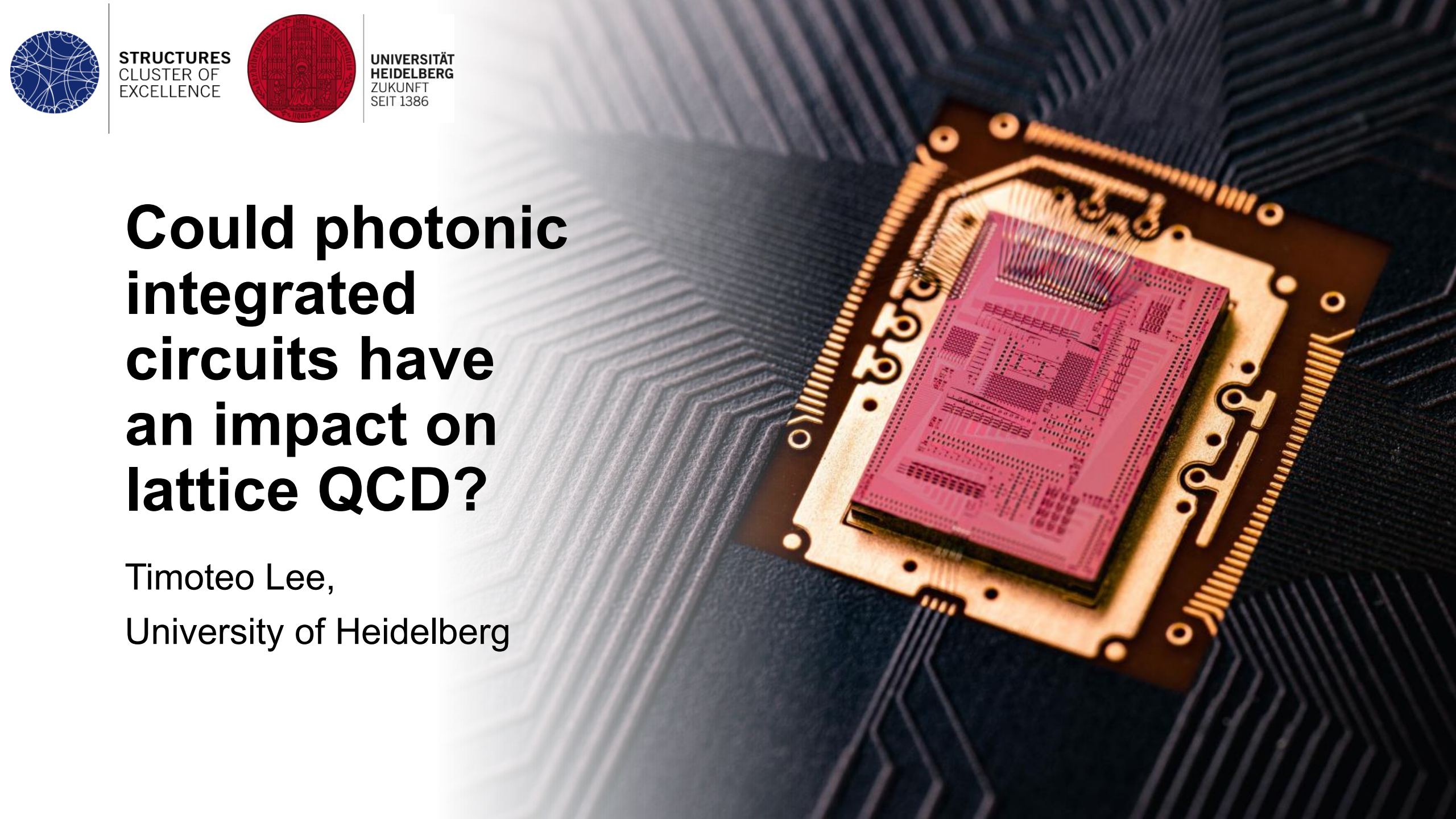

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Could photonic integrated circuits have an impact on lattice QCD?

Timoteo Lee,

University of Heidelberg

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Lattice and renormalization group

