Promise of quantum computation
- Quantum Optics and QIP intersection
- Spectral inhomogeneity challenges for scalable QIP platforms
- External control fields to supplement materials engineering
- Can overcome spectral diffusion with pulse protocols

Emission/absorption spectrum independent of the environment

Restored photon indistinguishability between different qubits

- Protocols can improve efficiency of critical QIP operations
- Outlook: two-qubit gates, ...

Acknowledgement

Collaborators:

- D. Awschalom (U Chicago)
- V. Dobrovitski (TU Delft)
- Kathy-Anne Soderberg (AFRL)
- David Hucul (AFRL)

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Thank You!

Model and Solution

Model: TLS coupled to bosonic bath + driving field.

Rotating Frame, Rotating-Wave Approximation:

$$H = \frac{\Delta}{2}\sigma_z + \sum_k \omega_k a_k^\dagger a_k - i \sum_k g_k \; a_k^\dagger \sigma_- - a_k \sigma_+ \; + \frac{\Omega_x(t)}{2}(\sigma_+ + \sigma_-)$$

$\Omega_x(t)$ is the external control field e.g periodic π pulses

Units Γ and Γ^{-1} for energy and time. With $\Gamma = 2$

Initially, Emitter in the excited state + all bosonic modes unoccupied

Emission profile: $N_\omega(t) = \langle a_\omega^\dagger(t) a_\omega(t) \rangle$.

$N_\omega(t = 0) = 0$. $N_\omega(t > 0) = ?$

Solve with different complementary methods

Solving the Problem

Analytical solution

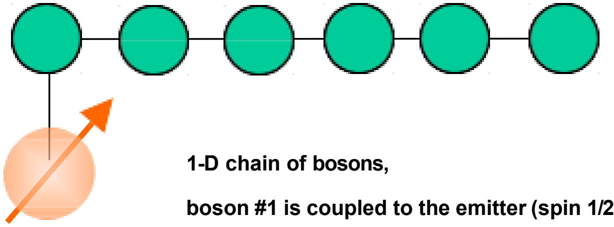
Integrate the E.O.M iteratively between consecutive pulses

- Large number of pulses
- Markovian approximation
- Evaluate integrals numerically.

Master equation

- Large number of bosonic modes
- Markovian approximation
- integrate out the bath
- iteratively integrate the master equation for ρ of the TLS.

Simulation with $t-$ *DMRG*



1-D chain of bosons,

boson #1 is coupled to the emitter (spin 1/2)

