Code-based Signatures from Secure Multiparty Computation

Thibauld Feneuil

SIAM AG23 — Advances in Code-based Signature

July 12, 2023, Eindhoven

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Registration and travel support for this presentation was provided by the Eindhoven University of Technology.

Introduction

Proof of knowledge

I know x such that $F(x) = y$.

Commitment

Challenge 1

Response 1

⋮

Challenge n

Response n

Prover

Verifier

I am convinced / I am not convinced.

- **Completeness:** Pr[verif ✓ | honest prover] = 1
- **Soundness:** Pr[verif ✓ | malicious prover] $\leq \varepsilon$ (e.g. 2^{-128})
- **Zero-knowledge:** verifier learns nothing on x

MPC in the Head

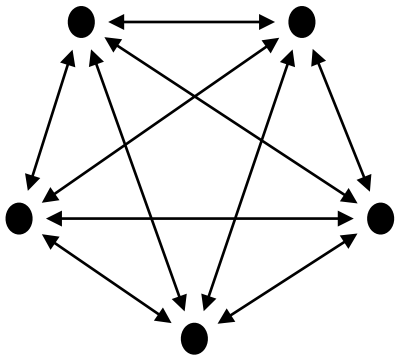
- **[IKOS07]** Yuval Ishai, Eyal Kushilevitz, Rafail Ostrovsky, Amit Sahai: "Zero-knowledge from secure multiparty computation" (STOC 2007)
- Turn an MPC protocol into a zero knowledge proof of knowledge
- **Generic**: can be apply to any cryptographic problem
- Convenient to build (candidate) **post-quantum signature** schemes
- **Picnic**: submission to NIST (2017)
- Recent NIST call (01/06/2023): 7 MPCitH schemes / 50 submissions

One-way function

$$F : x \mapsto y$$

E.g. AES, MQ system,
Syndrome decoding

Multiparty computation (MPC)

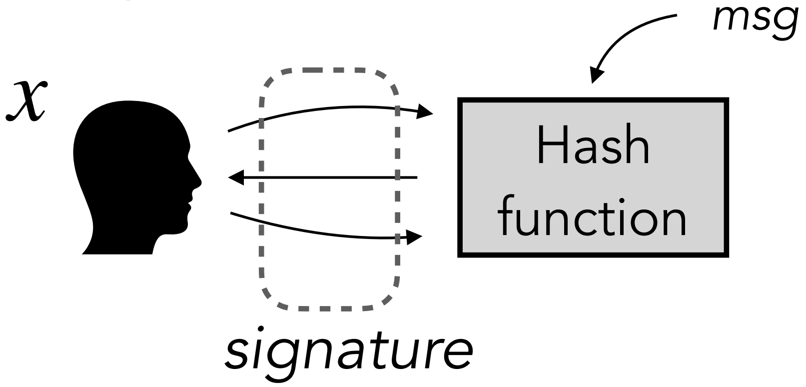


Input sharing $[\![x]\!]$

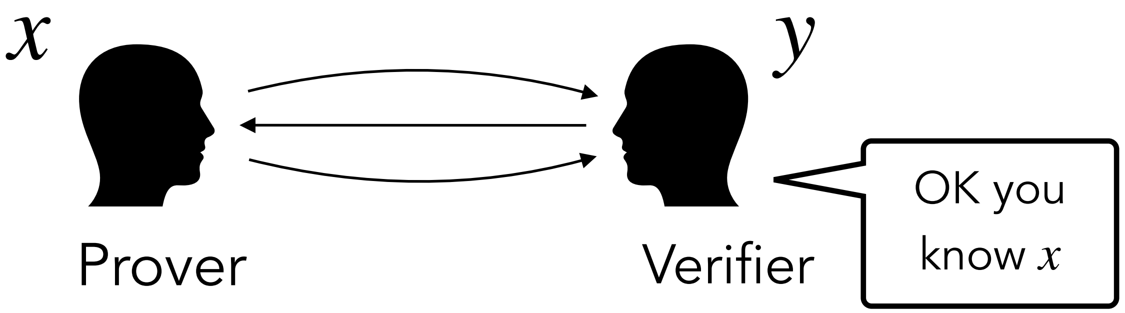
Joint evaluation of:

$$g(x) = \begin{cases} \text{Accept} & \text{if } F(x) = y \\ \text{Reject} & \text{if } F(x) \neq y \end{cases}$$

Signature scheme



Zero-knowledge proof



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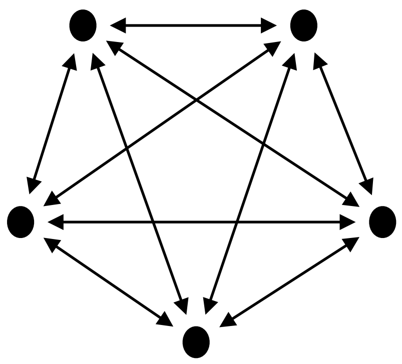

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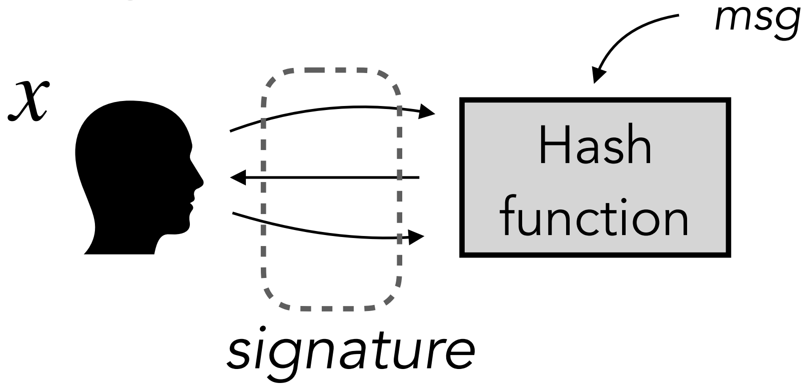

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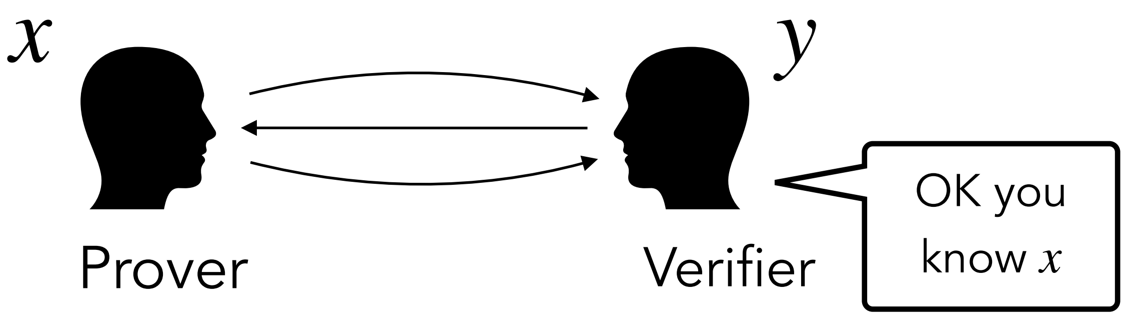

$[\![x]\!] = ([\![x]\!]_1, \ldots, [\![x]\!]_N)$ s.t. $x = [\![x]\!]_1 + \ldots + [\![x]\!]_N$

One-way function

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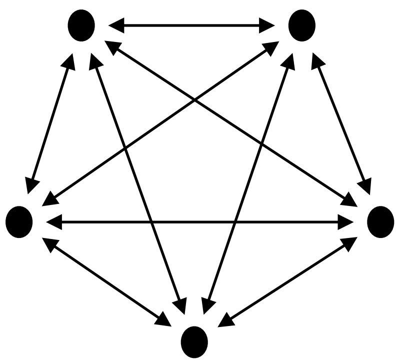

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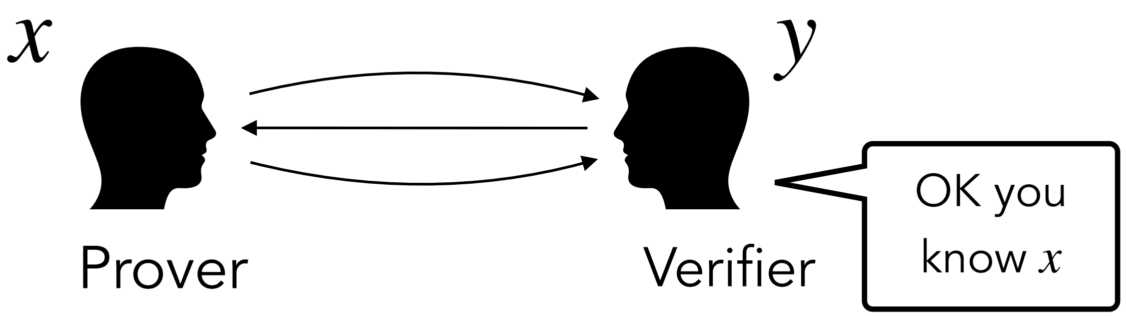