Jan M.
Pawlowski

Photonic integrated circuits

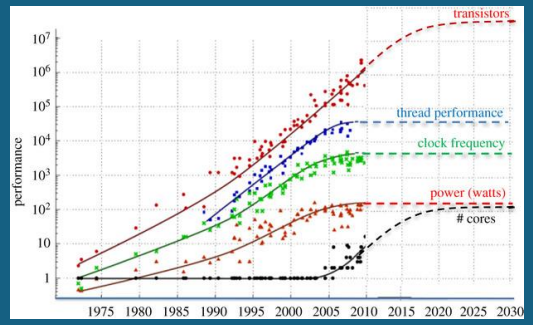
Wolfram
Pernice

Frank
Brückerhoff-
Plückelmann

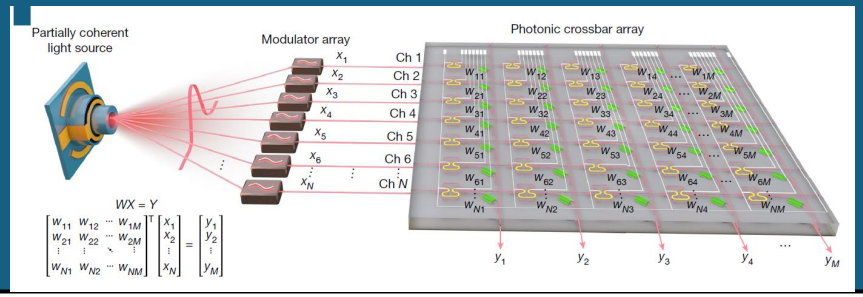
Jelle
Dijkstra

Outline

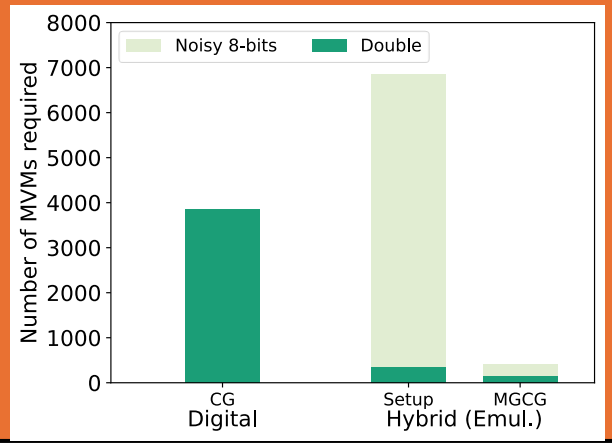
- Motivation
  - Modern hardware
  - Photonic integrated circuits (PICs)



  - Fast and energy efficient
  - Ultralow latency
  - Challenges



- Results and discussion
  - Mixed-precision photonic solvers
  - Test on actual hardware
  - Lattice QCD



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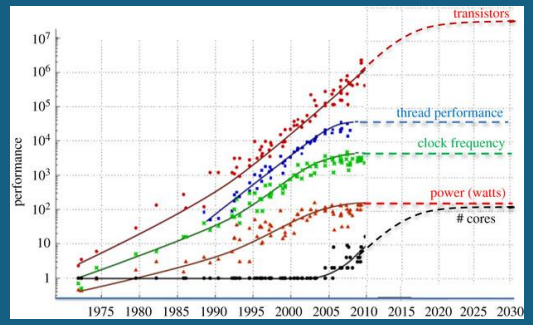

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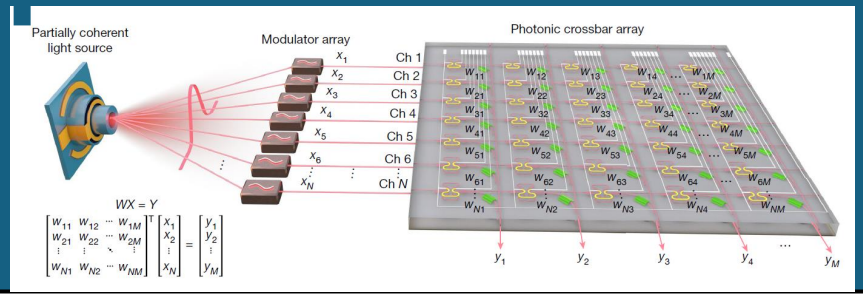

