On Algebraic Homomorphic Encryption and its Applications to Doubly-Efficient PIR

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Simon Pohmann[2], Christian Weinert[2]

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[2] Royal Holloway, University of London, UK

Some slides adapted from slides of Simon Pohmann

KDDI Research

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Background and prior work

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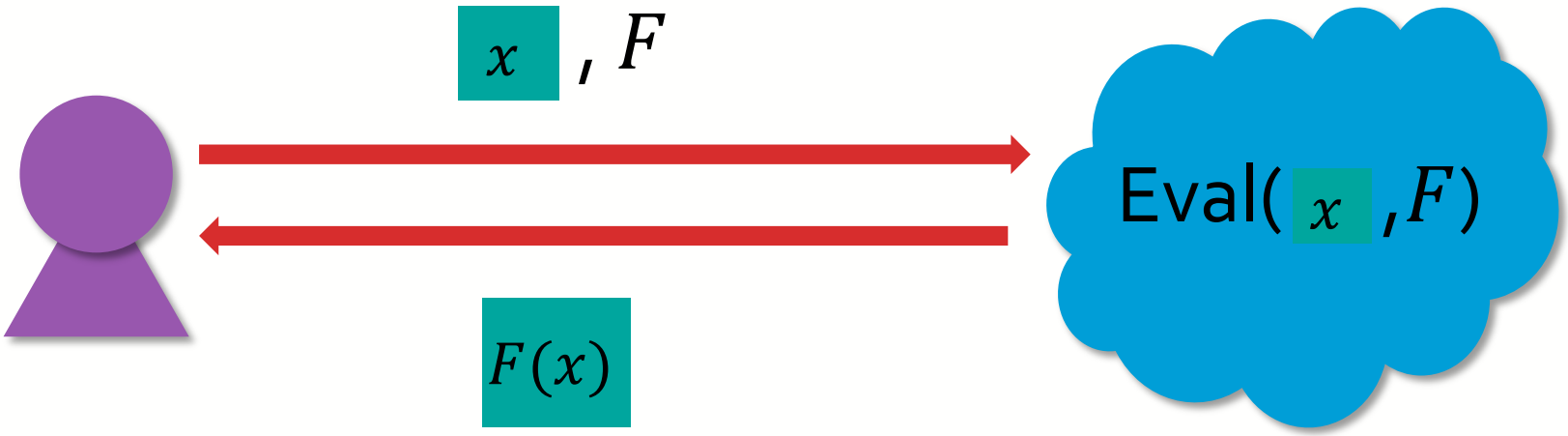
Homomorphic encryption

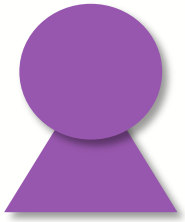


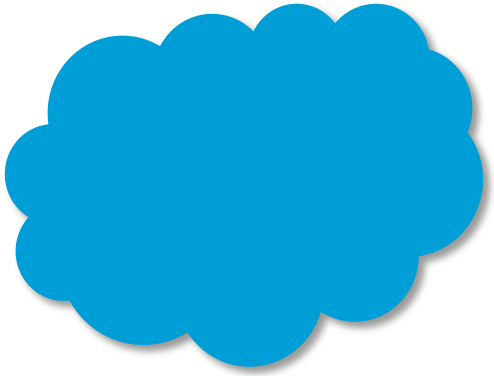
- Client can outsource computation of $F(x)$ on their data x
- Server does not learn x or $F(x)$

x : Encryption of x

F(x) : Encryption of $F(x)$

Private Information Retrieval (PIR)





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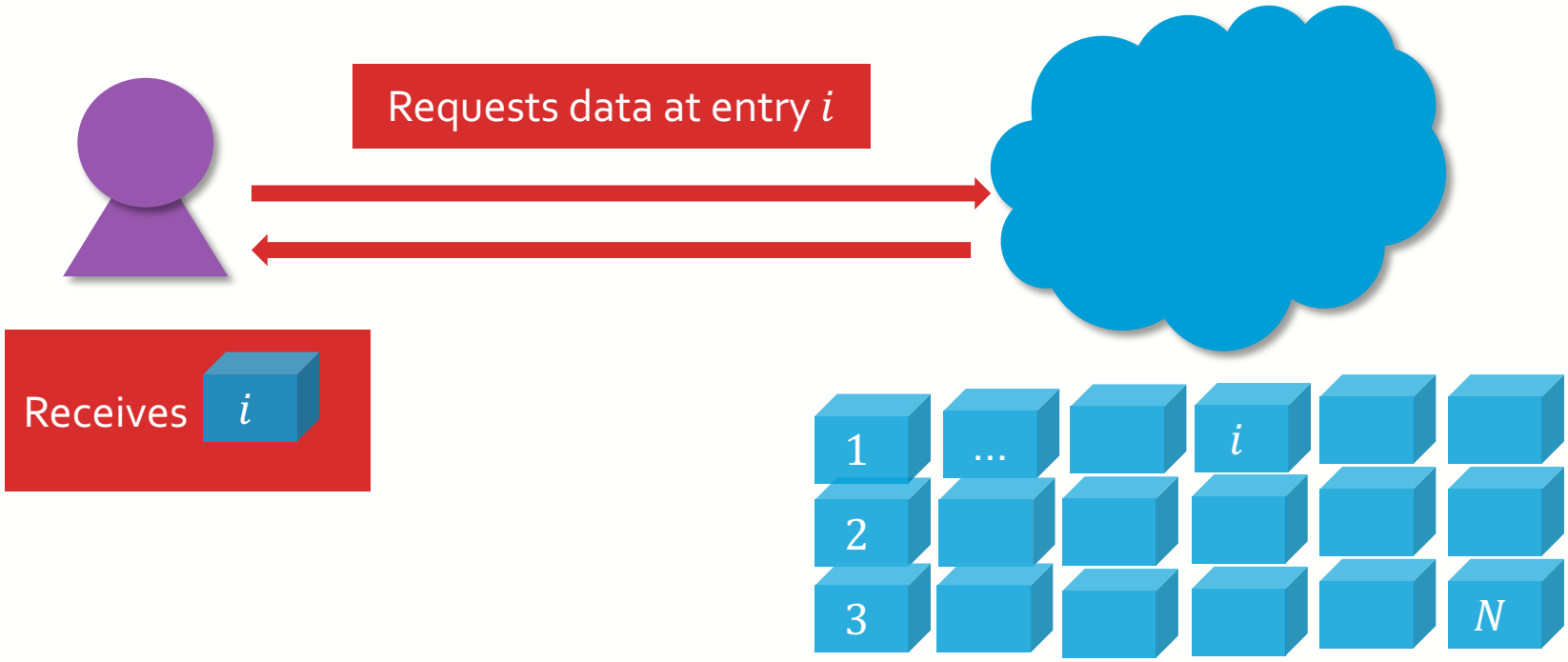

