Boson sampling simulation enhanced by FPGA based data-flow engines

Peter Rakyta

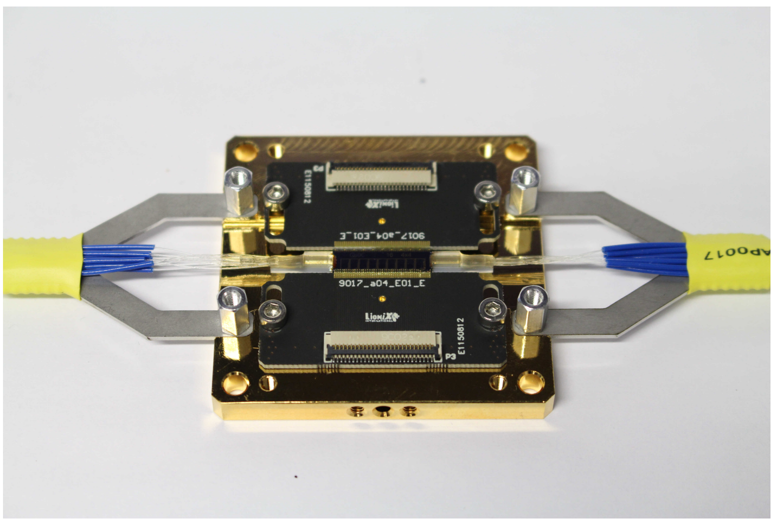
Department of Physics of Complex Systems

Optical Quantum Computing

Quantum Information
National Laboratory
HUNGARY

optical interferometers

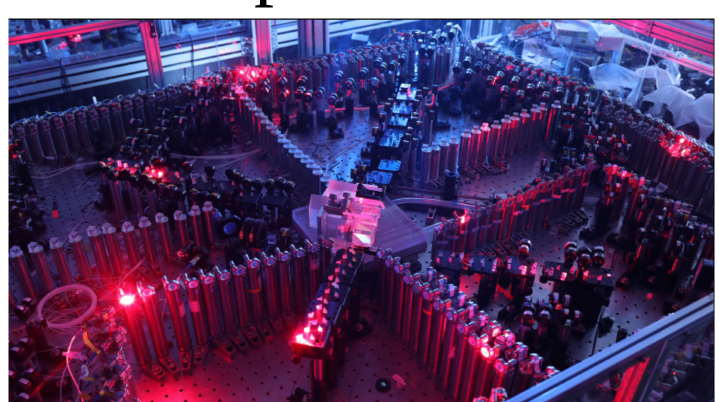
on chip



- N optical modes occupied by 0,1,2, ... N photons (instead of qubits)
- single photon sources or Gaussian sates

generated from coherent laser beams

on optical table



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Quantum advantage showed on Boson Sampling from a Gaussian state

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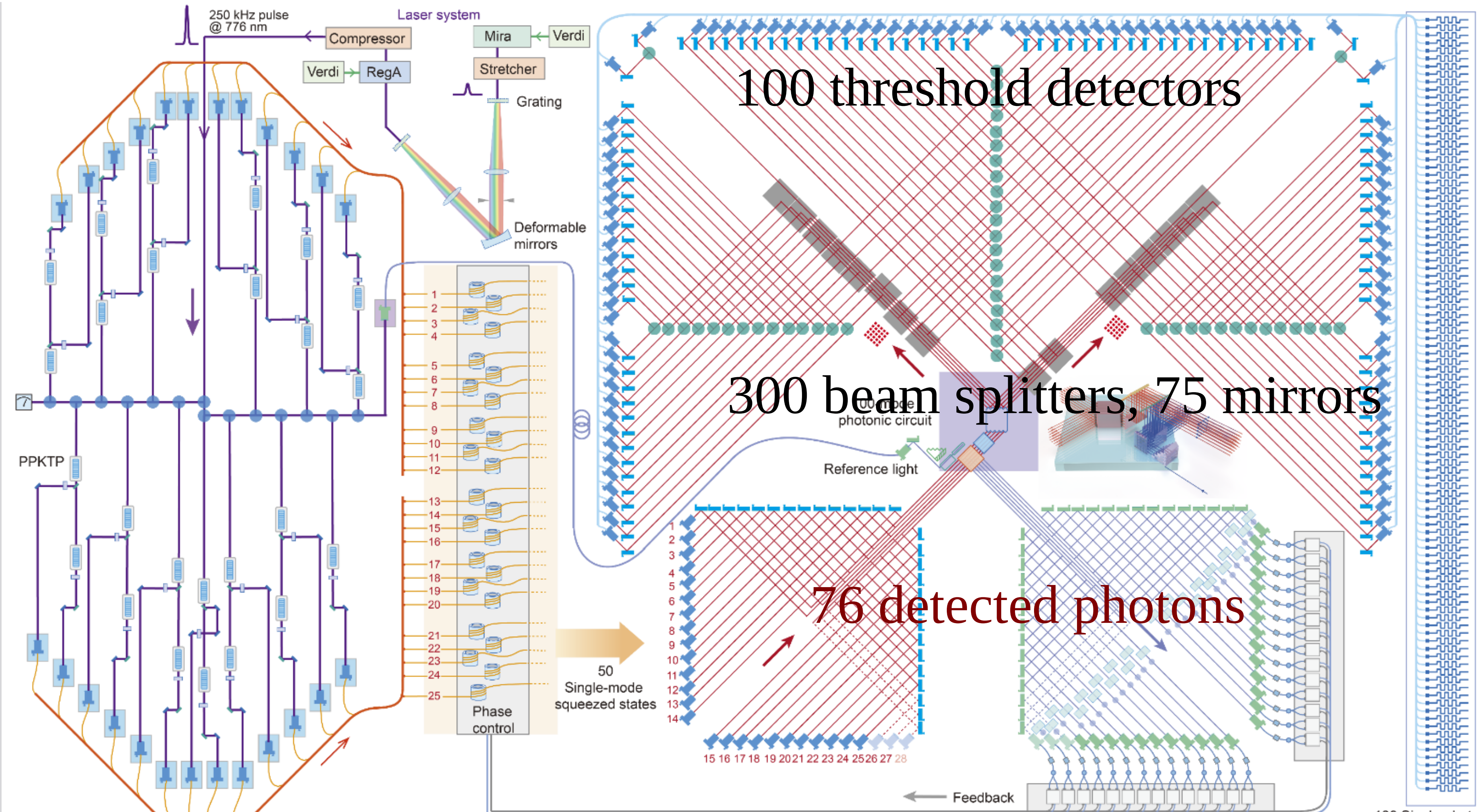

Quantum computational advantage using photons. Science, 370(6523):1460–1463, 2020.