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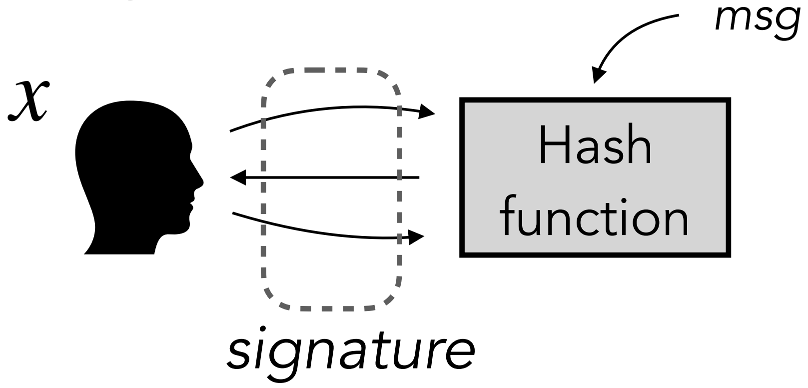

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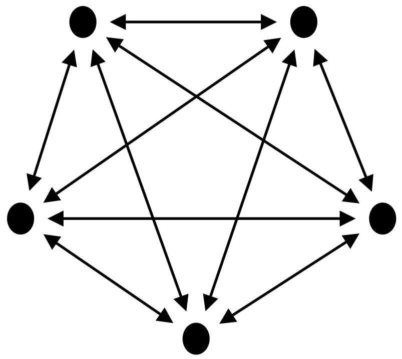

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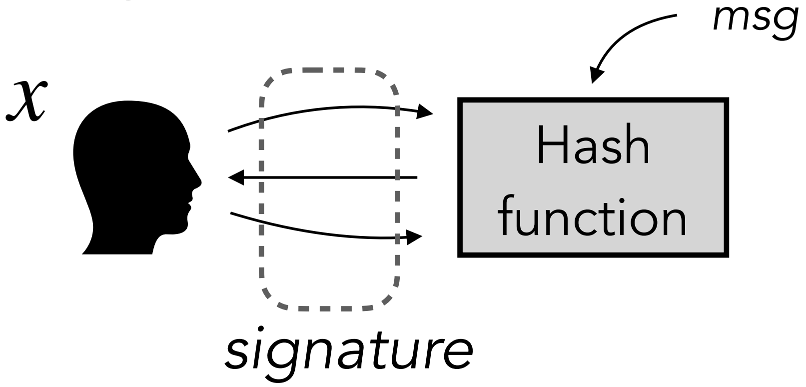

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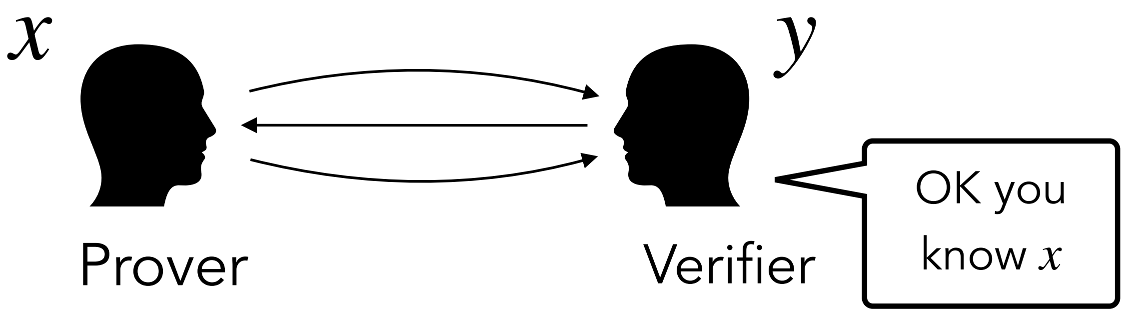

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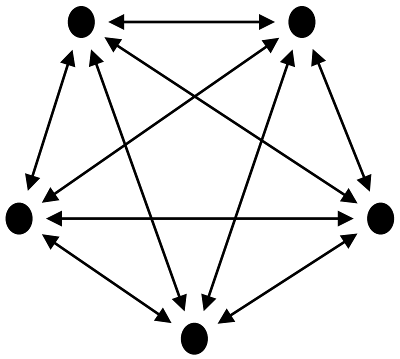

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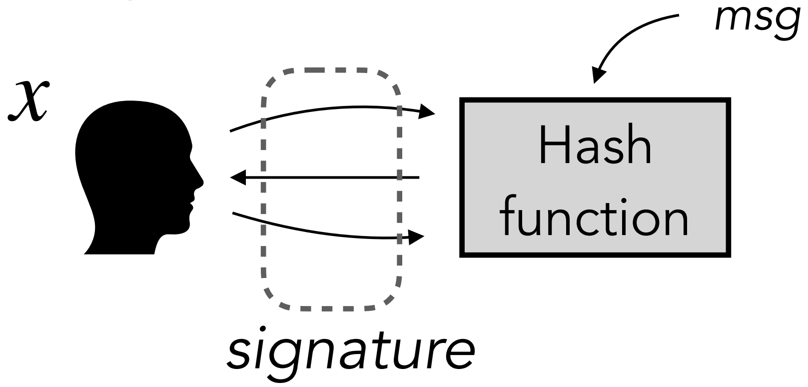

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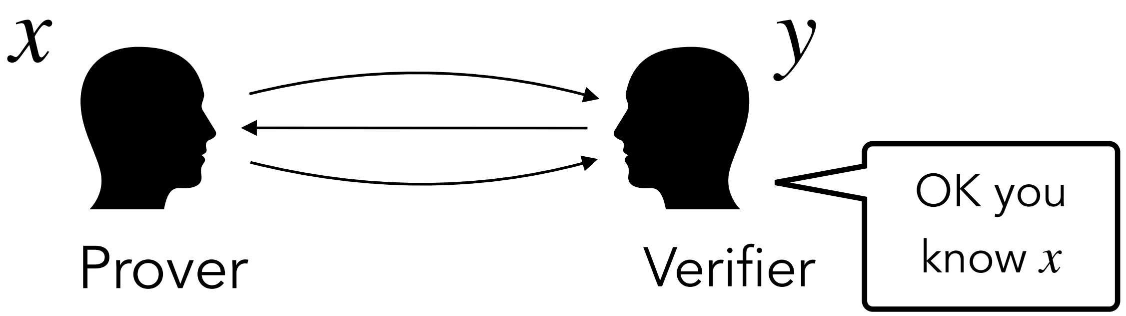