Finite number of pulses

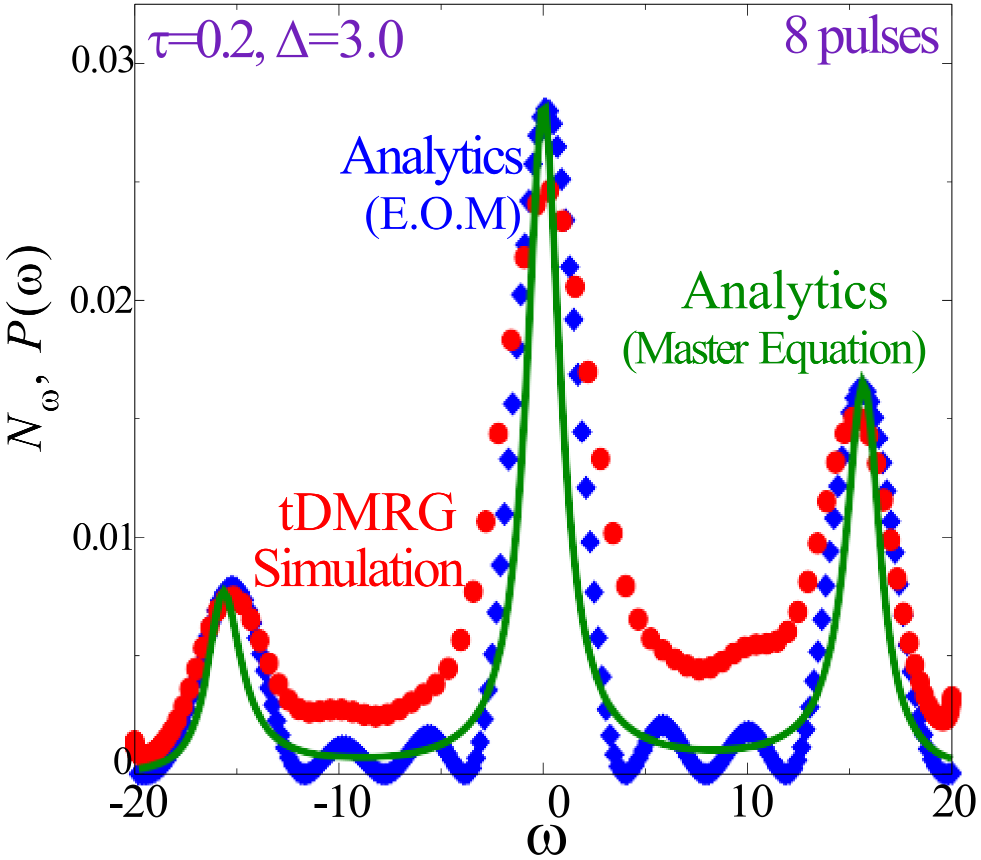
Number of modes

$\sim$ 151, 201, ...

A. E. Feiguin and C. A. Büsser, Phys. Rev. B **84**, 115403 (2011).
S. R. White and A. E. Feiguin, Phys. Rev. Lett. 93, 076401 (2004).

Simulation and Analytical Results

Periodic sequence of (instantaneous) π pulses, with period τ
Good agreement of emission lineshapes



Spectral weight kept at the desired frequency ($\omega_0 = 0$)

satellite peaks at $\pm\pi/\tau$, $\pm 2\pi/\tau$, ...

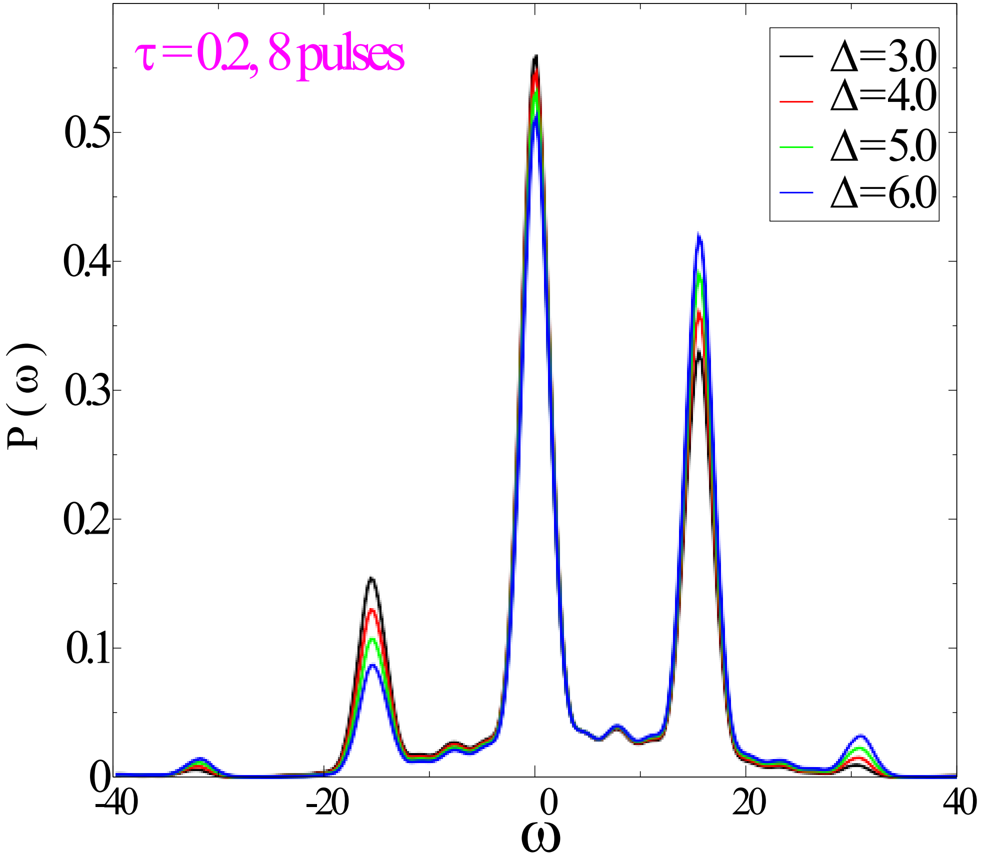
peak amplitude grows with time (number of pulses)