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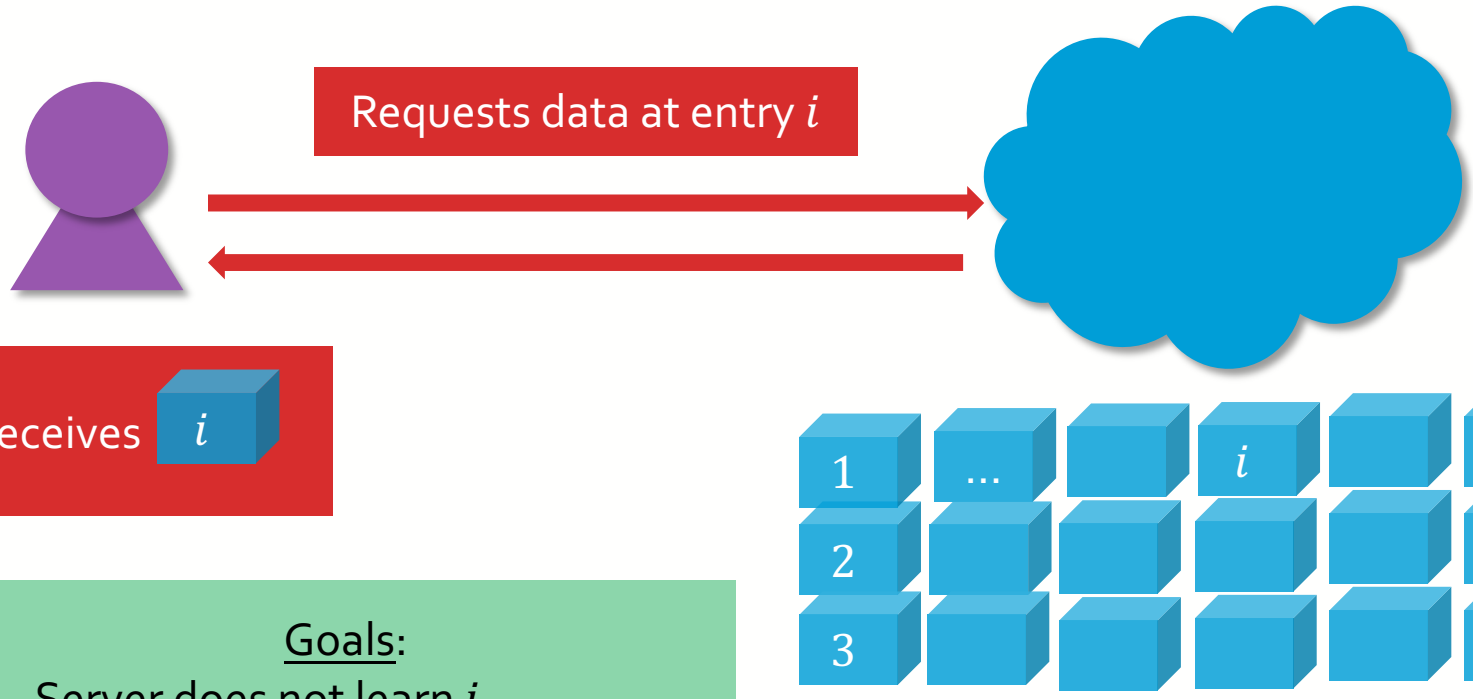

Goals:

- Server does not learn i
- Communication cost is less than downloading whole database (N)

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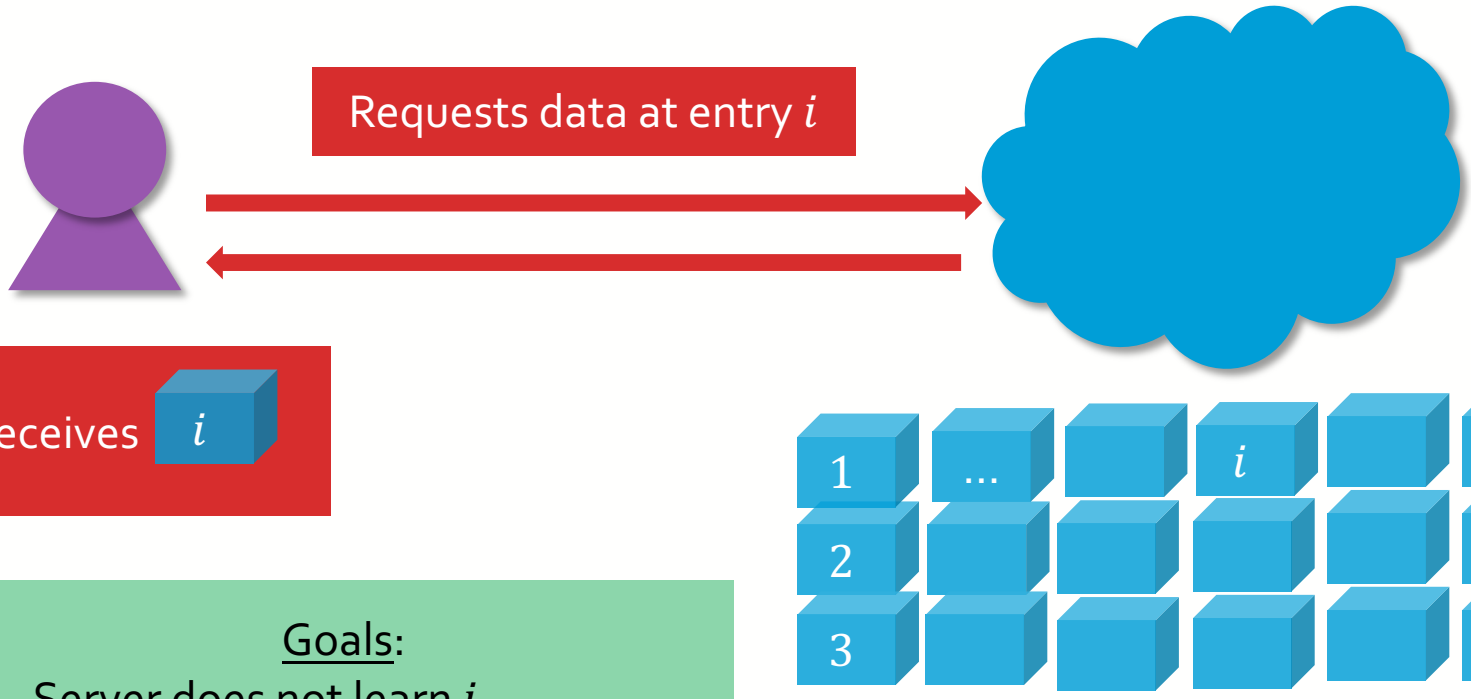