University of Science and Technology of China
Chinese Academy of Sciences, Tsinghua University, China

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Programable optical integrated circuits

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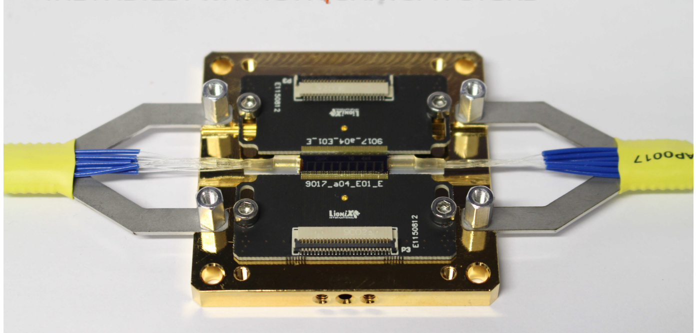
Spin-off University of Twente

QUIX

THE FASTEST WAY TO A QUANTUM FUTURE



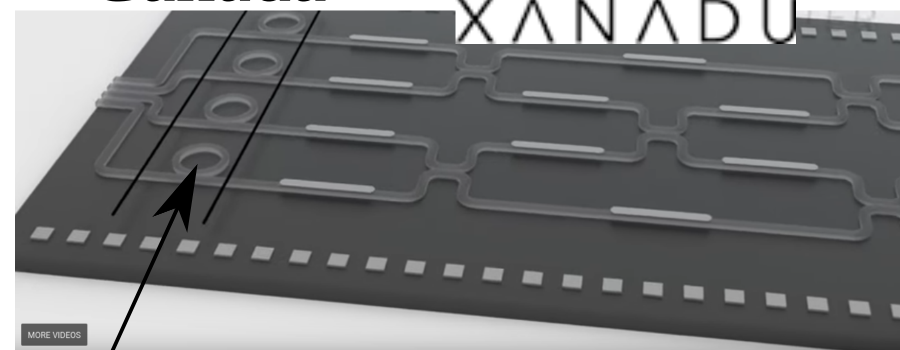
Netherlands

conencted to single photon
sources and PNR detectors

12 photonic modes

Canada

XANADU



creates squeezed state from
classical laser input - this is the qubit

24 photonic modes

Strawberry Fields:
quantum computer simulator

PennyLane:
first library for quantum machine learning

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The Piquasso project

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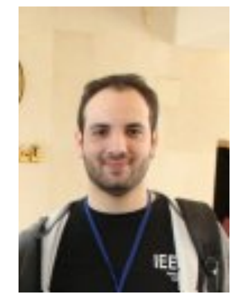
Why don't we put together a bosonic quantum simulator?

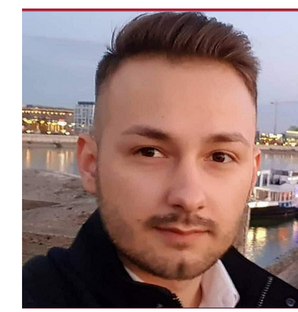
Zoltán Zimborás
Wigner

Kozsik tamás



Kareem El Safty

Poór Boldizsár

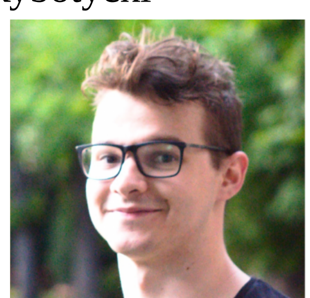


Jóczik Szabolcs

Michał Oszmaniec

Tomasz Rybotycki

Kaposi Ágoston



Kolarovszki Zoltán

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Boson Sampling

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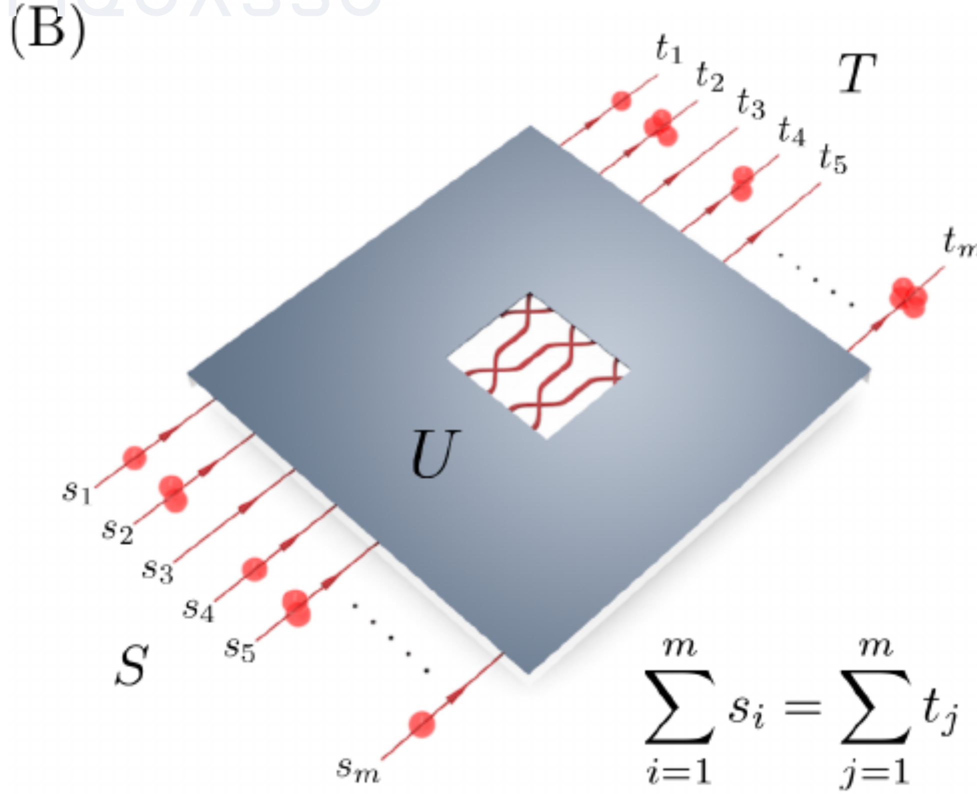
The Computational Complexity of Linear Optics