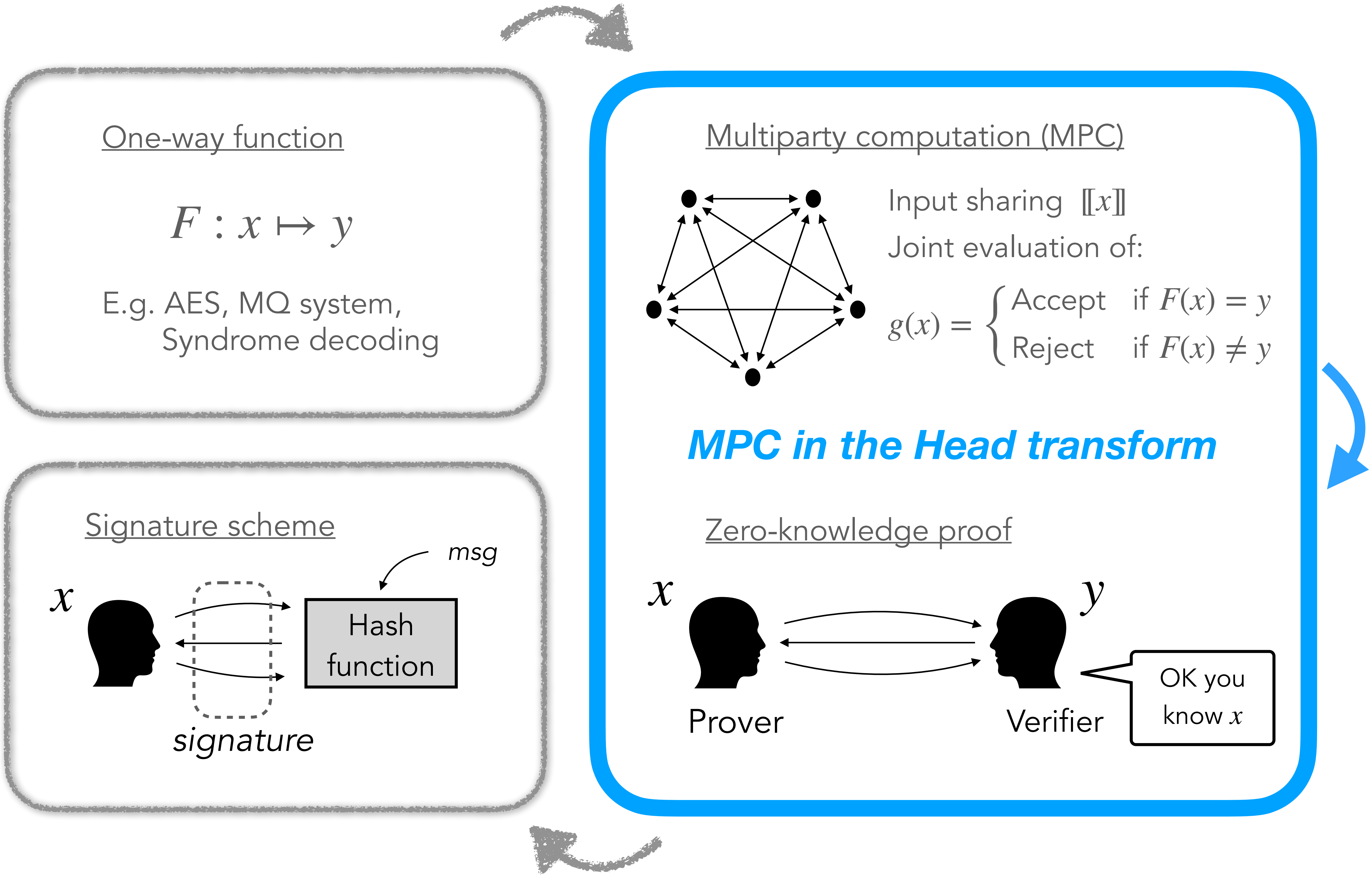

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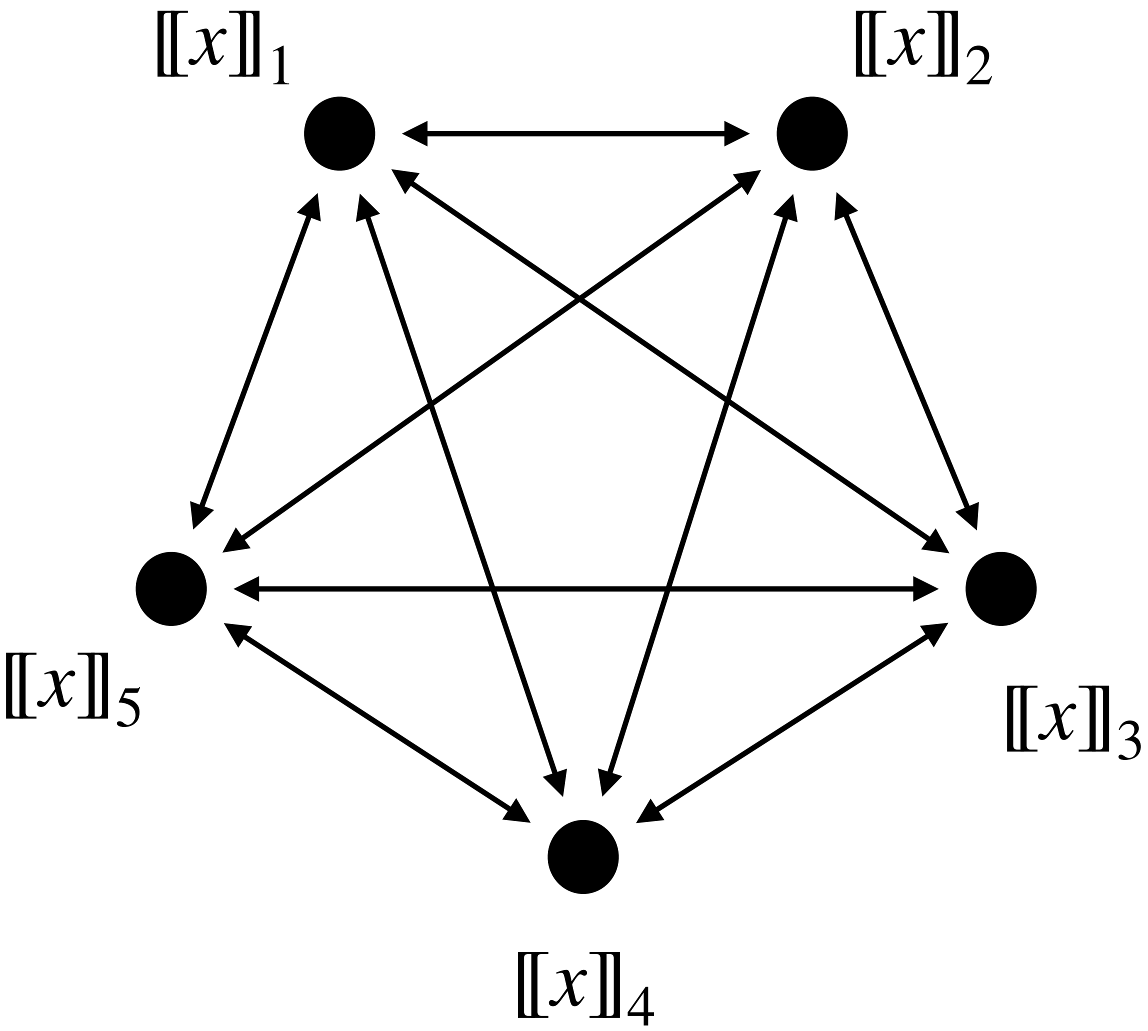
MPC in the Head transform