Goals:

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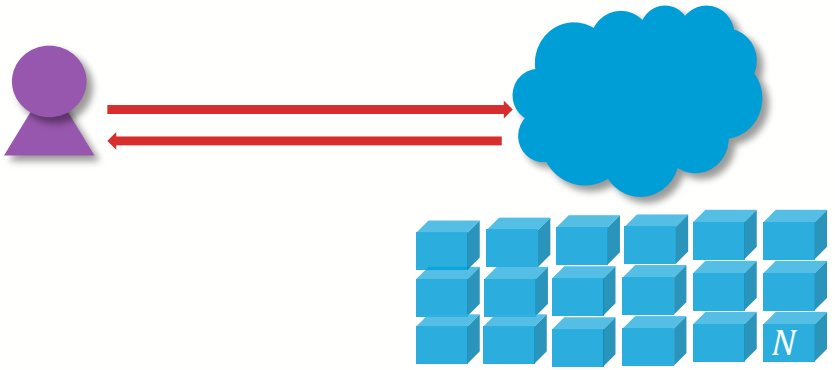
PIR can be achieved from HE with data x encoding i and polynomial $f_{DB}(x)$ encoding function "retrieve data at location x "

Doubly-Efficient PIR (DEPIR)

- Communication cost should be sublinear in N
- What about computational cost?



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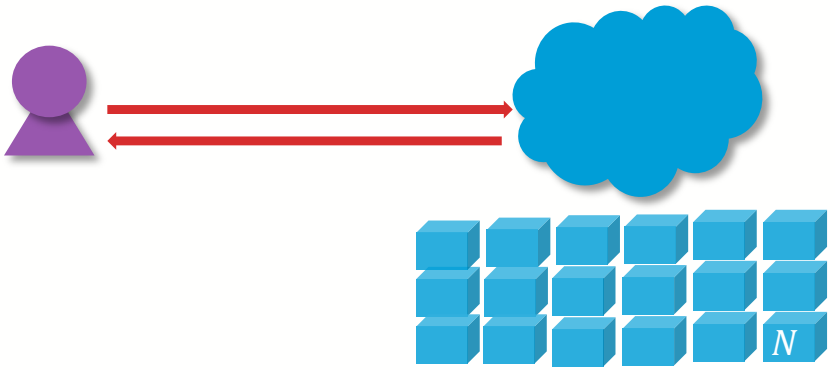

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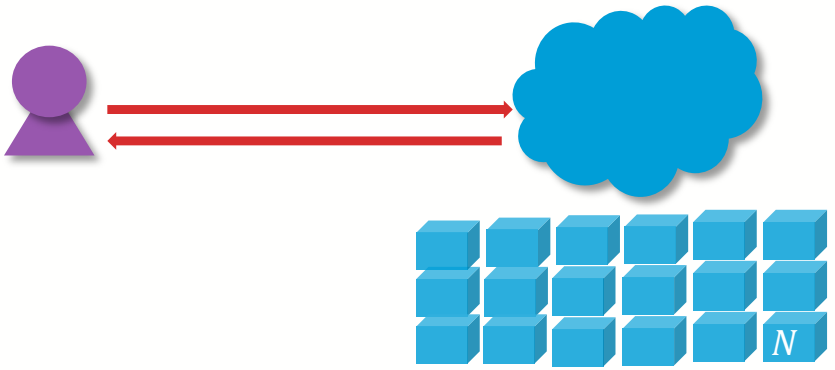

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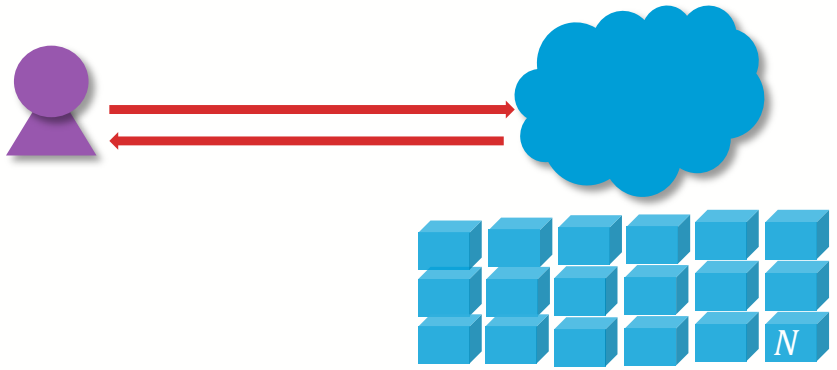