Scott Aaronson* Alex Arkhipov†



$$\sum_{i=1}^{m} s_i = \sum_{j=1}^{m} t_j = n$$

$$P[S \to T] = \frac{|Per(U_{S,T})|^2}{s_1! \ldots s_m! t_1! \ldots t_m!}$$

$$\mathrm{Per}\,(A) = \sum_{\sigma \in S_n} \prod_{i=1}^{n} a_{i\sigma(i)},$$

Set of permutations of (1,2,3 .... n)

$\mathcal{O}((n-1)\cdot n!)$

$\mathcal{O}(n^2 \cdot 2^n)$

Ryser's formula:

$$\mathrm{Per}(A) = (-1)^n \sum_{S \subseteq \{1,2,\ldots,n\}} (-1)^{|S|} \prod_{i=1}^{n} \sum_{j \in S} a_{ij}$$

BB/FG's formula:

$$\mathrm{Per}(A) = \frac{\sum_\delta \left(\prod_{k=1}^n \delta_k\right) \prod_{i=1}^n \sum_{j=1}^n \delta_j a_{ij}}{2^{n-1}}$$

$\delta = \{\delta_1, \delta_2, ..., \delta_n\}$ $\delta_1 = 1$ and $\delta_i \in \{-1, 1\}$ for $2 \leq i \leq n$

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Permanent calculation complexity

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Further complexity improvements by Gray code ordering:

0	000	0	000
1	001	1	001
2	010	3	011
3	011	2	010
4	100	6	110
5	101	7	111
6	110	5	101
7	111	4	100

$\mathcal{O}(n^2 \cdot 2^n)$ complexity reduced to $\mathcal{O}(n \cdot 2^n)$

data recycling in expressions:

$$\sum_{j \in S} a_{ij} \qquad \sum_{j=1}^{n} \delta_j a_{ij}$$

in exchange of scalability reduction?

Strawberry Fields

Ryser's formula: $\mathrm{Per}(A) = (-1)^n \sum_{S \subseteq \{1,2,\ldots,n\}} (-1)^{|S|} \prod_{i=1}^{n} \sum_{j \in S} a_{ij}$

Piquasso

BB/FG's formula: $\mathrm{Per}(A) = \dfrac{\sum_\delta \left(\prod_{k=1}^{n} \delta_k\right) \prod_{i=1}^{n} \sum_{j=1}^{n} \delta_j a_{ij}}{2^{n-1}}$

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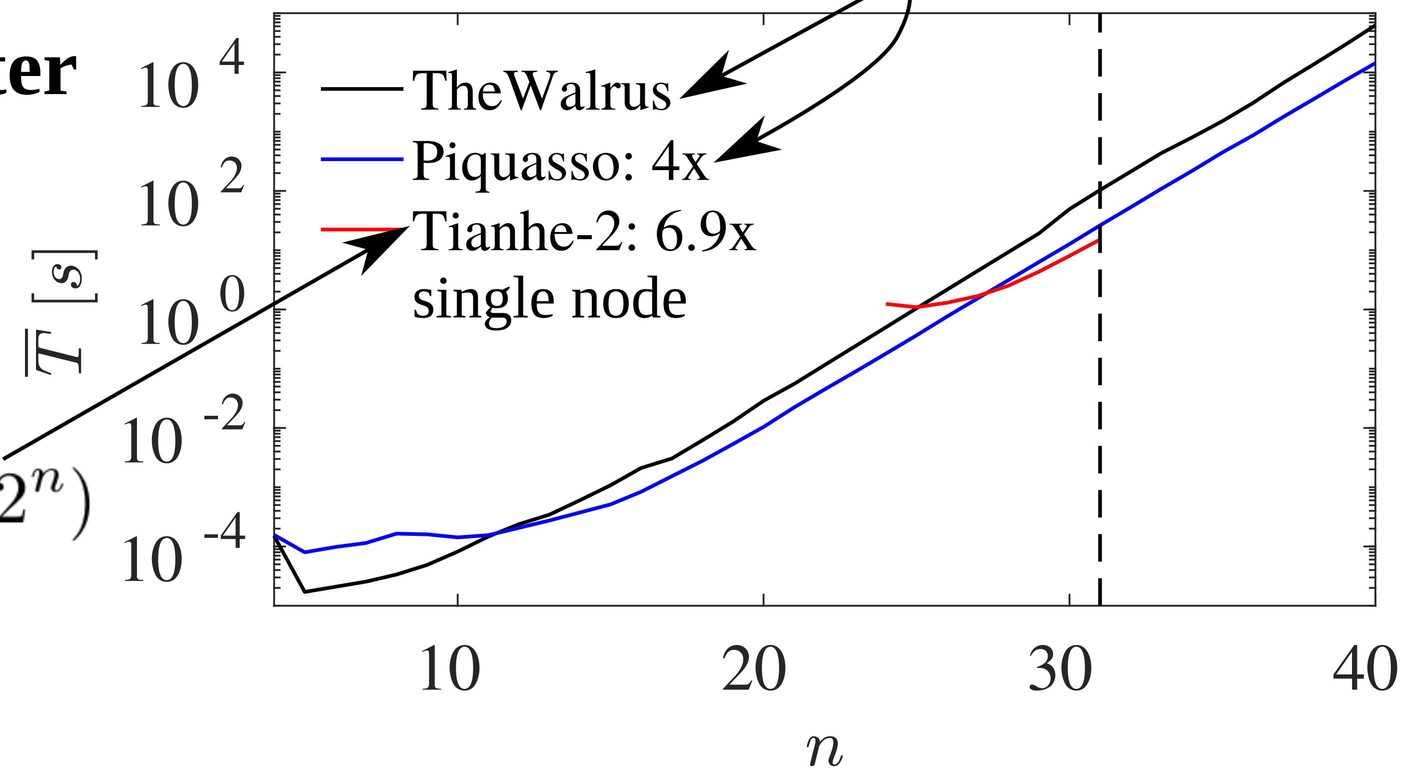
Permanent calculation benchmark

$\mathcal{O}(n \cdot 2^n)$

Intel Xeon Gold 6130, 24 threads

Tianhe-2 supercomputer

$\mathcal{O}(n^2 \cdot 2^n)$



16 000 computing nodes

Intel Xeon E5: dual socet x 12 cores x 2 multithread = 48 threads

Xeon Phi 31S1P: 3 PCI cards x 57 cores x 4 multithreads = 684 threads

total: 33.86 petaflops

limit: permanent of n=50 matrix in 1 hour

National Science Review, Volume 5, Issue 5, September 2018, Pages 715–720

FPGA based data-flow engines (DFE's)