Zero-knowledge proof

MPCitH: general principle

MPC model

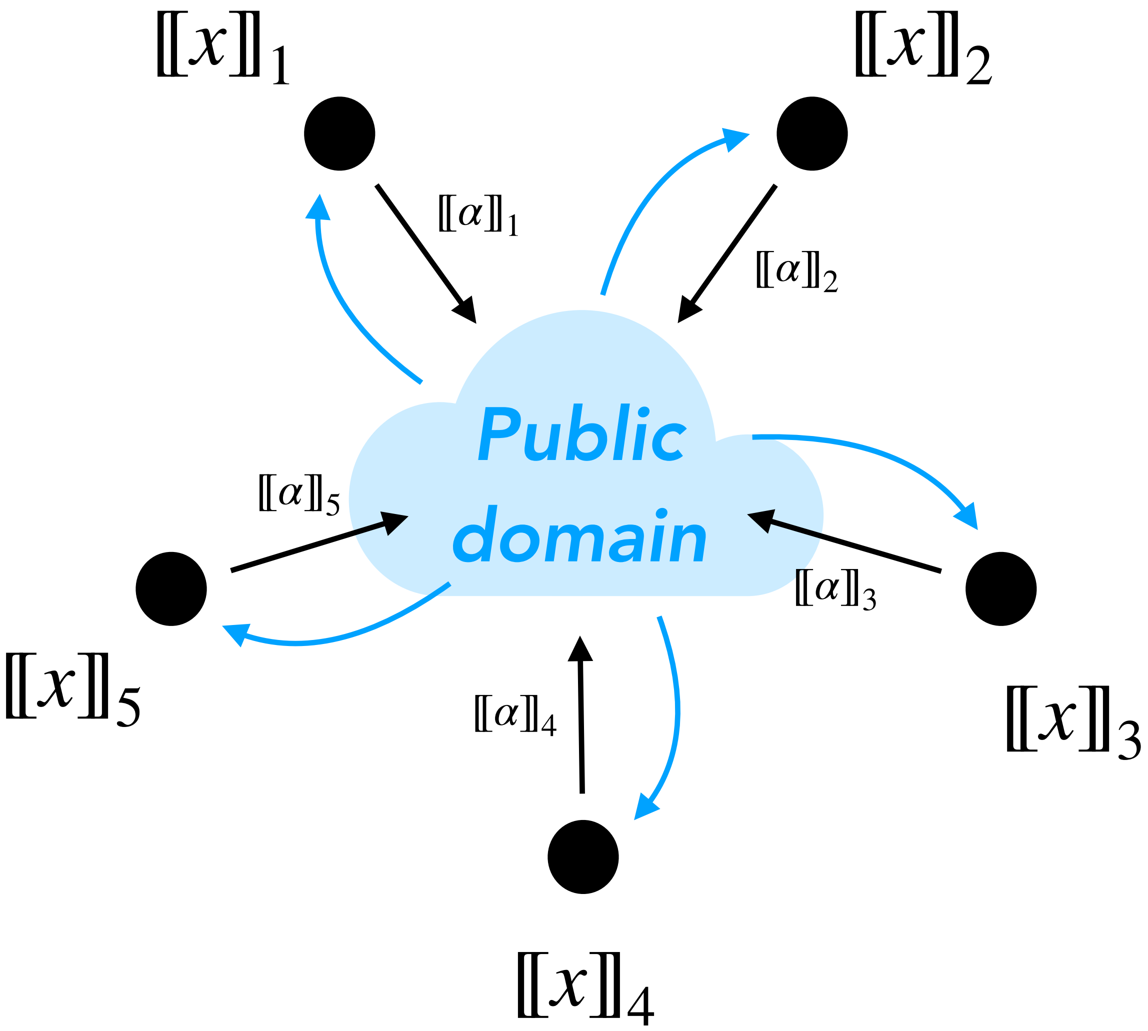


- **Jointly compute**

$$g(x) = \begin{cases} \text{Accept} & \text{if } F(x) = y \\ \text{Reject} & \text{if } F(x) \neq y \end{cases}$$

- $(N-1)$ **private:** the views of any $N-1$ parties provide no information on x
- **Semi-honest model:** assuming that the parties follow the steps of the protocol

MPC model



- **Jointly compute**

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- $(N-1)$ **private:** the views of any $N-1$ parties provide no information on x
- **Semi-honest model:** assuming that the parties follow the steps of the protocol
- ***Broadcast model***
  - *Parties locally compute on their shares* $[\![x]\!] \mapsto [\![\alpha]\!]$
  - *Parties broadcast* $[\![\alpha]\!]$ *and recompute* α
  - *Parties start again (now knowing* α*)*

MPCitH transform

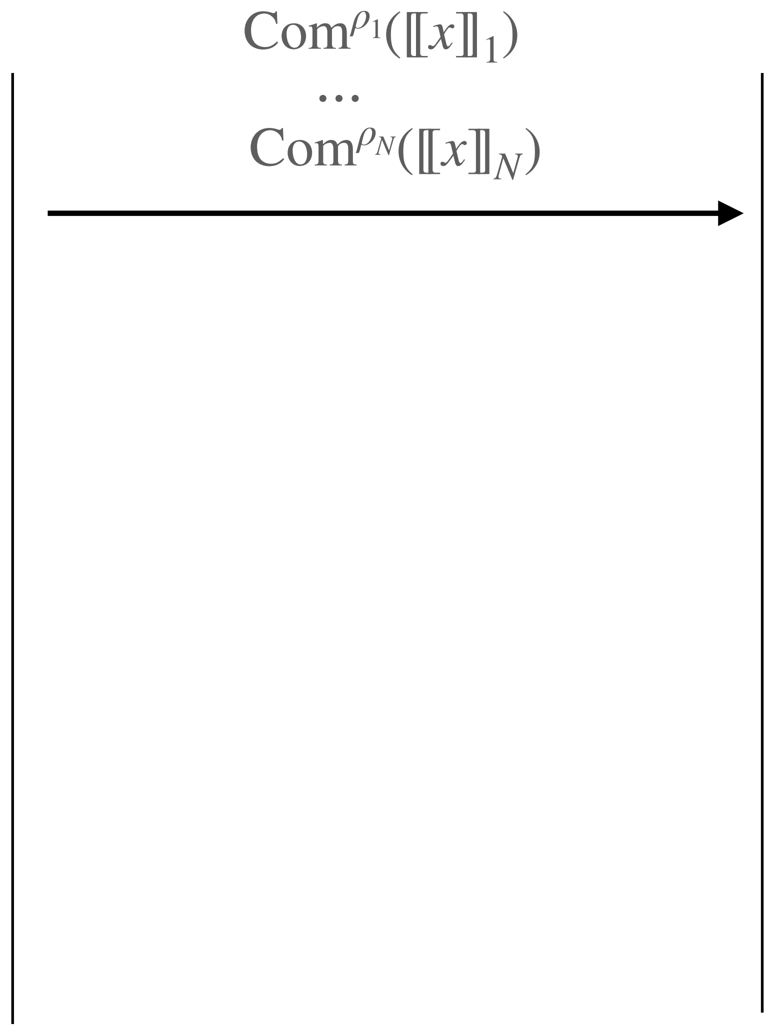
Prover

Verifier

MPCitH transform

① Generate and commit shares

$[\![x]\!] = ([\![x]\!]_1, \ldots, [\![x]\!]_N)$



$\mathrm{Com}^{\rho_1}([\![x]\!]_1)$

$\ldots$

$\mathrm{Com}^{\rho_N}([\![x]\!]_N)$

Prover

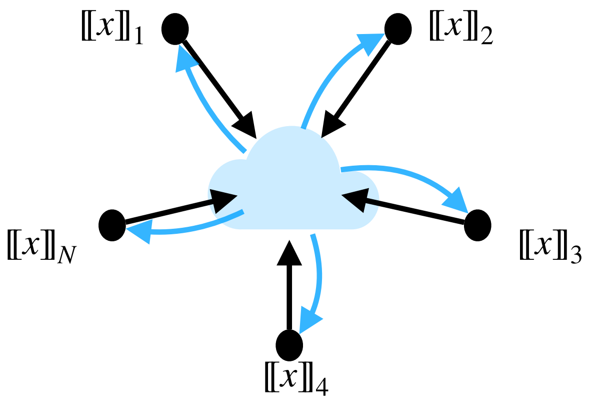
Verifier

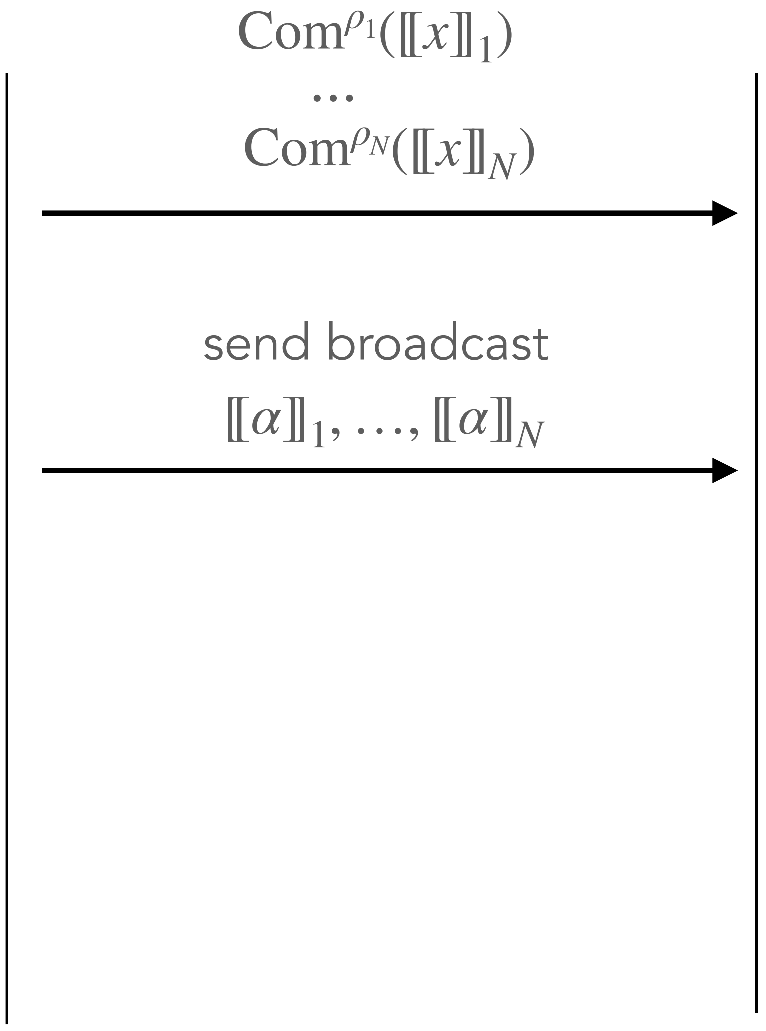
MPCitH transform

① Generate and commit shares

$[\![x]\!] = ([\![x]\!]_1, \ldots, [\![x]\!]_N)$

② Run MPC in their head





$\mathrm{Com}^{\rho_1}([\![x]\!]_1)$

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$\mathrm{Com}^{\rho_N}([\![x]\!]_N)$

send broadcast

$[\![\alpha]\!]_1, \ldots, [\![\alpha]\!]_N$

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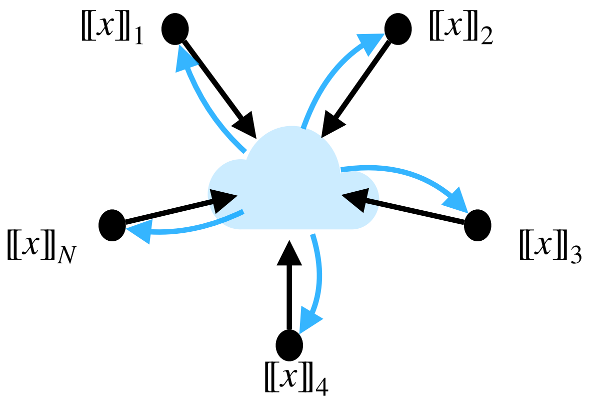