satellite peaks suppressed with smaller τ

H.F.F., A.E. Feiguin, D.D. Awschalom, V. V. Dobrovitski, PRL **116**, 033603 (2016)

Simulation and Analytical Results

Periodic sequence of (instantaneous) π pulses
Little dependence on the environment



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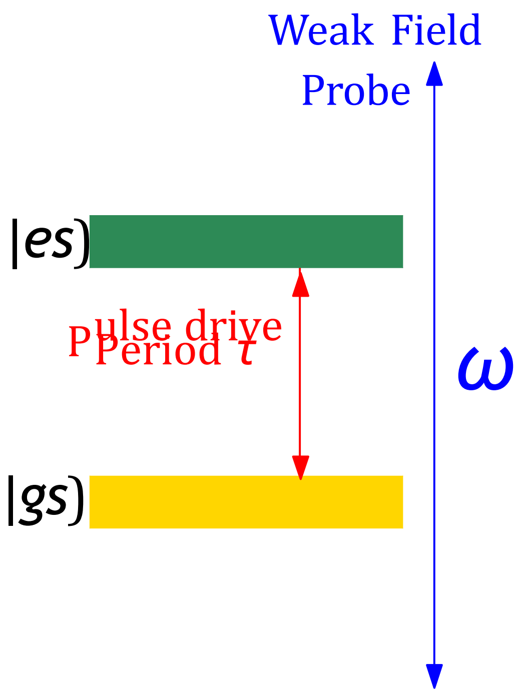
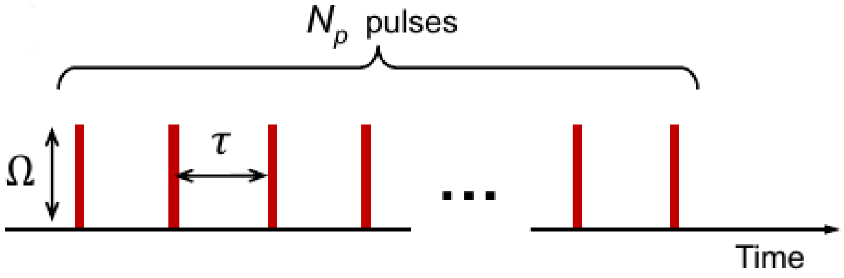
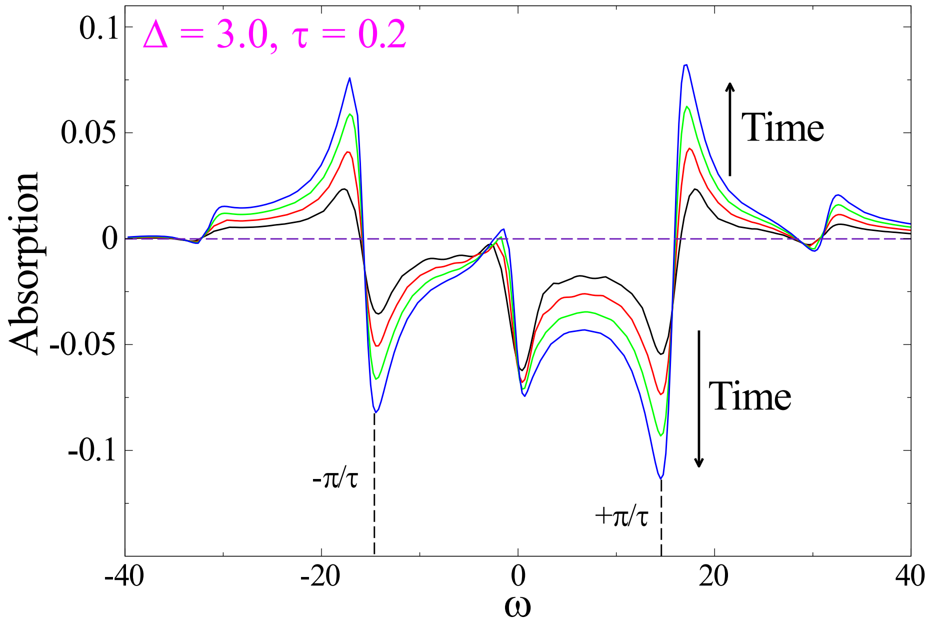
H.F.F., A.E. Feiguin, D.D. Awschalom, V. V. Dobrovitski, PRL **116**, 033603 (2016)