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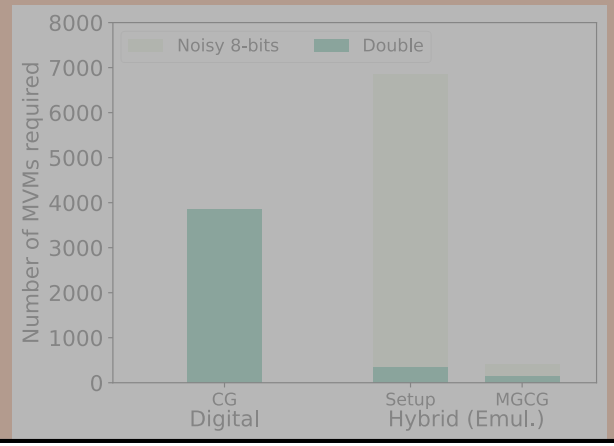
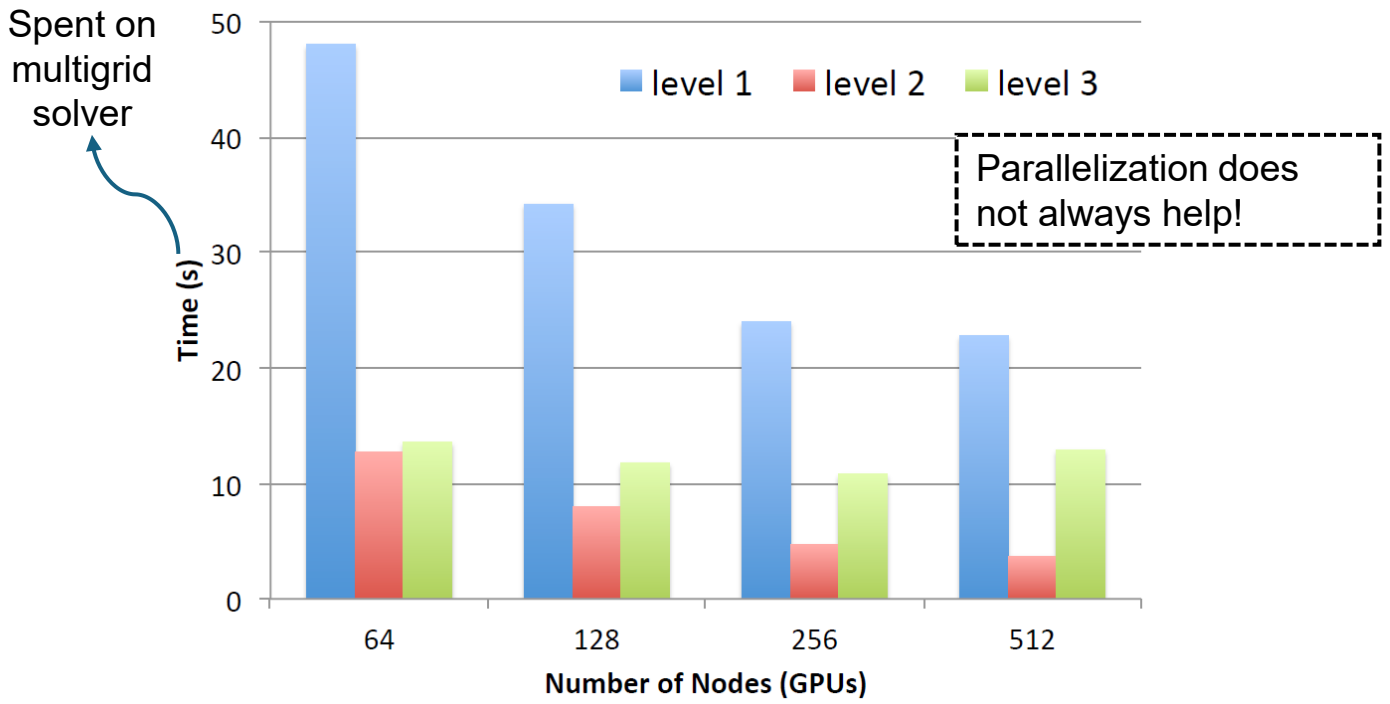


Algorithm vs hardware

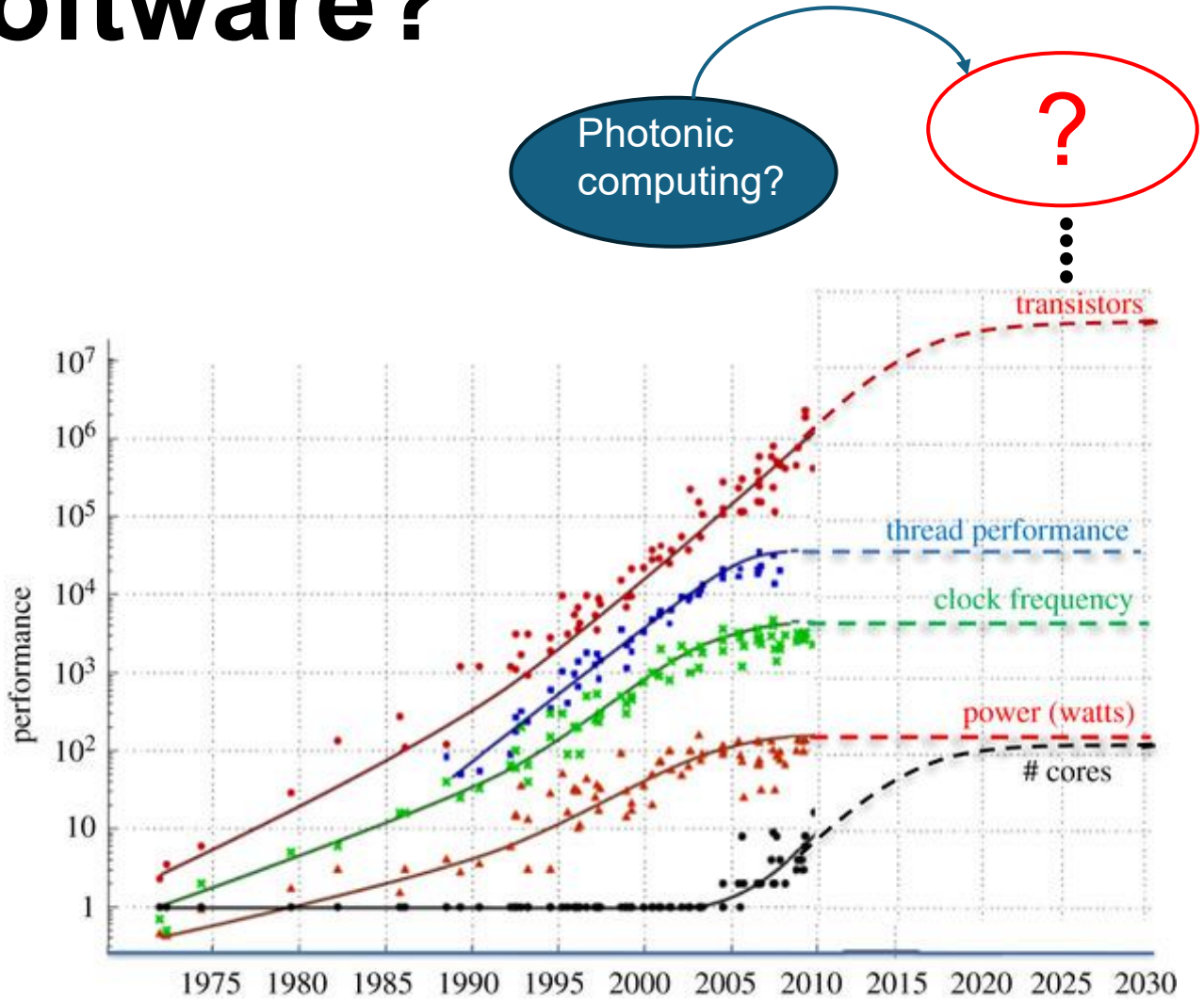
- Hardware: parallel and local
- Algorithms for solving $Ax = b$: Sequential
- Performance: fraction of peak performance