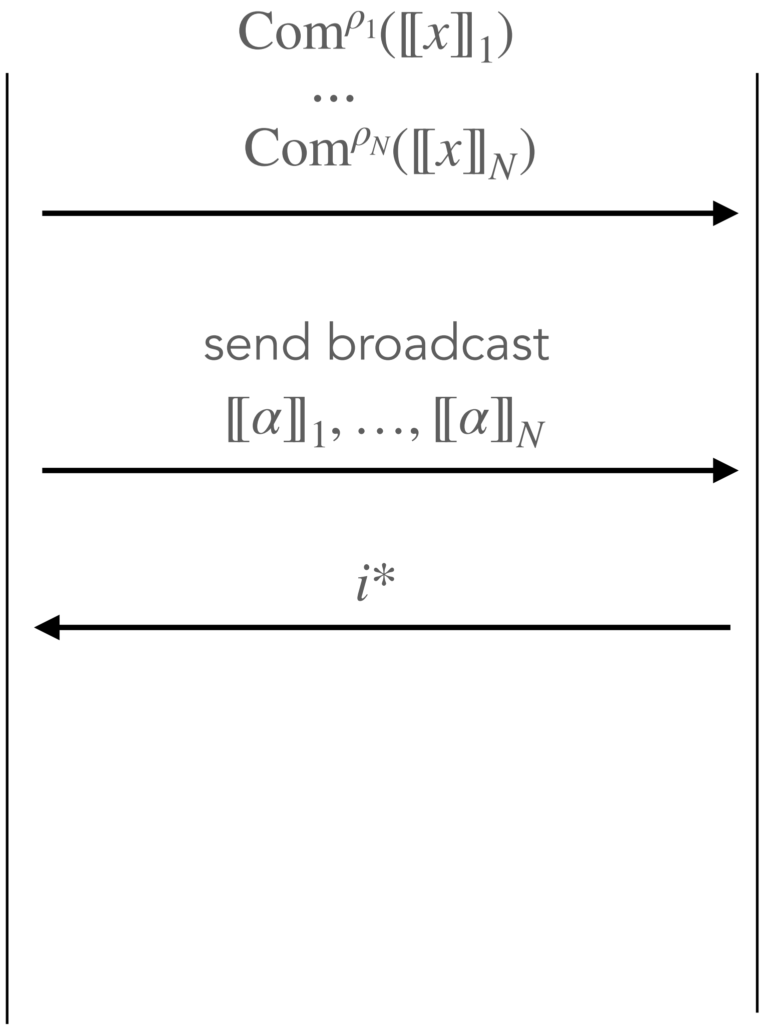

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send broadcast

$[\![\alpha]\!]_1, \ldots, [\![\alpha]\!]_N$

i^*

③ Choose a random party

$i^* \xleftarrow{\$} \{1, \ldots, N\}$

Prover

Verifier

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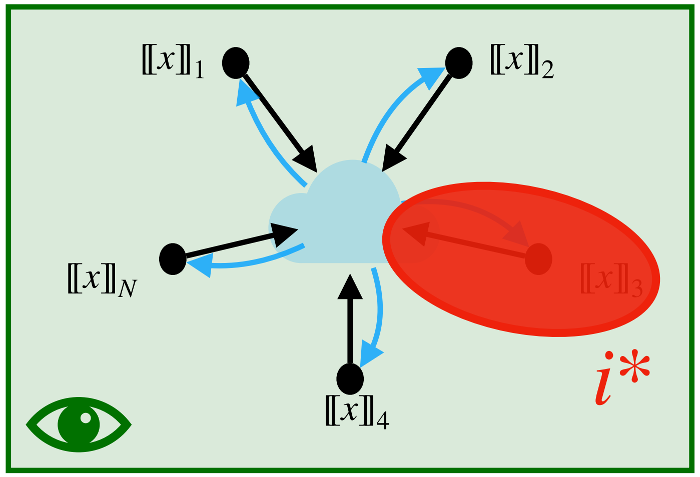
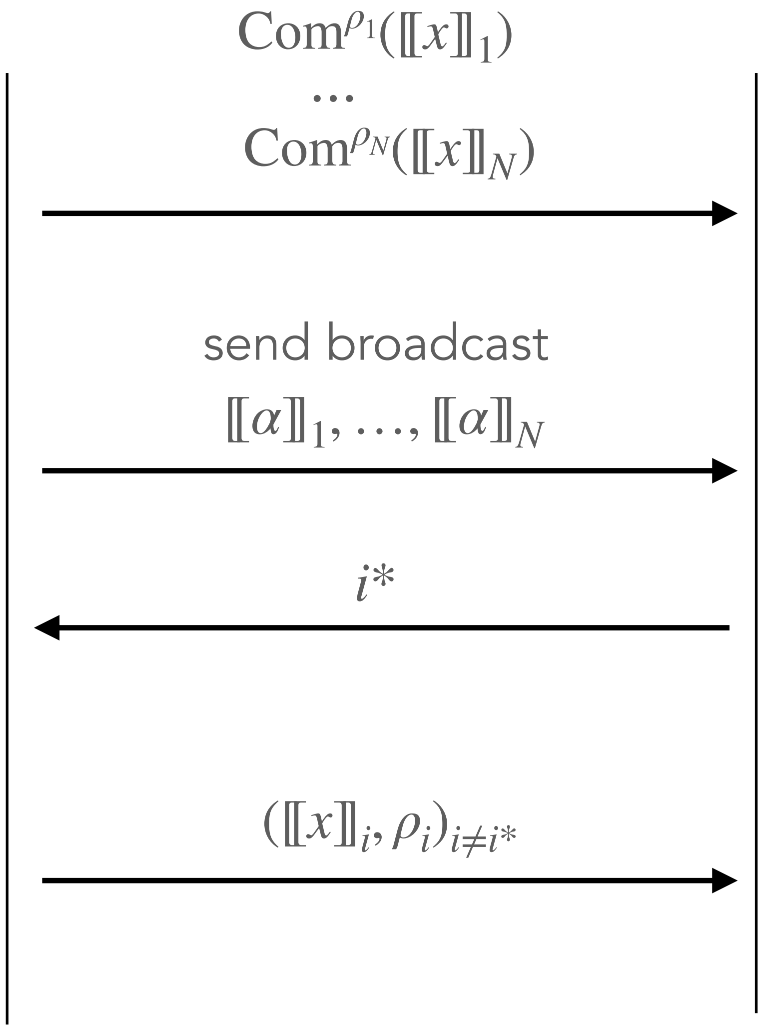


④ Open parties $\{1,\ldots,N\}\backslash\{i^*\}$



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send broadcast

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i^*

$([\![x]\!]_i, \rho_i)_{i \neq i^*}$

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$\mathrm{Com}^{\rho_N}([\![x]\!]_N)$ →