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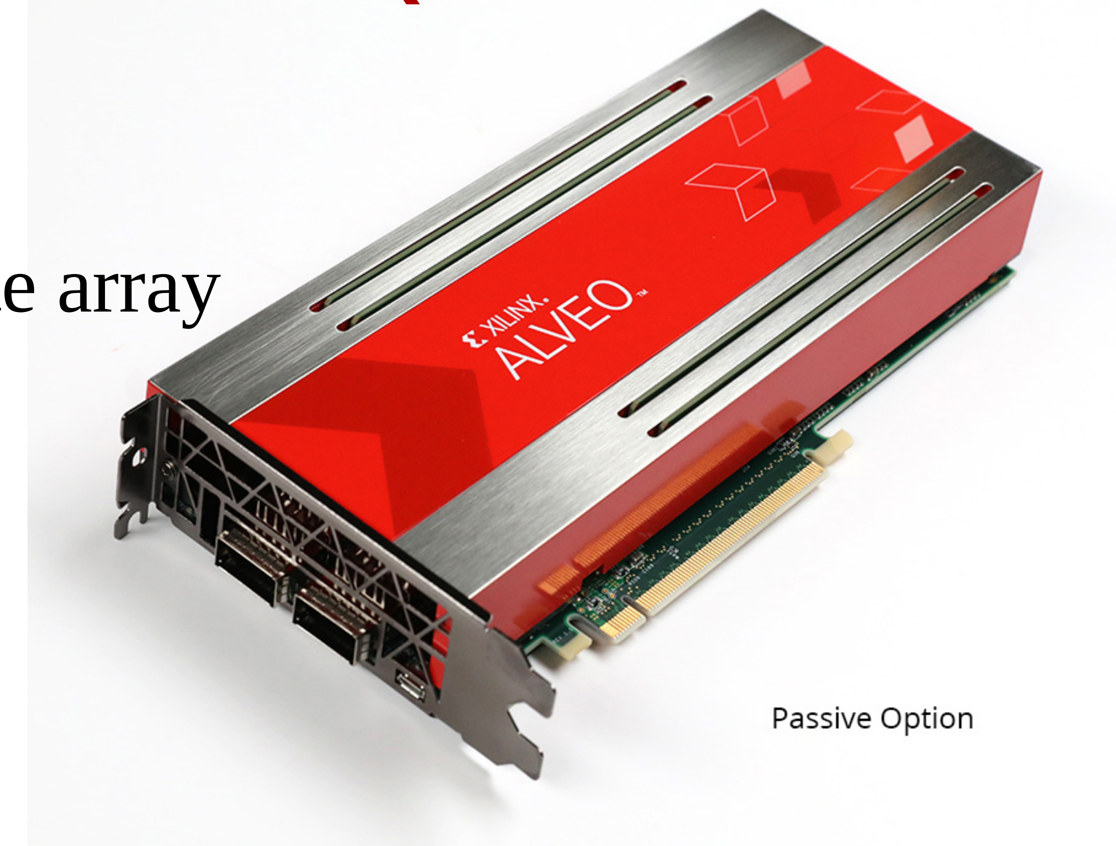
FPGA: field-programmable gate array



programmable logic gates,
memory units,
arithmeic units,
or other elements

particularly useful for prototyping application-specific integrated circuits (ASICs) or processors.

Quamtum Computing inspired ASICs?
Coprocessors for real Quantum Hardware?

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FPGA based data-flow engines (DFE's)

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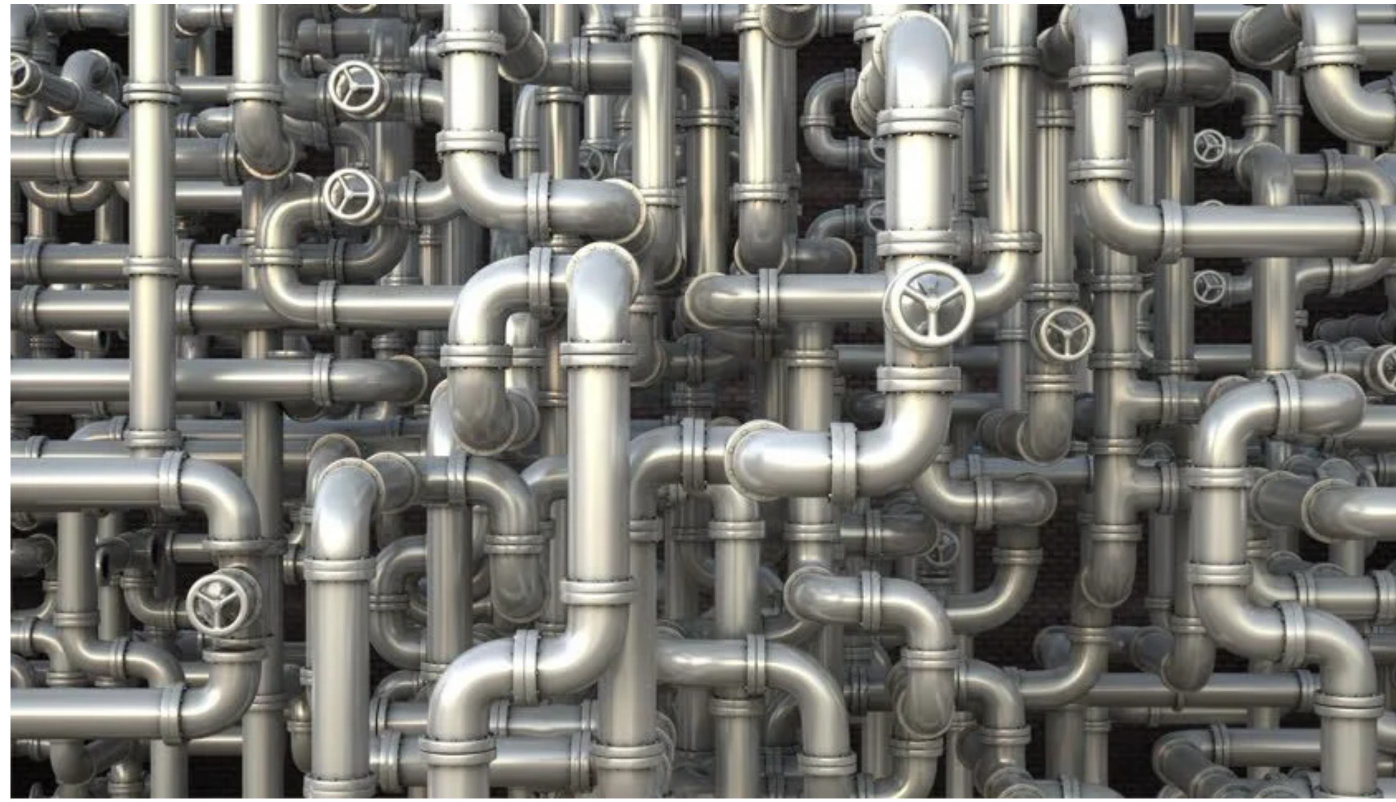