Absorption Spectrum

How does the absorption spectrum change under a pulse sequence?







- Negative and Positive spectral weights
- Peaks at $\pm n\pi/\tau$
- Similarity with CW

System not driven on resonance.

H. F. F and V. V. Dobrovitski, Phys. Rev. B **95**, 214301 (2017).

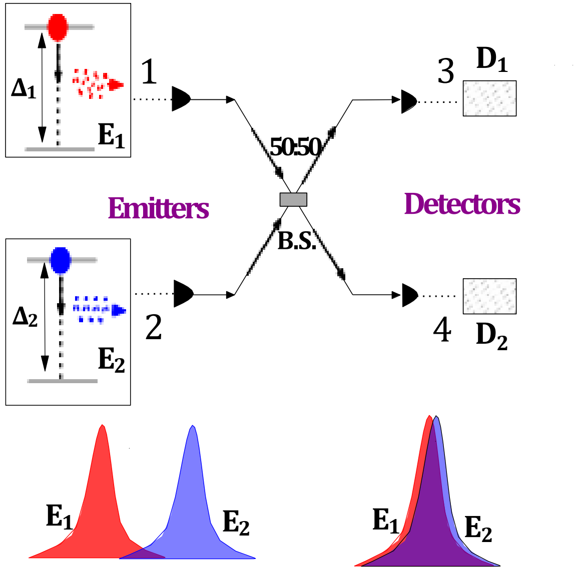
External Protocols to Mitigate the Effects of Spectral Diffusion

HOM with pulse-driven quantum emitters:

Two-Level System coupled to a bosonic bath + control protocol

Rotating Frame, Rotating-Wave Approximation:

$$H = \sum_k \omega_k a_k^\dagger a_k + \frac{\Delta}{2}\sigma_z - i\sum_k g_k \quad a_k^\dagger \sigma_- - a_k \sigma_+ + \frac{\Omega_x(t)}{2}(\sigma_+ + \sigma_-)$$



$$G^{(2)}_{34}(t,\theta) = \langle a_3^\dagger(t) a_4^\dagger(t+\theta) a_4(t+\theta) a_3(t)\rangle$$

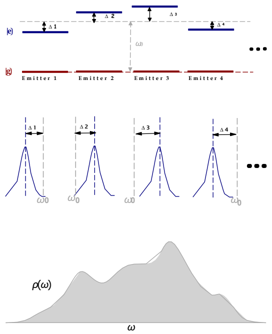
$$g^{(2)}_{34}(\theta) = \lim_{T\to\infty} \int_0^T G^{(2)}_{34}(t,\theta)dt$$