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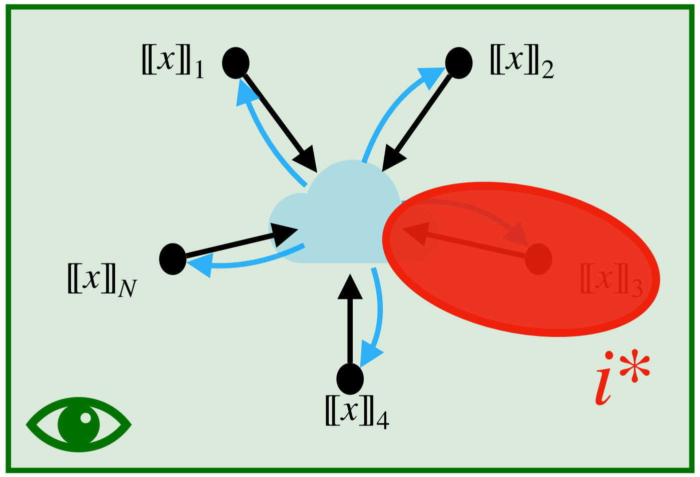

send broadcast

$[\![\alpha]\!]_1, \ldots, [\![\alpha]\!]_N$ →

③ Choose a random party

$i^* \xleftarrow{\$} \{1,\ldots,N\}$

← i^*

④ Open parties $\{1,\ldots,N\}\backslash\{i^*\}$

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⑤ Check $\forall i \neq i^*$

- Commitments $\mathrm{Com}^{\rho_i}([\![x]\!]_i)$
- MPC computation $[\![\alpha]\!]_i = \varphi([\![x]\!]_i)$

Check $g(y, \alpha) =$ Accept

Prover

Verifier

MPCitH transform

① Generate and commit shares

$[\![x]\!] = ([\![x]\!]_1, \ldots, [\![x]\!]_N)$

We have $F(x) \neq y$ where

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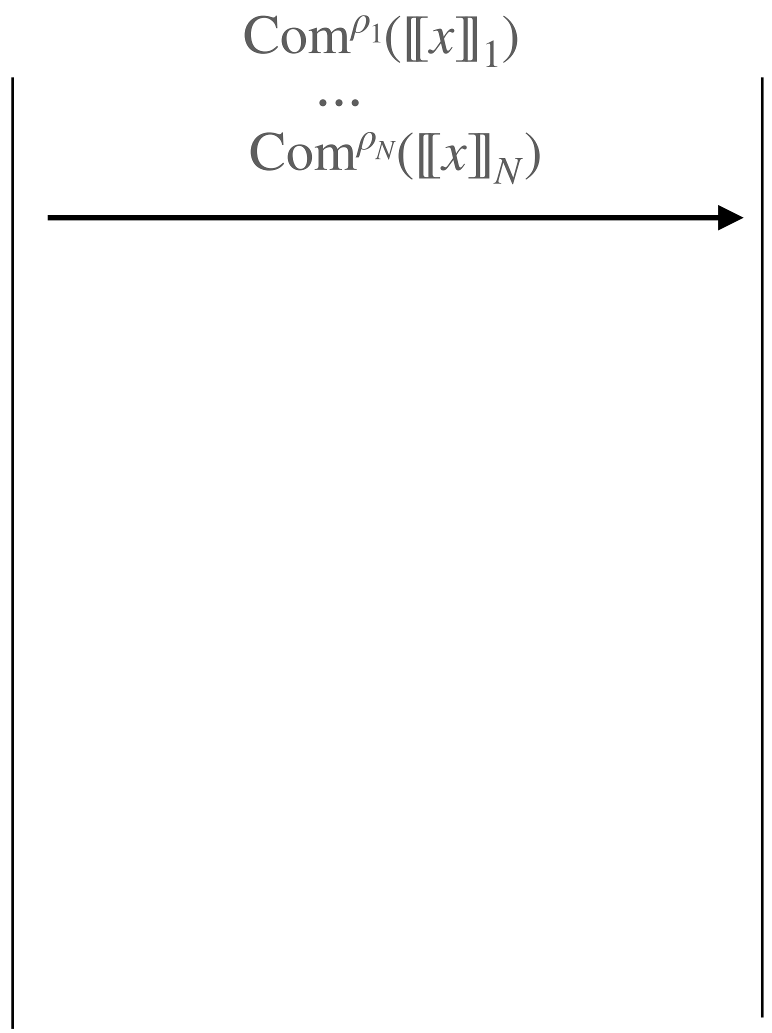

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Malicious Prover

Verifier

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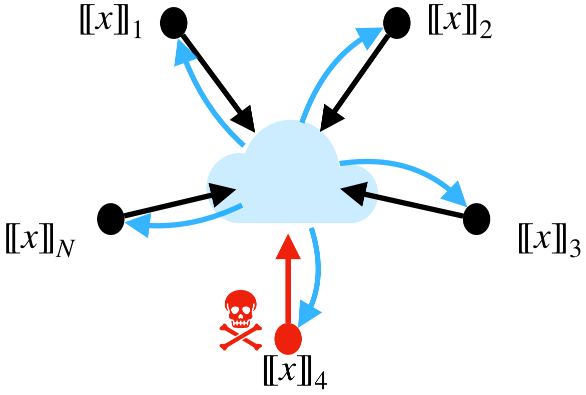

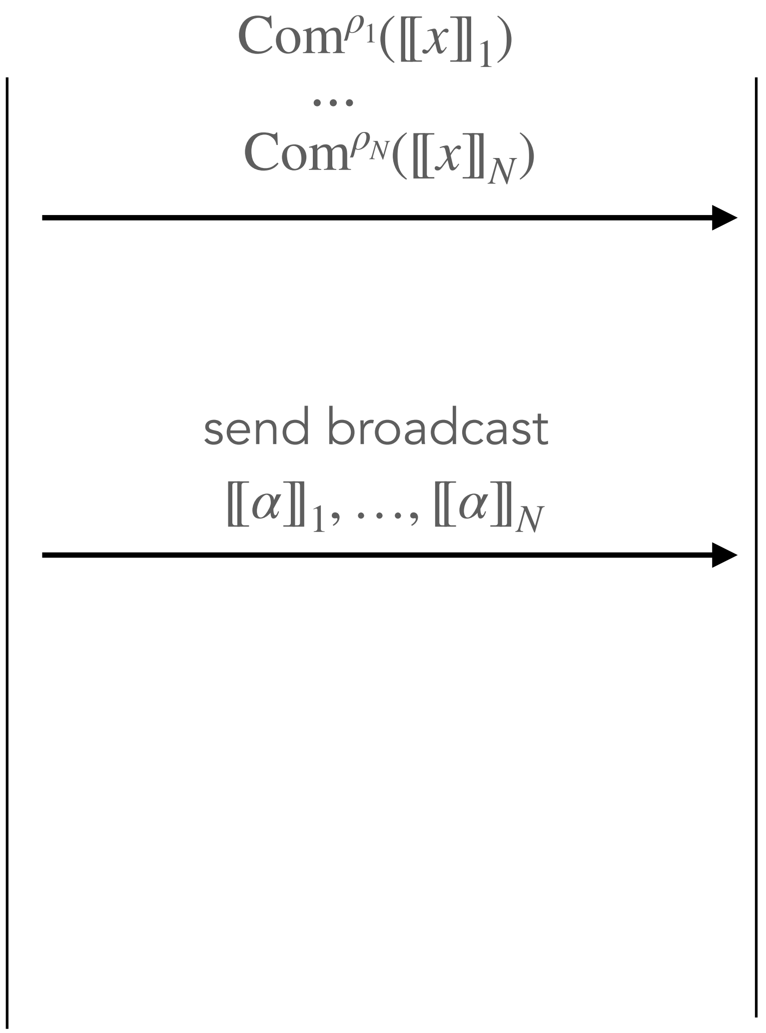

Malicious Prover

Verifier

MPCitH transform

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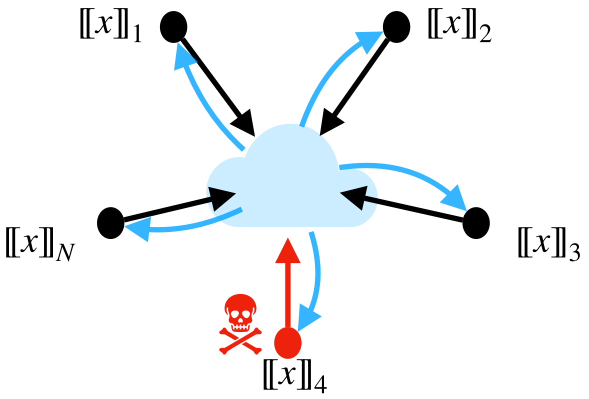