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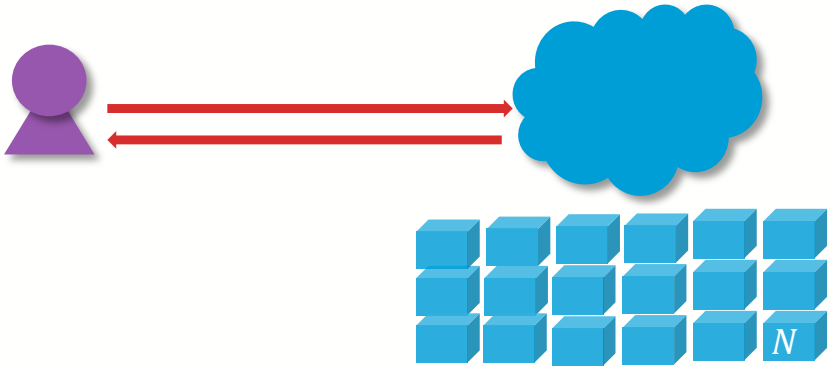

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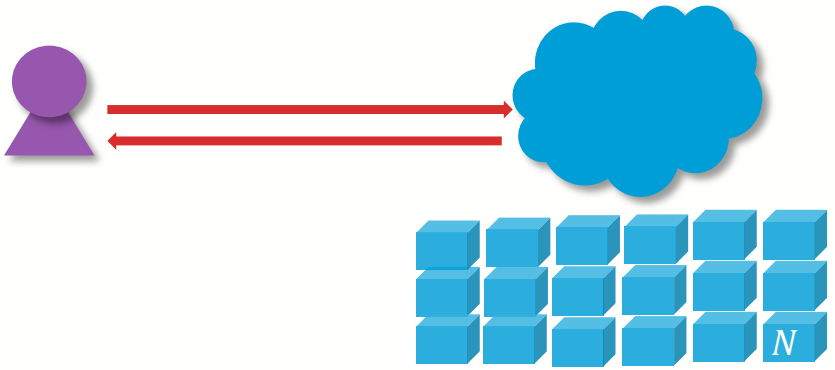

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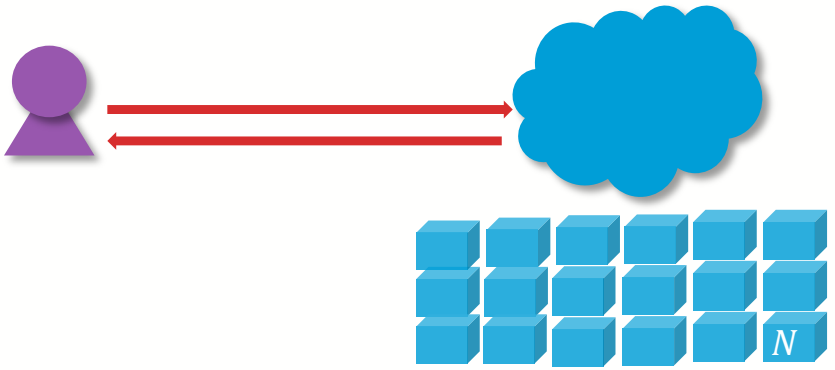

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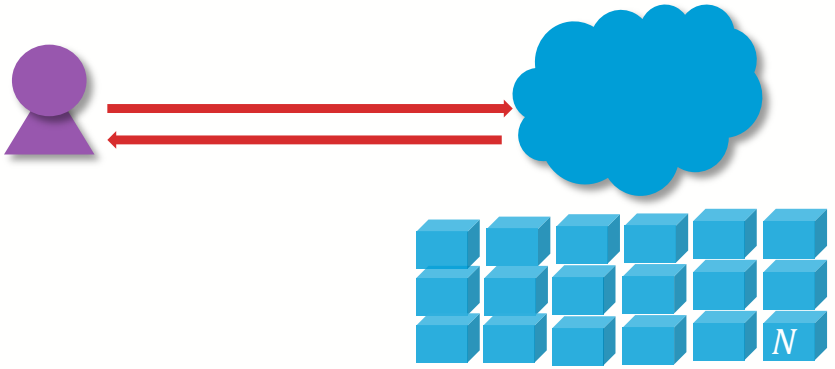

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DEPIR construction of [LMW23]

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[KU11, Theorem 2.1]
Let $f \in R[X_1, \dots, X_m]$ be a degree-d polynomial. Then we can build a datastructure that allows us to compute $f(x_1, \dots, x_m)$ in time poly$(d, m, \log \#R)$

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Algebraic Somewhat Homomorphic Encryption (ASHE)

A somewhat homomorphic encryption scheme such that for polynomial f:

$$\text{Eval}(f, ct_1, \dots, ct_m) = f(ct_1, \dots, ct_m)$$

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The ciphertext space must be a ring!

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Our contributions

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Performance of ASHE

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Theorem (informal)

A post-quantum ASHE scheme that can evaluate polynomials of degree d has ciphertext ring size $\Omega(2^d)$

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BV	☑	$O(2^{d^2})$

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Scheme	ASHE?	Ciphertext ring/space size
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→ Can we build ASHE with ciphertext ring size $O(2^d)$?

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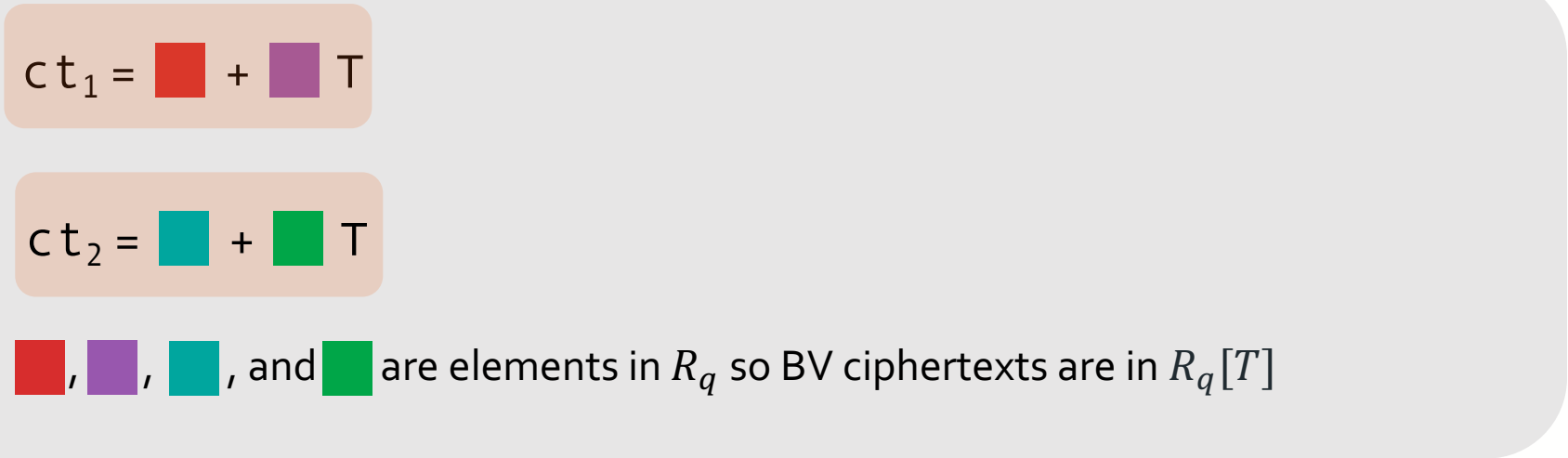