Master equation + Quantum Regression Theorem

Photon Indistinguishability ⇒ “HOM dip in” $g^{(2)}_{34}(\theta)$

Inhomogeneous Broadening - Refocusing With External Pulses

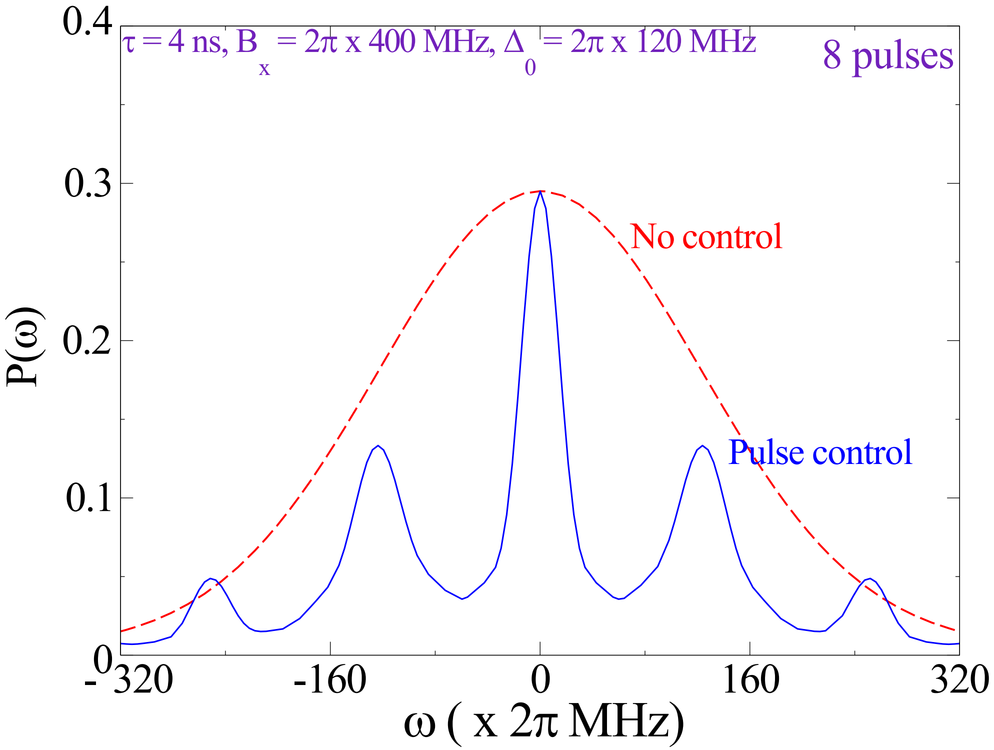
Periodic pulse sequence



Ensemble with Gaussian distribution.

Periodic sequence of π pulses.

Ensemble of quantum emitters

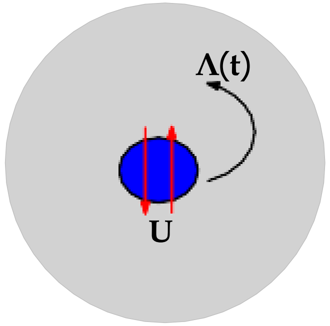


HFF, Phys. Rev. A 107, 023719 (2023)

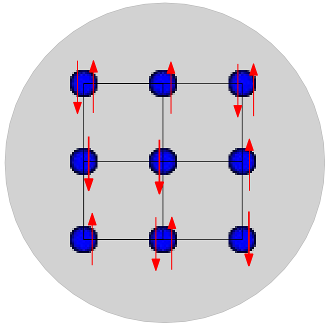
Correlated Systems, the Scientific Difficulties:

- Diagrammatic perturbative treatments inaccurate. Systems are **strongly** correlated (Hubbard with $U \gtrsim J$)
- Exact Numerical methods constrained by poor scaling (exponential scaling of computer resources needed)
  - Exact Diagonalization (ED)
  - Quantum Monte Carlo (QMC)
- Embedding schemes:

Dynamical Mean Field Theory



Dynamical Cluster Approximation



Two length scales:

- **Short**: Exact, ED or QMC
- **Long**: Mean-field

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