M. A. Clark et al., 2016

Could hardware be the new software?

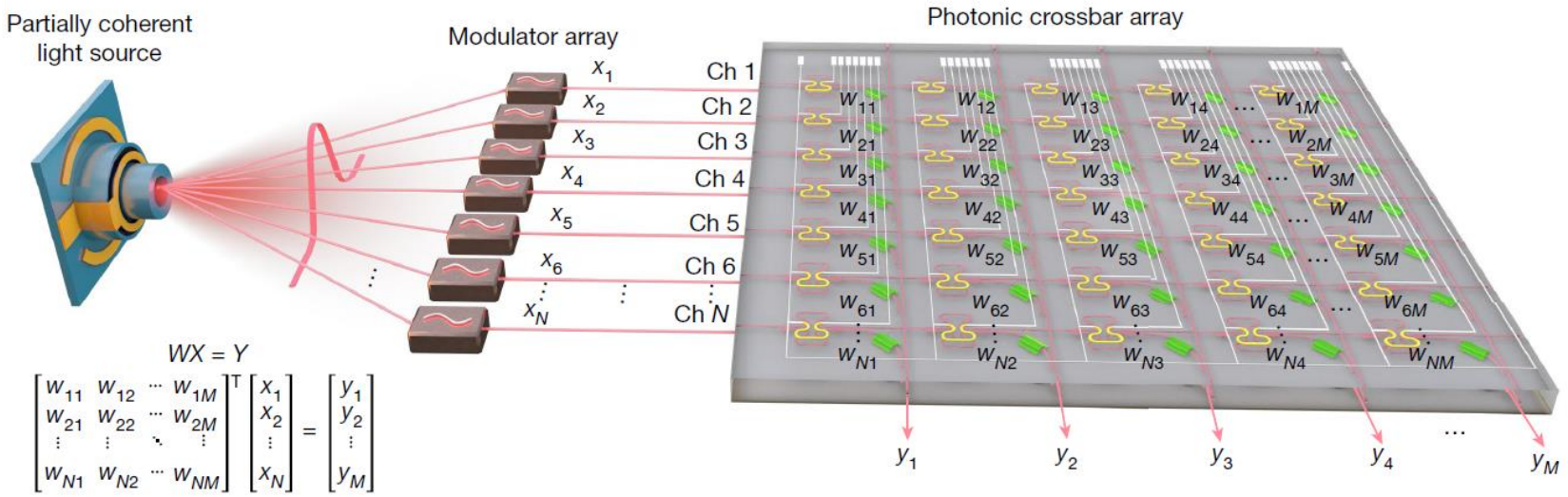
- Alternative: co-optimize algorithms and **hardware**
- In the last decade: ASICs and FPGAs not practical
- Changing scene:
  - Slowing down of Moore's Law
  - More AI-hardware
  - New computing paradigms
- Use all available tools to gain considerable performance!