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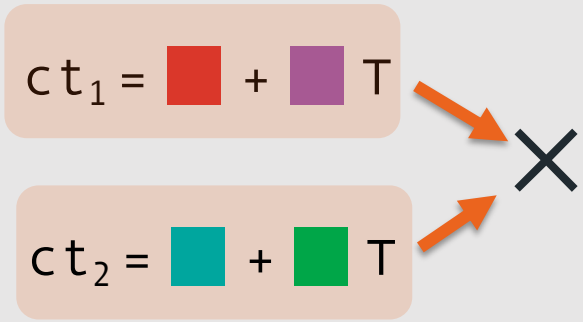

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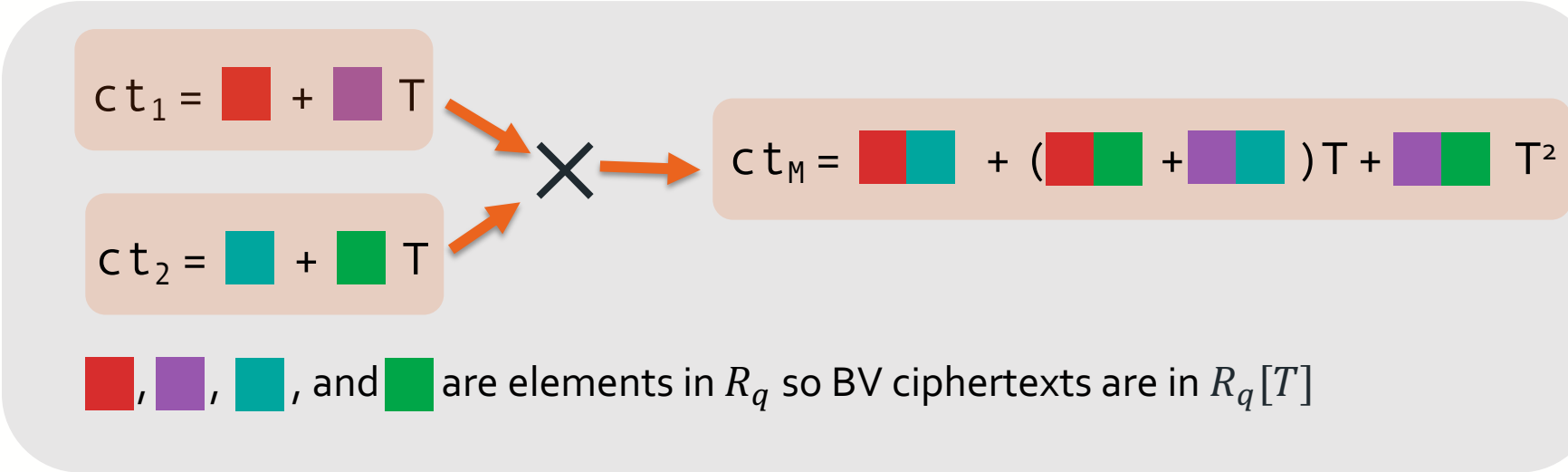

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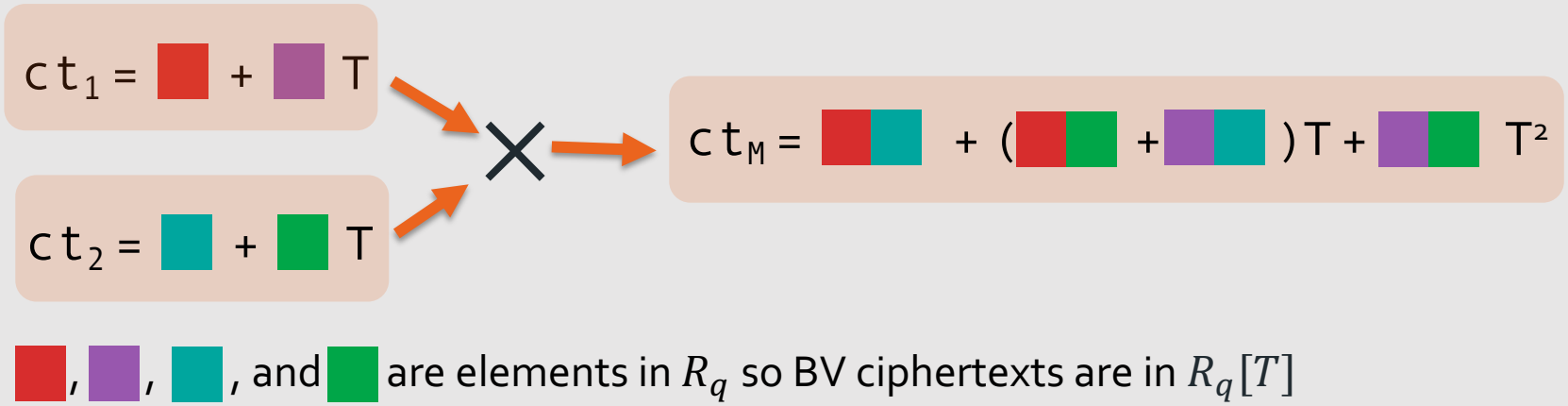