Data streams flowing through the FPGA chip

automatized time and space constraints

FPGA hardware + data-flow programming model = DFE

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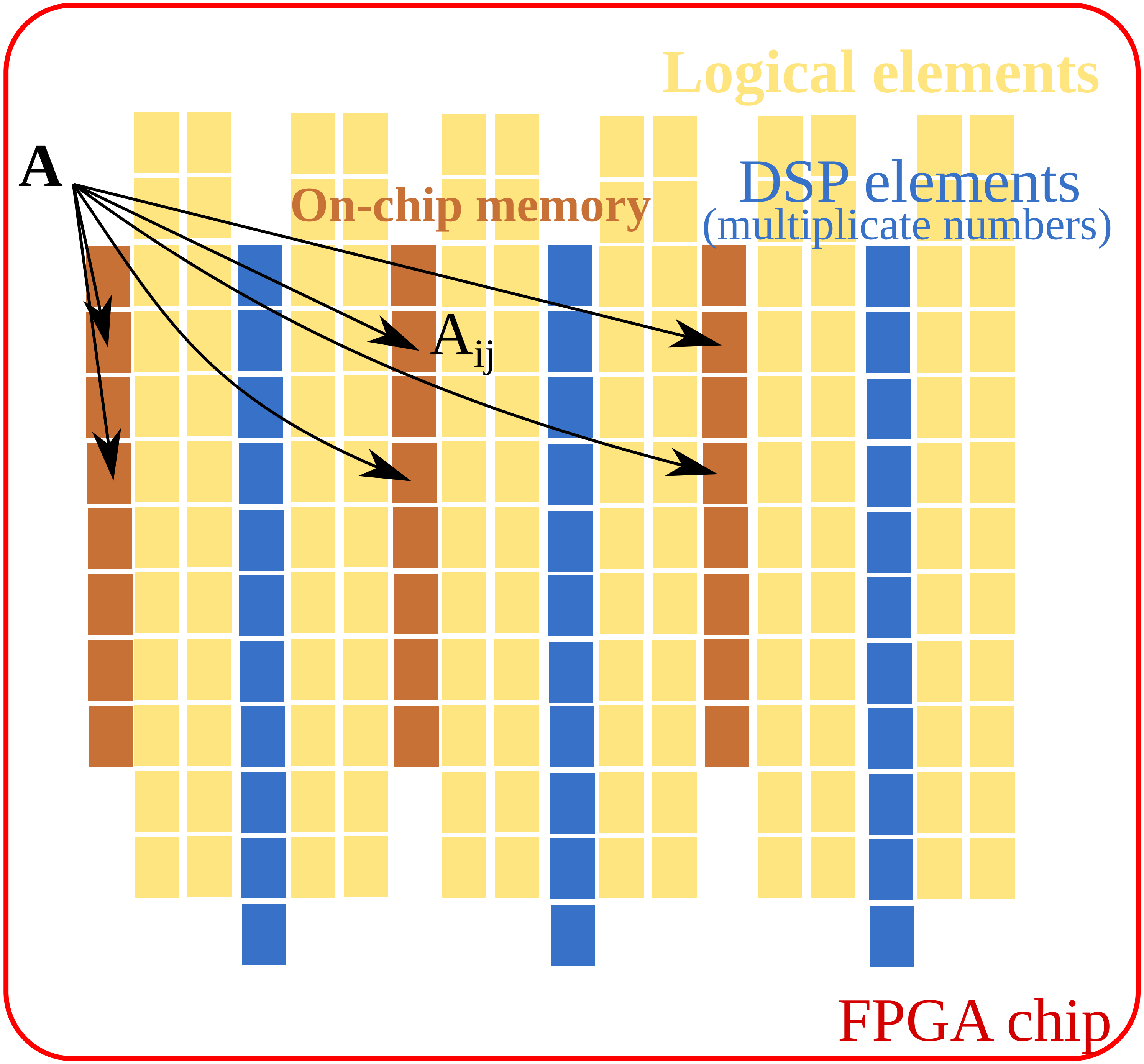
supported by Xilinx University Program

DFE implementation of permanent calculation

$$\mathrm{Per}(A) = \frac{\sum_{\delta}\left(\prod_{k=1}^{n}\delta_k\right)\prod_{i=1}^{n}\sum_{j=1}^{n}\delta_j a_{ij}}{2^{n-1}}$$

spread over the FPGA chip

step 1:
upload matrix A into on-chip memories



DFE implementation of permanent calculation

$$\mathrm{Per}(A) = \frac{\sum_\delta \left(\prod_{k=1}^n \delta_k\right) \prod_{i=1}^n \sum_{j=1}^n \delta_j a_{ij}}{2^{n-1}}$$