John Shalf, 2022

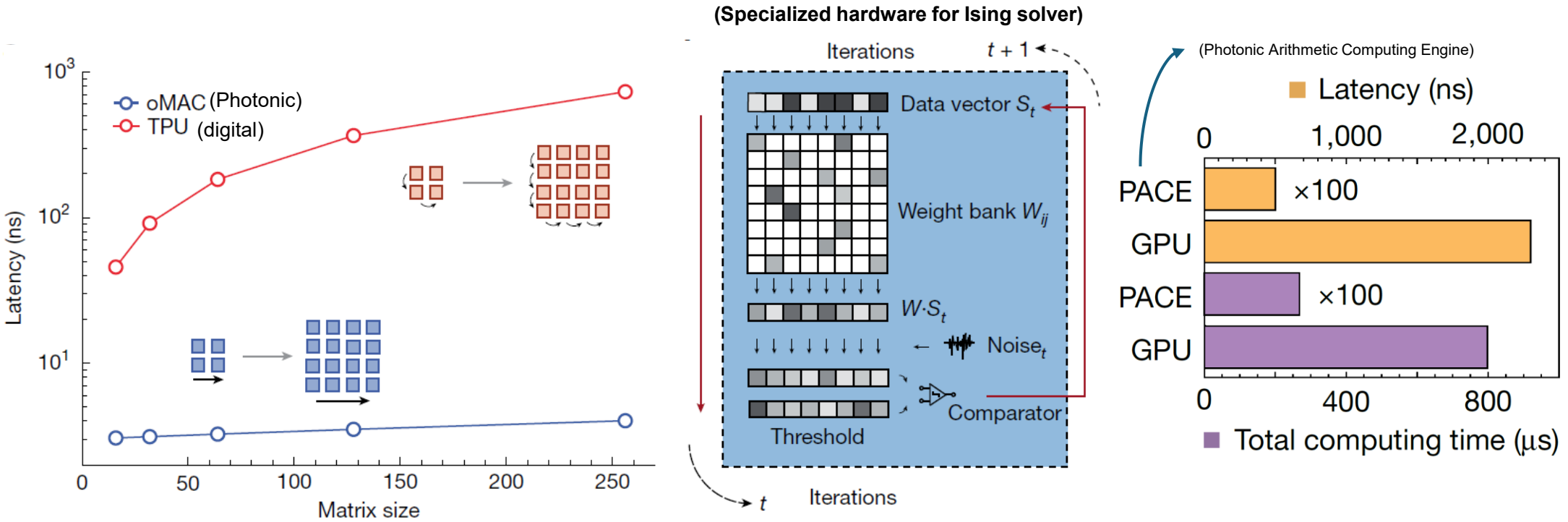
Photonic integrated circuits (PICs)

- Analog data processing
- Less heat dissipation than electrons moving through wires
- In-memory computing
- …and more…



*Dong, B. et al., Nature **632**, 55–62 (2024)*

Ultralow latency

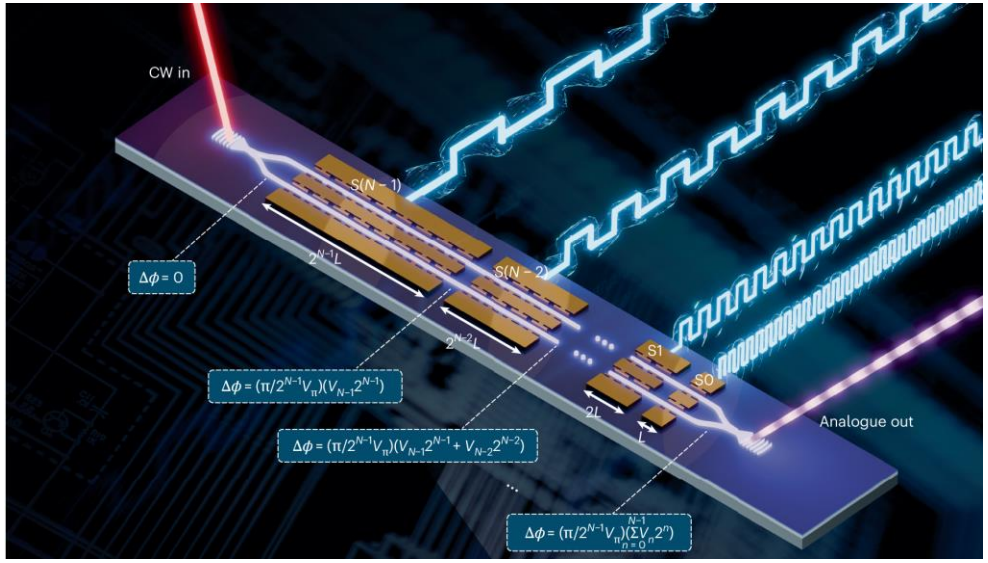


*Hua, S. et al, Nature **640**, 361–367 (2025)*

- Latency scales well with matrix size for PICs
- Specialized hardware for Ising problem provide considerable performance boost