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Idea: Decompose the polynomial f being evaluated as

$$f(b_1 + a_1 T, \ldots, b_m + a_m T) = \sum_i T^i f_i(a_1, \ldots, a_m, b_1, \ldots, b_m)$$

to evaluate $2m$-variate polynomials over $\mathbb{F}_p$

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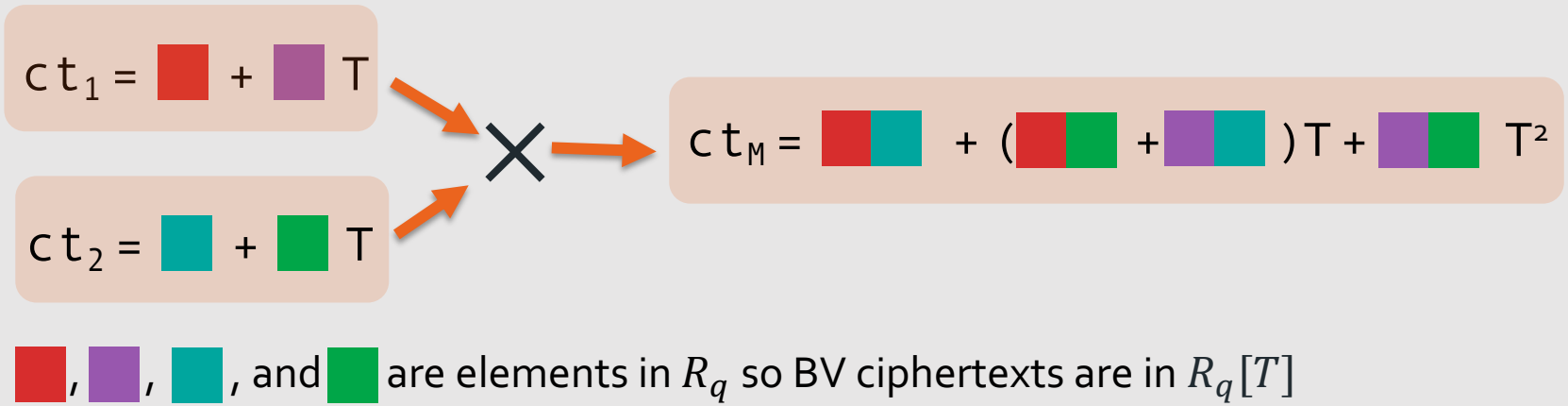

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Fixing $b_i \in \{0,1\}$ means modifying the underlying RLWE assumption to one where the the "b" part has CRT components in $\{0,1\}$

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$\{0,1\}$-CRT-RLWE

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Definition ($\{0,1\}$-CRT set)

Define S as the set of elements in R_q such that $S := \iota^{-1}(\{0,1\}^{nr})$ where ι is the double-CRT isomorphism and r is the number of divisors of q.

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Definition (Decision $\{0,1\}$-CRT-RLWE)

Let $s \in R_q$ be secret. Distinguish samples (a_i, b_i) from uniform, where $b_i \in S$ and $a_i = s^{-1}(b_i - e_i)$ for e_i chosen from some small error distribution.

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Theorem (informal)

Let q satisfy some technical constraints. If standard RLWE with preprocessing on R_q is hard, then $\{0,1\}$-CRT-RLWE with preprocessing on R_q is also hard.

$\{0,1\}$-CRT-RLWE

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Definition ($\{0,1\}$-CRT set)

Define S as the set of elements in R_q such that $S := \iota^{-1}(\{0,1\}^{nr})$ where ι is the double-CRT isomorphism and r is the number of divisors of q.

Definition (Decision $\{0,1\}$-CRT-RLWE)

Let $s \in R_q$ be secret. Distinguish samples (a_i, b_i) from uniform, where $b_i \in S$ and $a_i = s^{-1}(b_i - e_i)$ for e_i chosen from some small error distribution.

Theorem (informal)

Let q satisfy some technical constraints. If standard RLWE with preprocessing on R_q is hard, then $\{0,1\}$-CRT-RLWE with preprocessing on R_q is also hard.

The adversary is allowed to run a preprocessing phase with only R and q as input before querying the RLWE oracle

Performance compared to [OPPW24]

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Reduction in read queries:

- $8\times$ for parameters we can run
- $23\times$ for larger parameters

[OPPW24] H. Okada, R. Player, S. Pohmann, C. Weinert. Towards Practical Doubly-Efficient Private Information Retrieval. Financial Cryptography 2024.

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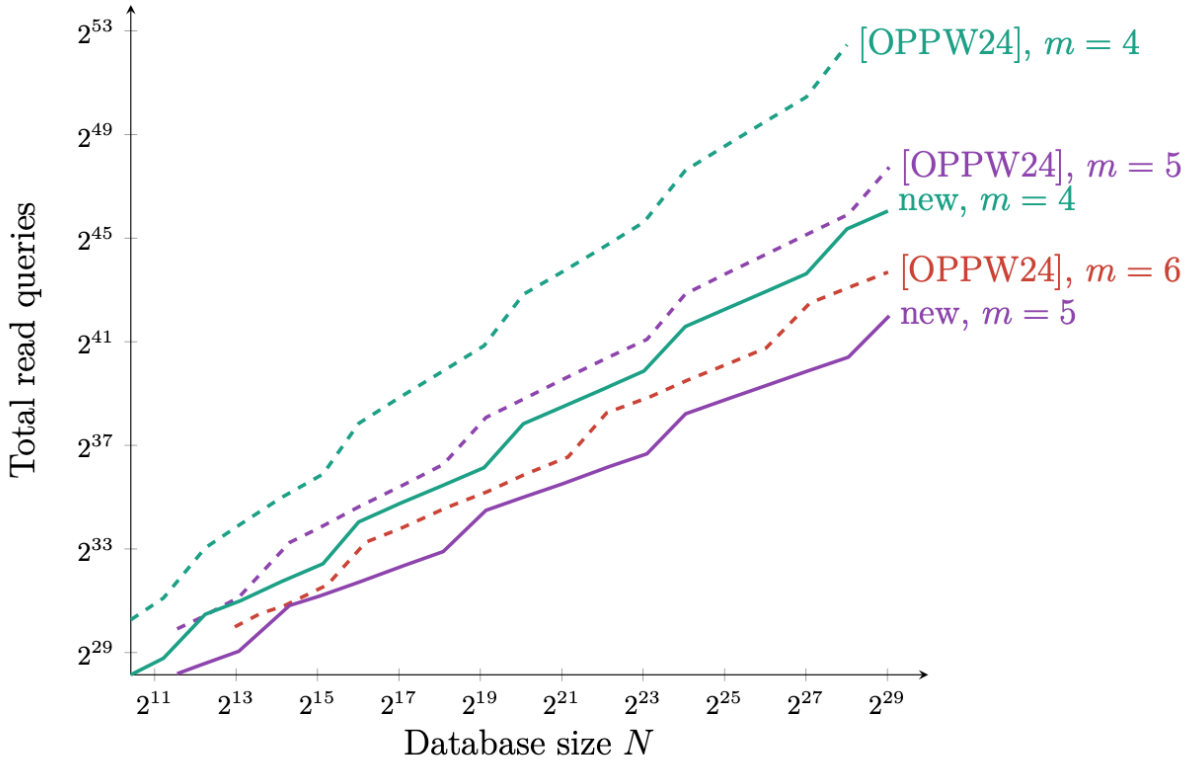