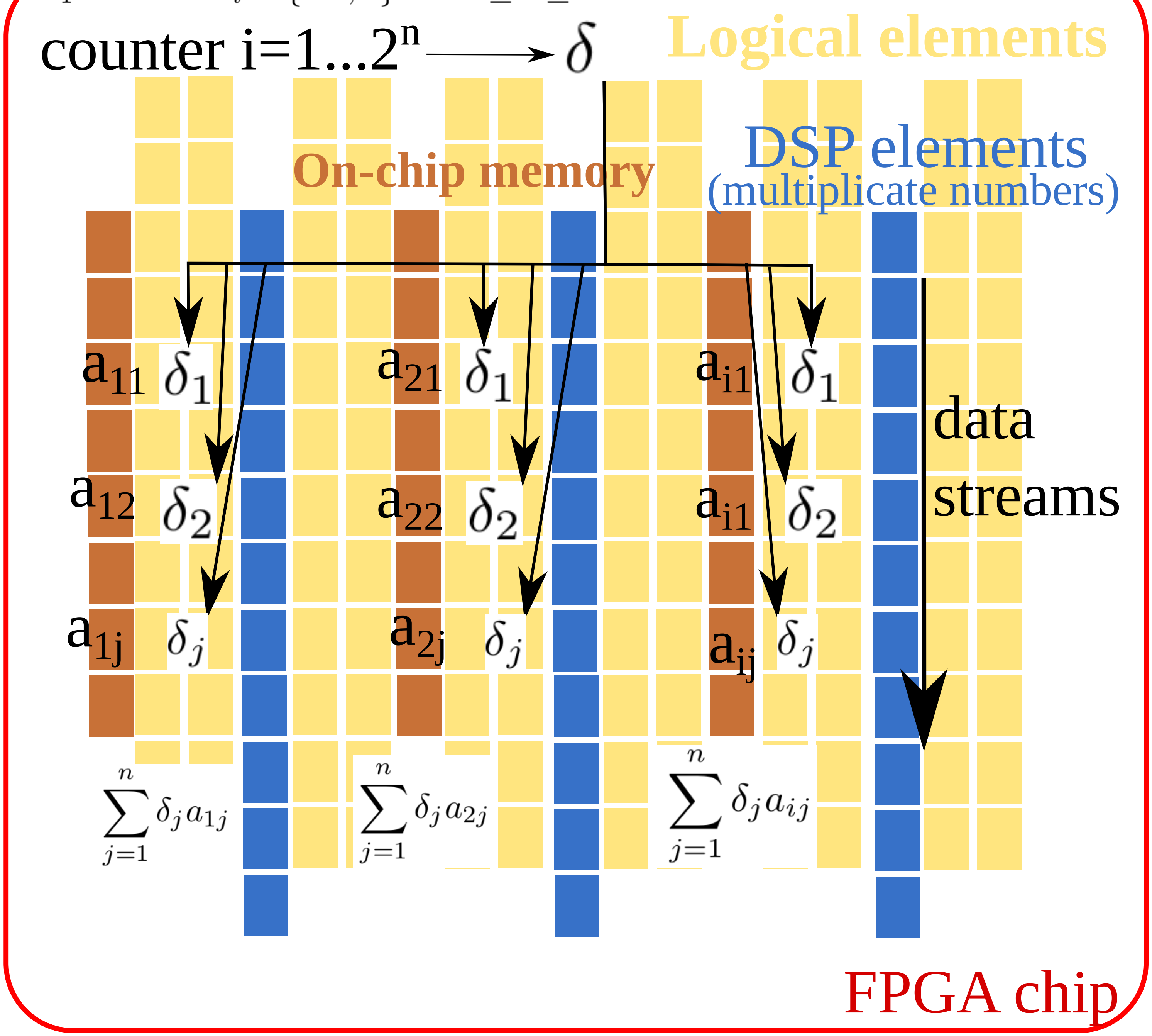
$\delta_1 = 1$ and $\delta_i \in \{-1, 1\}$ for $2 \leq i \leq n$

step 2:

create counter for δ

split it into bits: δ_j

calculate for each i $\sum_{j=1}^{n} \delta_j a_{ij}$



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DFE implementation of permanent calculation

$$\mathrm{Per}(A) = \frac{\sum_\delta \left(\prod_{k=1}^n \delta_k\right) \prod_{i=1}^n \sum_{j=1}^n \delta_j a_{ij}}{2^{n-1}}$$

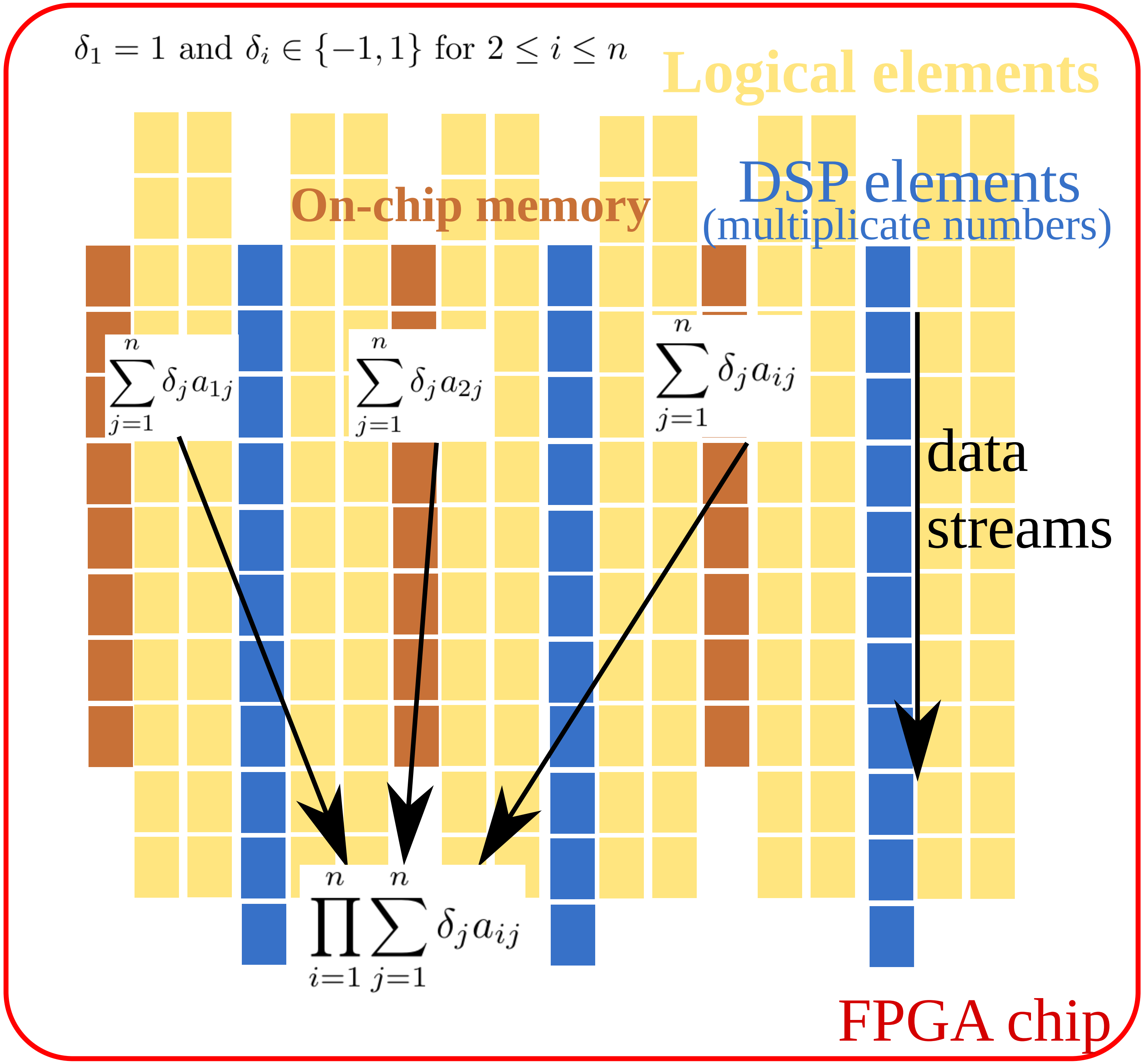
step 3:

calculate product

$$\prod_{i=1}^n \sum_{j=1}^n \delta_j a_{ij}$$

step 4:

sum up the addends and return to CPU



DFE implementation of permanent calculation

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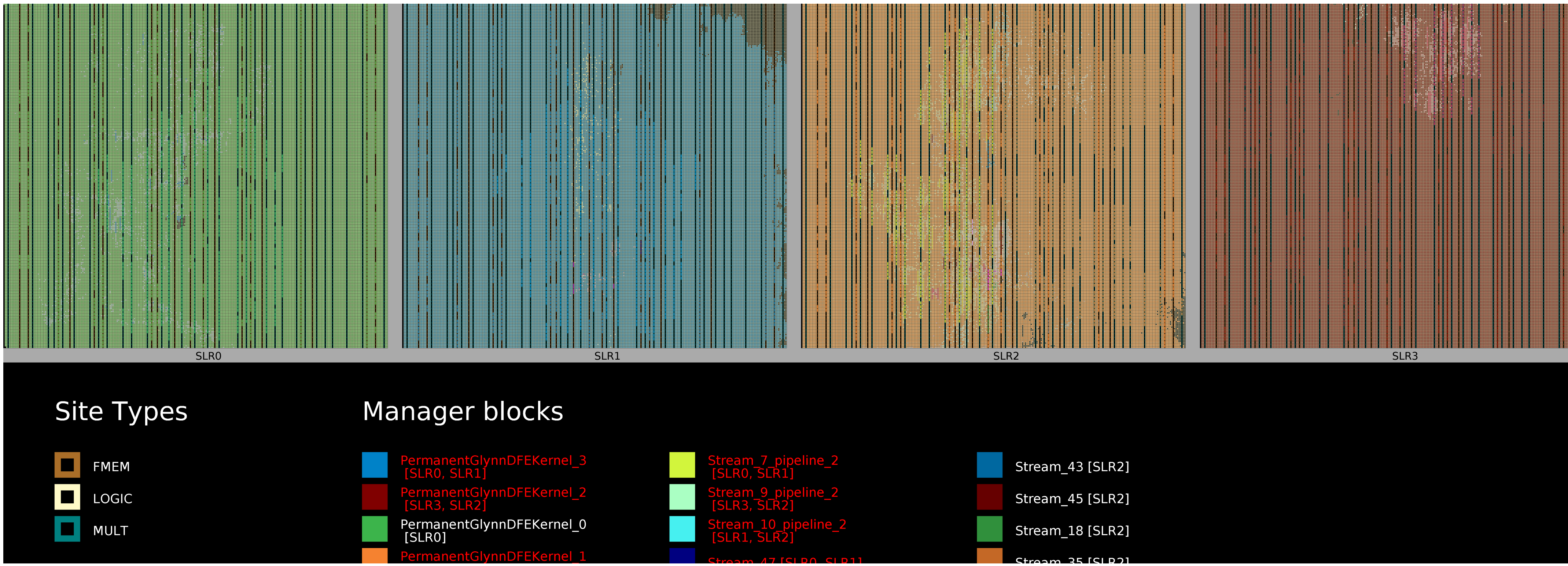
clock frequency: 180 MHz



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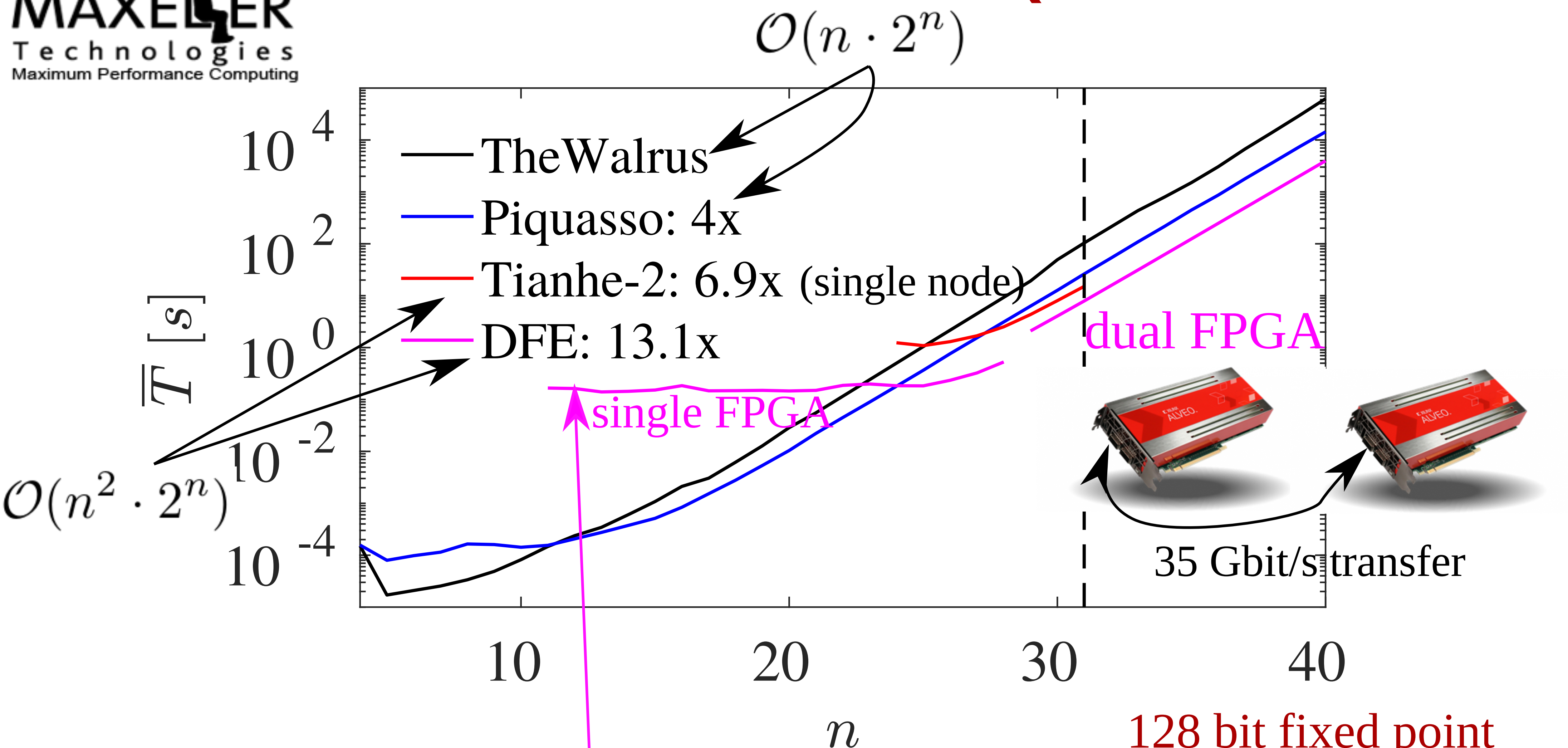
Logic utilization:	3750968 / 5184000 (72.36%)
LUTs:	1665146 / 1728000 (96.36%)
Primary FFs:	2085822 / 3456000 (60.35%)
DSP blocks:	4000 / 12288 (32.55%)
Block memory (BRAM18):	3365 / 5376 (62.59%)
Block memory (URAM):	12 / 1280 (0.94%)