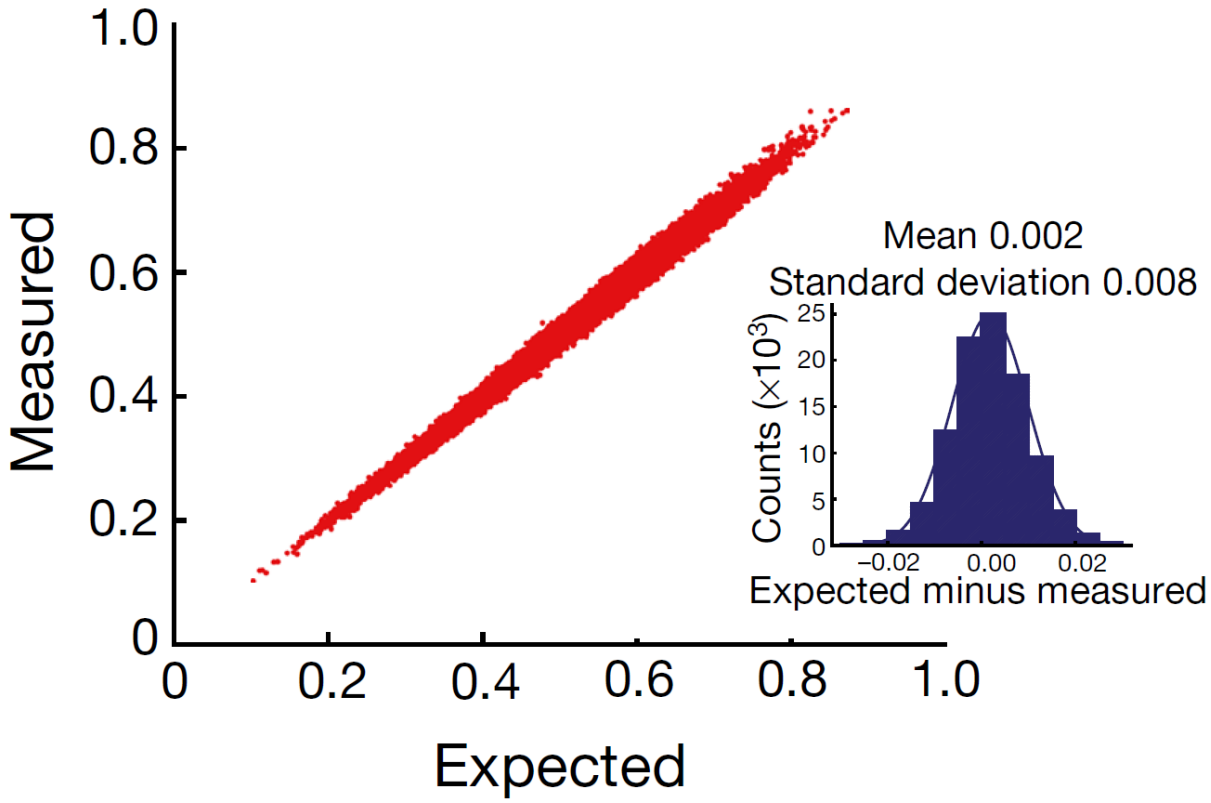
Challenges

- Converters between analog and digital domain



Song, Y. *et al., Nat. Photon.* **19**, 1107–1115 (2025)

- Low-accuracy



*Feldmann, J. et al., Nature **589**, 52–58 (2021)*

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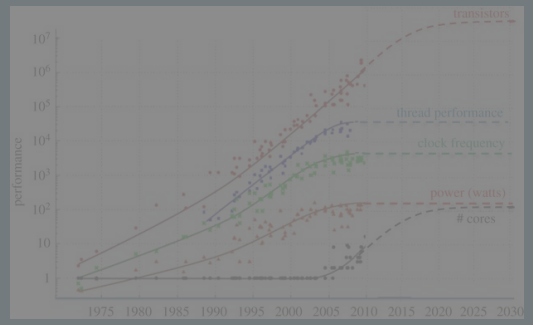

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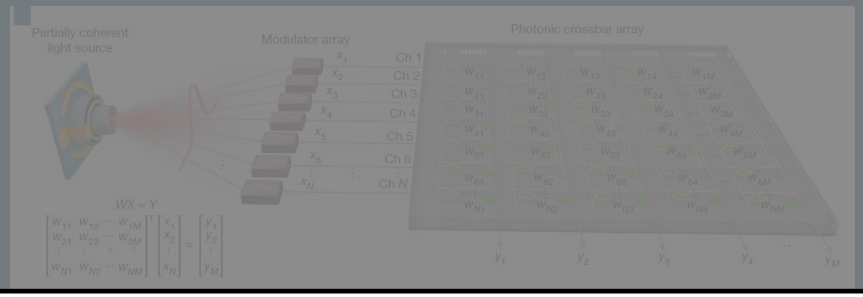

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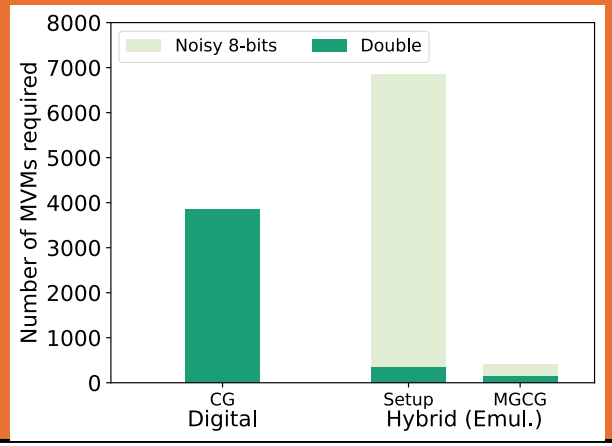
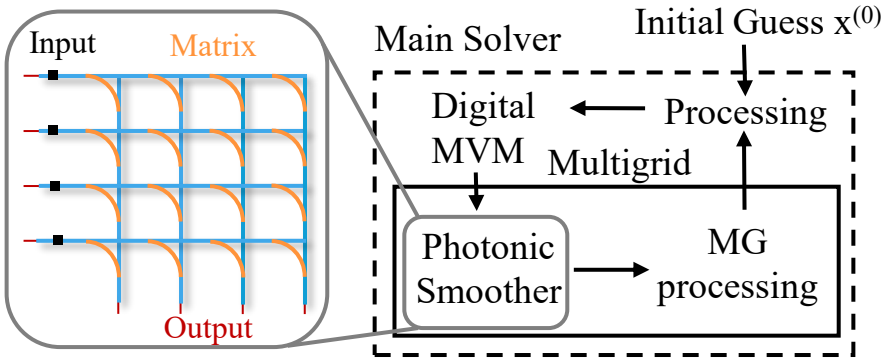