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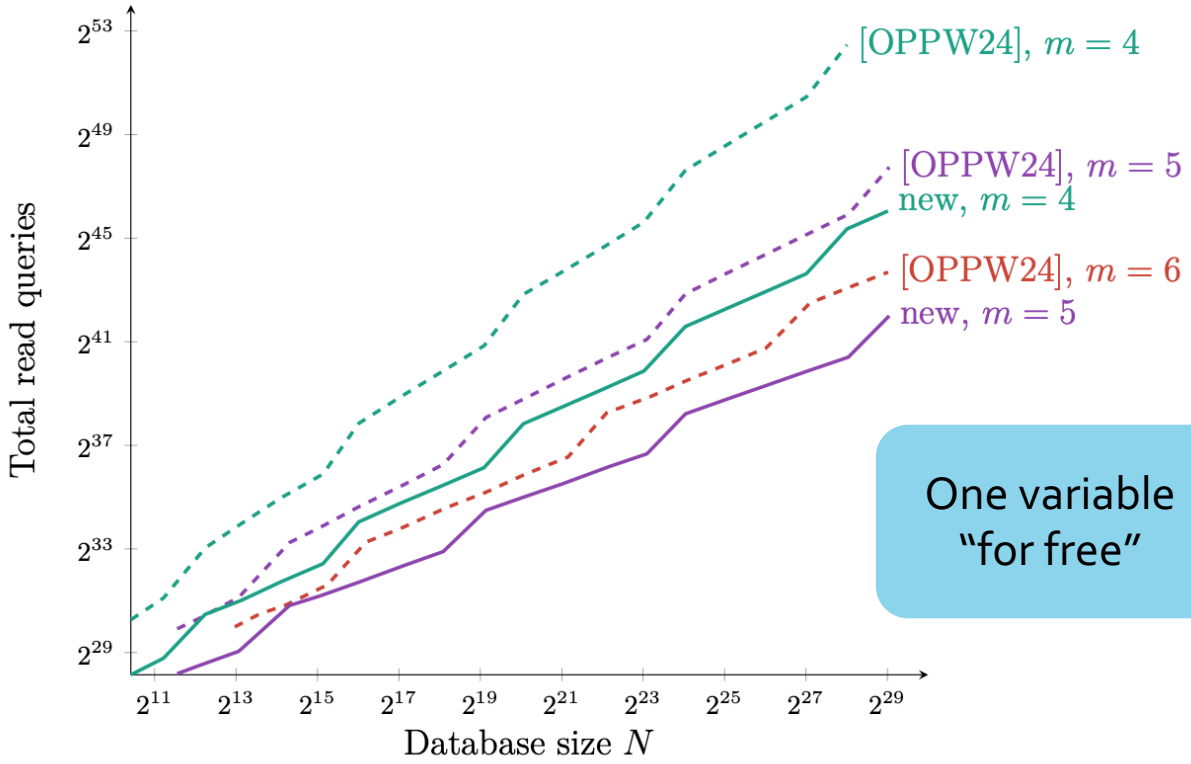

One variable "for free"