Permanent benchmark again



uploading the program to FPGA takes time

128 bit fixed point number representation

Time complexity on DFE: $\mathcal{O}(C \cdot 2^n)$

n^2 operations are dispersed in space over the FPGA chip

Numerical error of permanent calculation

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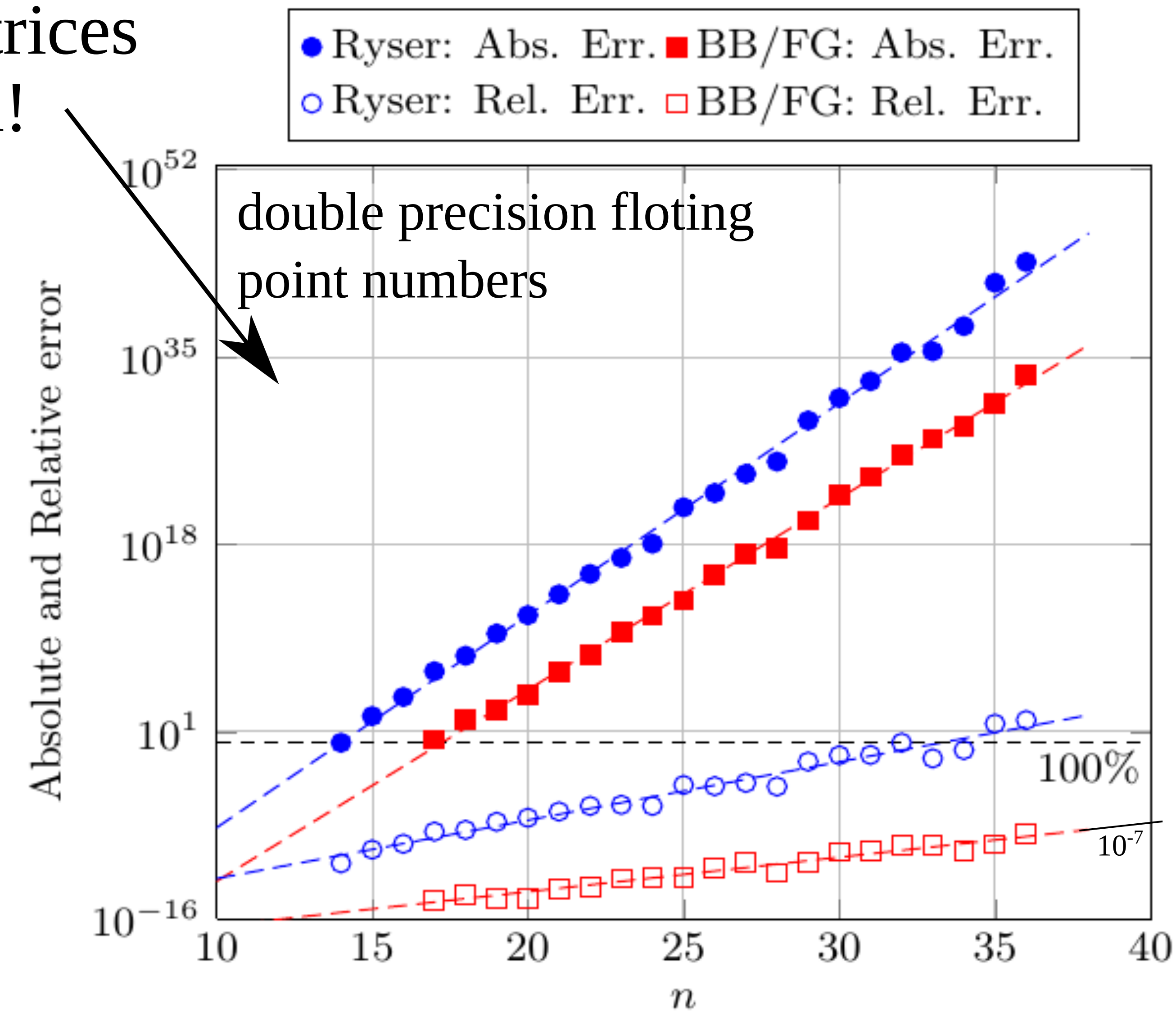
Junjie Wu, Yong Liu, Baida Zhang, Xianmin Jin, Yang Wang, Huiquan Wang, Xuejun Yang, National Science Review, Volume 5, Issue 5, September 2018

n x n all-ones matrices

Perm(A) = n!



If A = 40 x 40 unitary,

$$a_{ij} \sim \frac{1}{\sqrt{40}}$$

$$\mathrm{Perm}(A) \sim 10^{-12}$$

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Aknowledgement

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