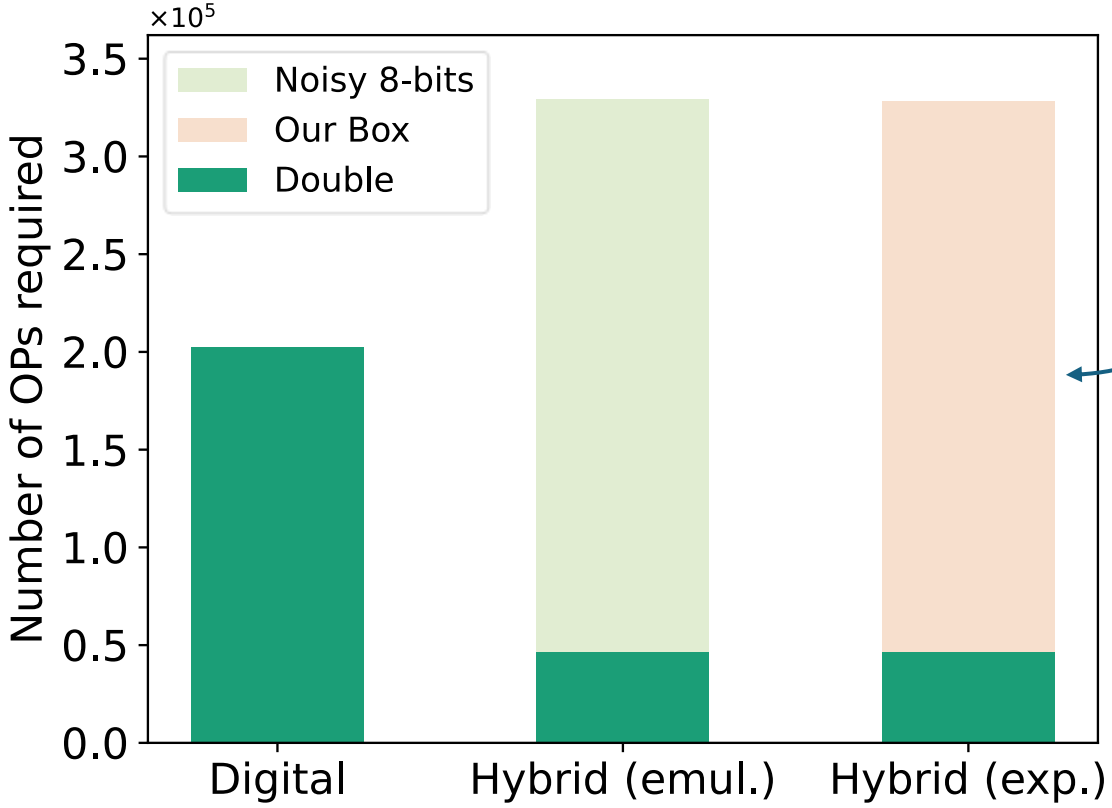
Mixed-precision photonic solvers

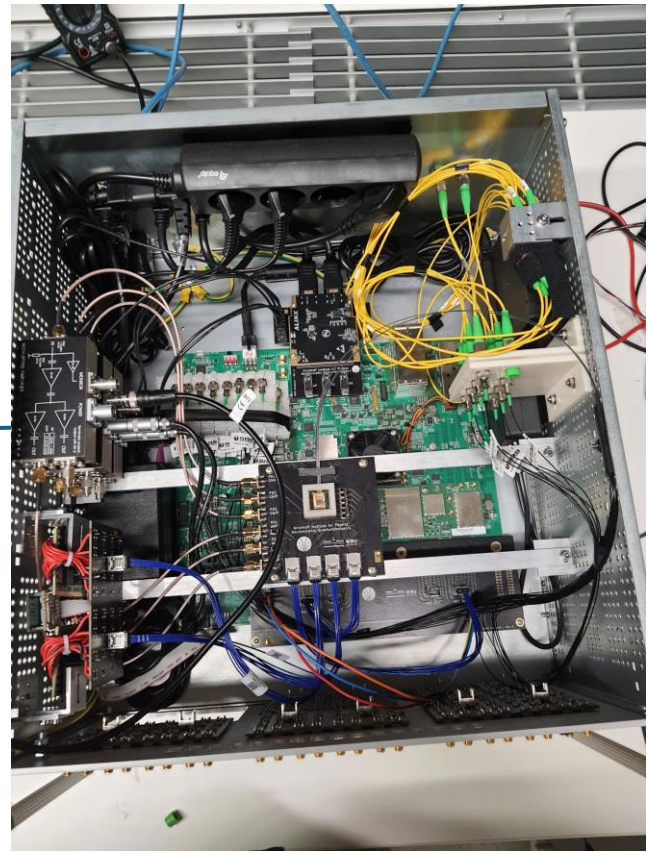
- Krylov solvers with multigrid preconditioners
- Richardson smoother is offloaded to the optical domain
- Performance estimation:
  - Assumption: optimized domain-specific hardware based on PICs are infinitely better than digital hardware
  - Consequence: Only digital operations contribute to computation time and energy consumption