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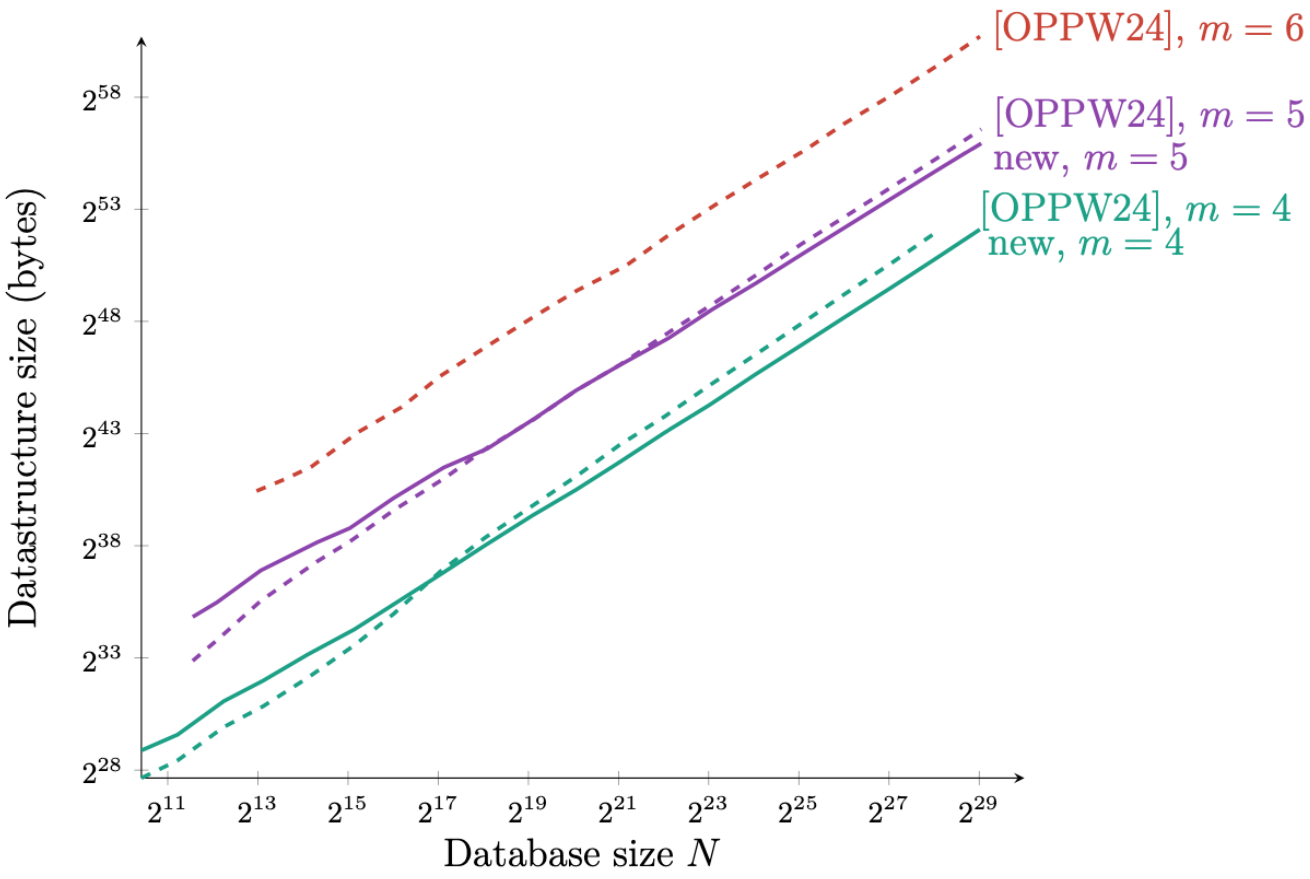

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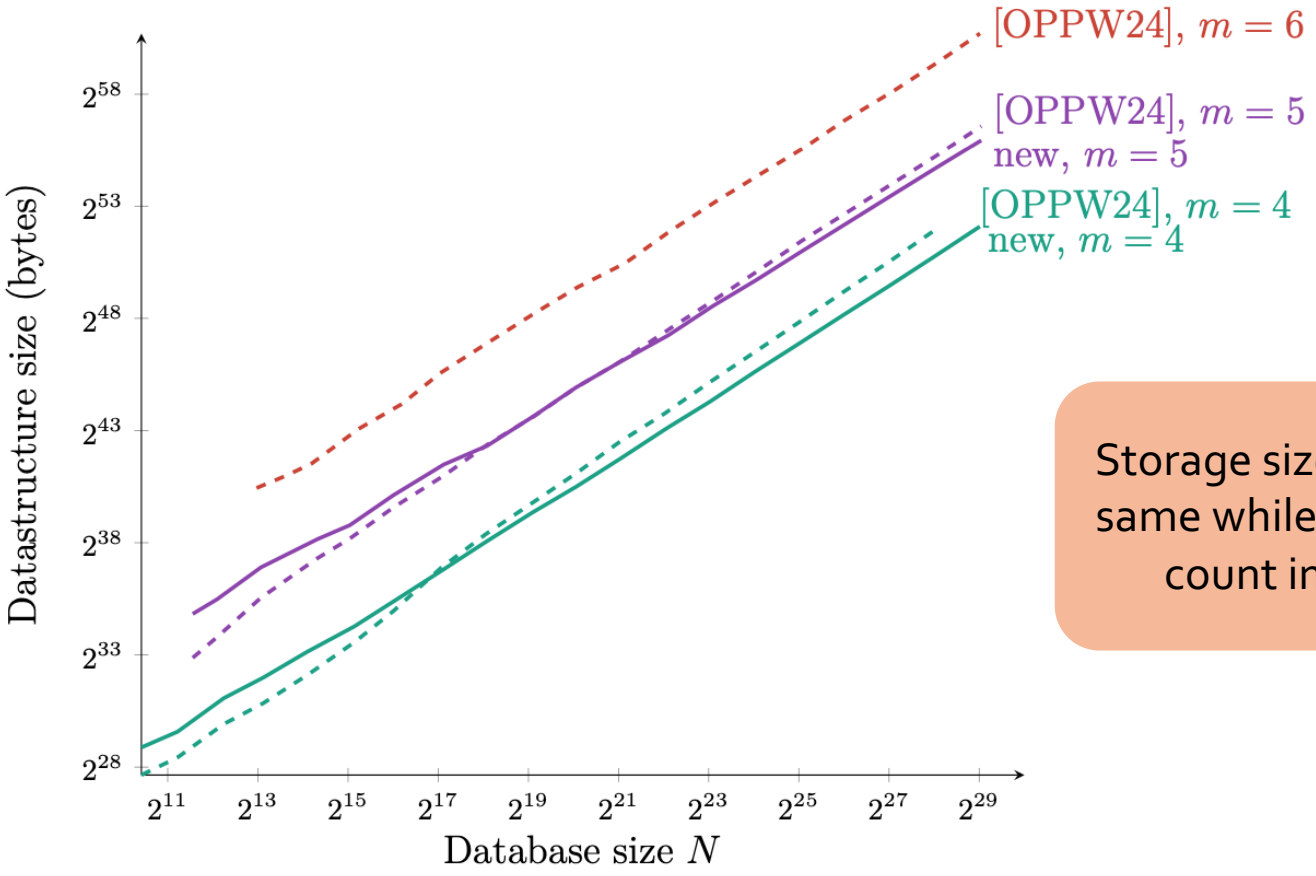

Storage size about the same while read query count improves

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Conclusion

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Summary of contributions

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Lower bound on performance of post-quantum ASHE

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Modified BV scheme based on $\{0,1\}$-CRT-RLWE

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Preliminary cryptanalysis of $\{0,1\}$-CRT-RLWE

Open questions

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Are our reduced entropy RLWE variants useful for other applications?

Thank you!
Any questions?

Full version on eprint: 2024/1307
Implementation: github.com/FeanorTheElf/ashe-depir

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https://rachelplayer.github.io

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