First tests

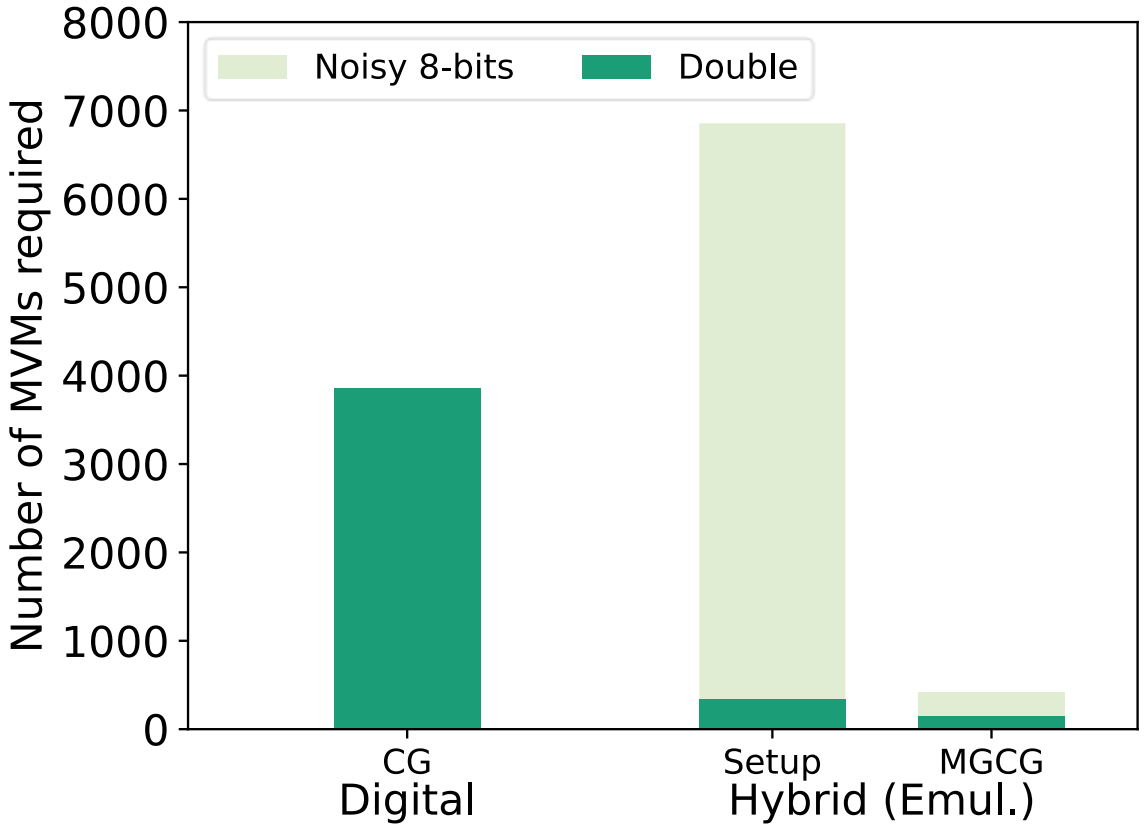
- Goal: check that the technology is understood properly
- Problem: one dimensional quantum quartic anharmonic oscillator
- Use emulation (Emul.) to test new algorithms





Lattice QCD

- 2D U(1) Schwinger model
- Normal equation
- Random RHS
- Adaptive method (setup)
- Two-grid scheme
- For SRHS: performance gain of one order of magnitude both in terms of speed and energy efficiency



Discussion

- No infinite sources of parallelism
- Analog specialized hardware as a new tool
- Photonic integrated circuits achieve ultralow latency
- Not replace, but complement digital hardware
- Optimization of mixed-precision algorithms
- Outlook: Understand the challenges of implementation

Thank you for your attention!

arXiv:2511.01005

Calculation Parameters

- Quench approximation U(1)
- $S_G[U] = \beta \sum_{n\in\Lambda} \sum_{\mu<\nu} Re\, tr\left[\mathbb{1} - U_{\mu\nu}(n)\right]$, with β = 6
- 128 x 128 lattice
- m = -0.063
- 10 different gauge fields each with 10 different random RHS
- Accuracy defined by ||r|| = 10^{-10}
- $$D_{x,y}[U] = -\frac{1}{2}\sum_{\mu=1}^{2}\left[(1-\gamma_\mu)U_x^\mu \delta_{x+\hat{\mu},y} + (1+\gamma_\mu)\left(U_{x-\hat{\mu}}^\mu\right)^\dagger \delta_{x-\hat{\mu},y}\right] + (2+m)\delta_{x,y}$$