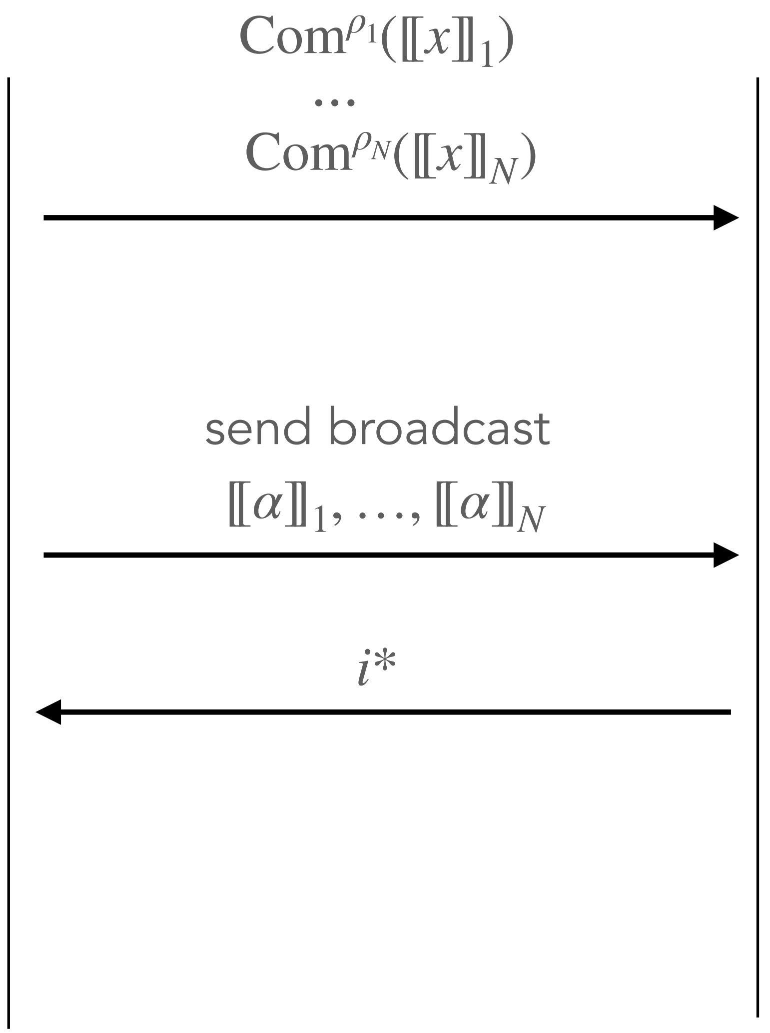

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send broadcast

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Malicious Prover

Verifier

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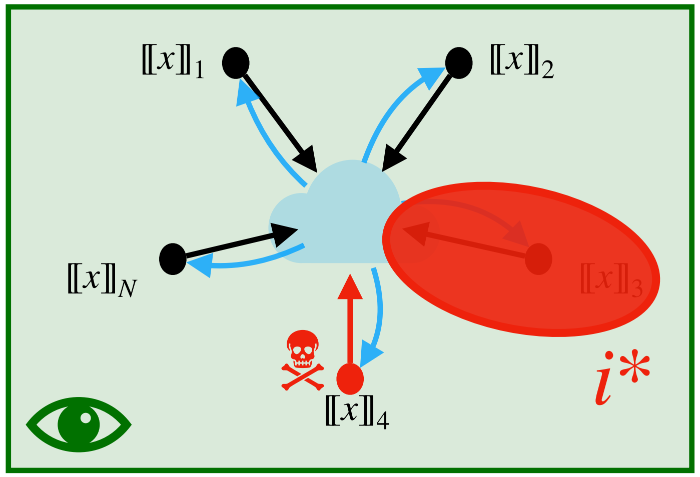

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→

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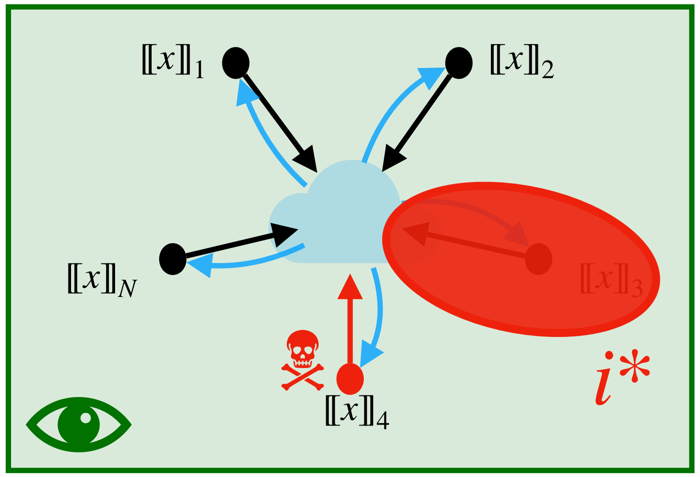

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←

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→

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- MPC computation $[\![\alpha]\!]_i = \varphi([\![x]\!]_i)$

Check $g(y, \alpha) =$ Accept

Malicious Prover

Verifier

❌ **Cheating detected!**

MPCitH transform

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$\mathrm{Com}^{\rho_1}([\![x]\!]_1)$

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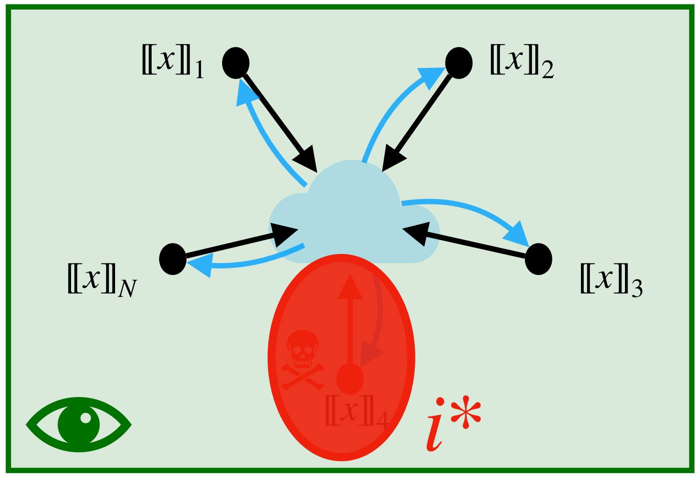
$\mathrm{Com}^{\rho_N}([\![x]\!]_N)$

$\longrightarrow$

② Run MPC in their head



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$[\![\alpha]\!]_1, \dots, [\![\alpha]\!]_N$

$\longrightarrow$

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$\longleftarrow$

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Malicious Prover

Verifier

✓ **Seems OK.**

MPCitH transform

- **Zero-knowledge** $\iff$ MPC protocol is $(N-1)$-private

MPCitH transform

- **Zero-knowledge** $\iff$ MPC protocol is $(N-1)$-private

- **Soundness:**

$$\begin{aligned}\mathbb{P}(\text{malicious prover convinces the verifier}) \\ &= \mathbb{P}(\text{corrupted party remains hidden}) \\ &= \frac{1}{N}\end{aligned}$$

MPCitH transform

- **Zero-knowledge** $\iff$ MPC protocol is $(N-1)$-private
- **Soundness:**

$$
\begin{aligned}
&\mathbb{P}(\text{malicious prover convinces the verifier}) \\
&\qquad = \mathbb{P}(\text{corrupted party remains hidden}) \\
&\qquad = \frac{1}{N}
\end{aligned}
$$

- **Parallel repetition**

Protocol repeated τ times in parallel → soundness error $\left(\frac{1}{N}\right)^{\tau}$

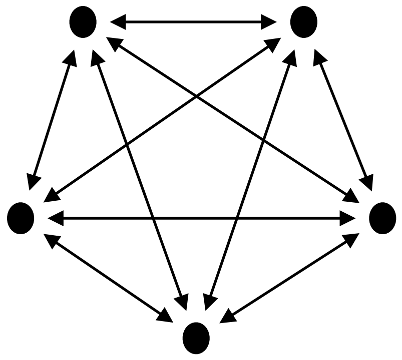
Code-based signature schemes

One-way function

$$F : x \mapsto y$$

E.g. AES, MQ system,
Syndrome decoding

Multiparty computation (MPC)



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Joint evaluation of:

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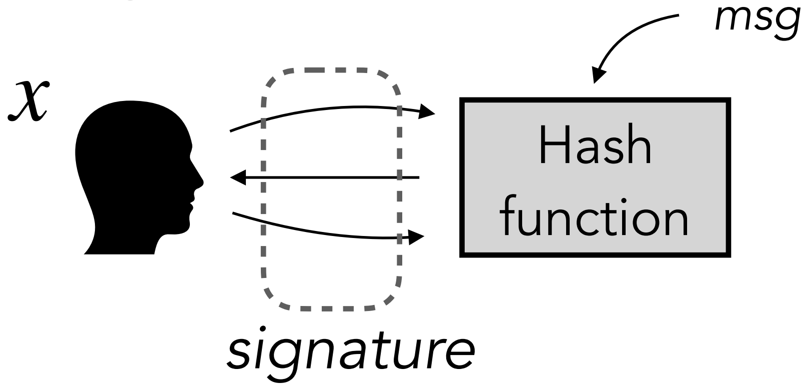
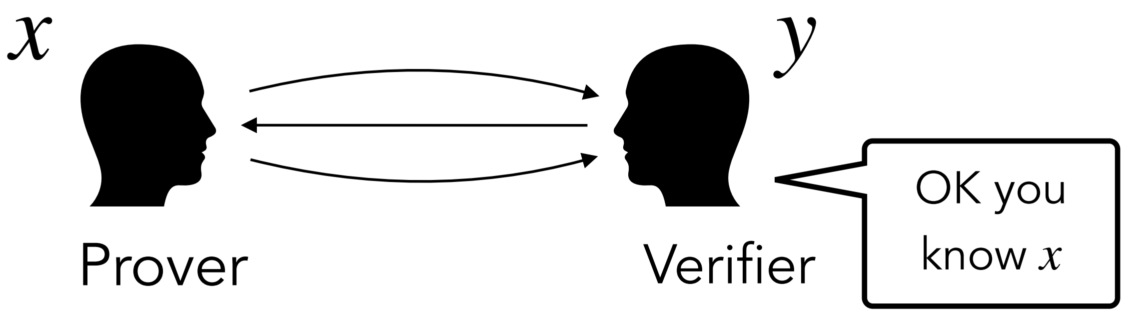
Signature scheme



Zero-knowledge proof



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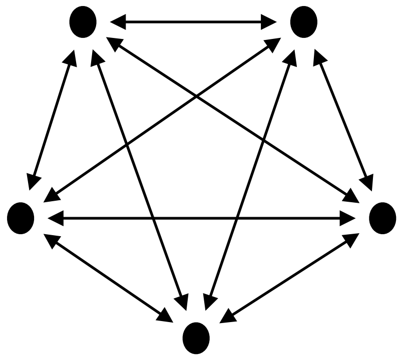


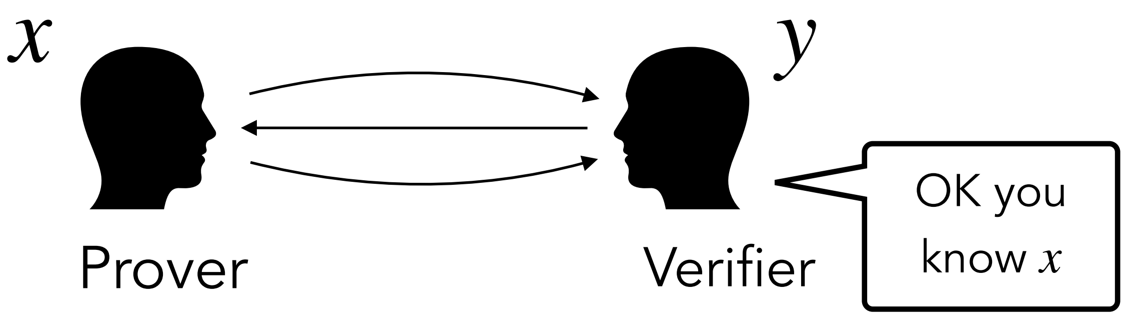
Input sharing $[\![x]\!]$

Joint evaluation of:

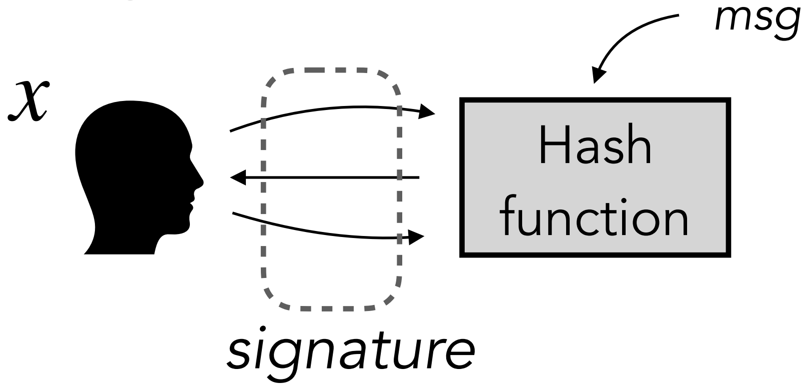
$$g(x) = \begin{cases} \text{Accept} & \text{if } F(x) = y \\ \text{Reject} & \text{if } F(x) \neq y \end{cases}$$

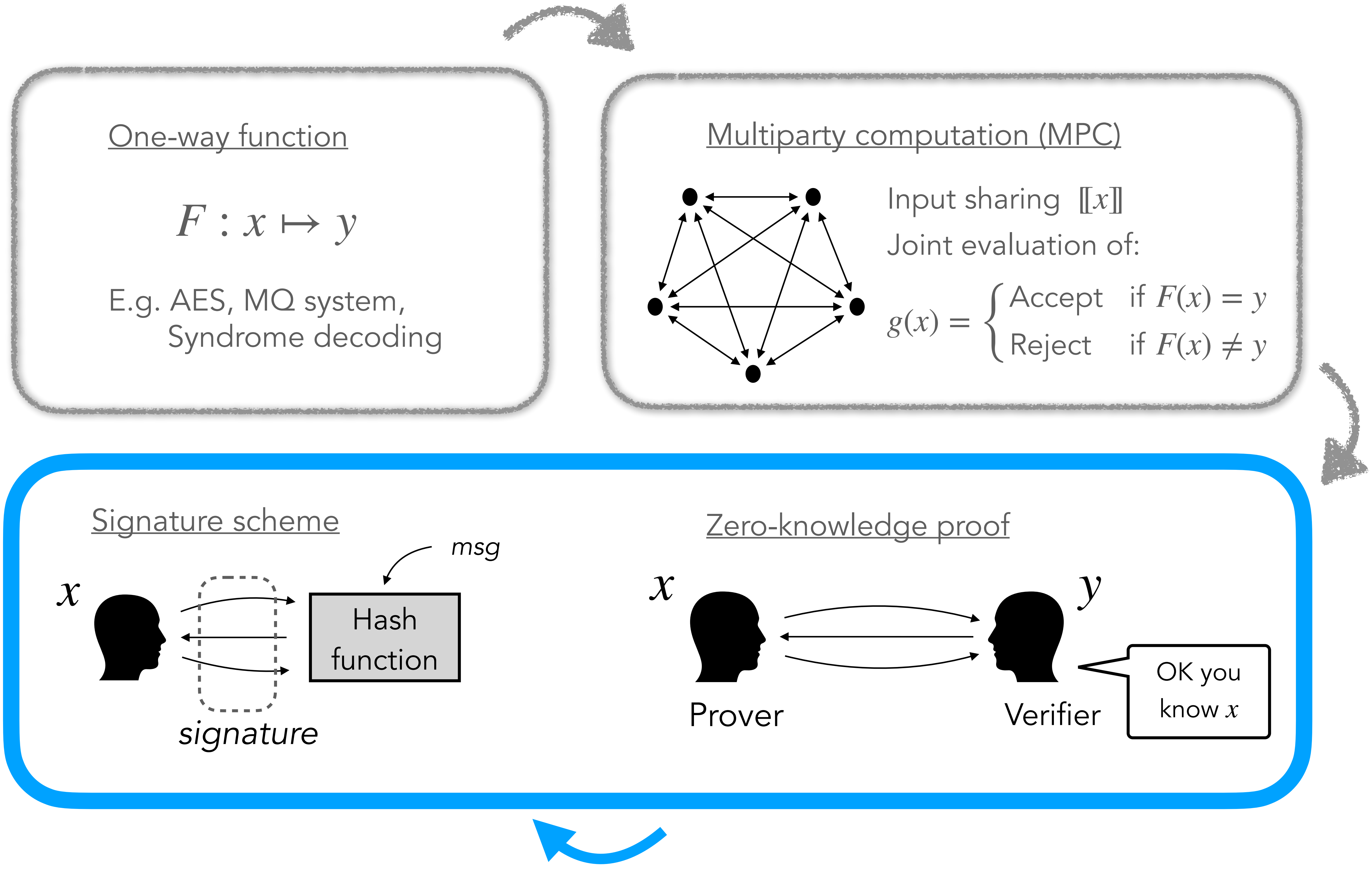
MPC in the Head transform

Zero-knowledge proof



Signature scheme





One-way function

$F : x \mapsto y$

E.g. AES, MQ system,
Syndrome decoding

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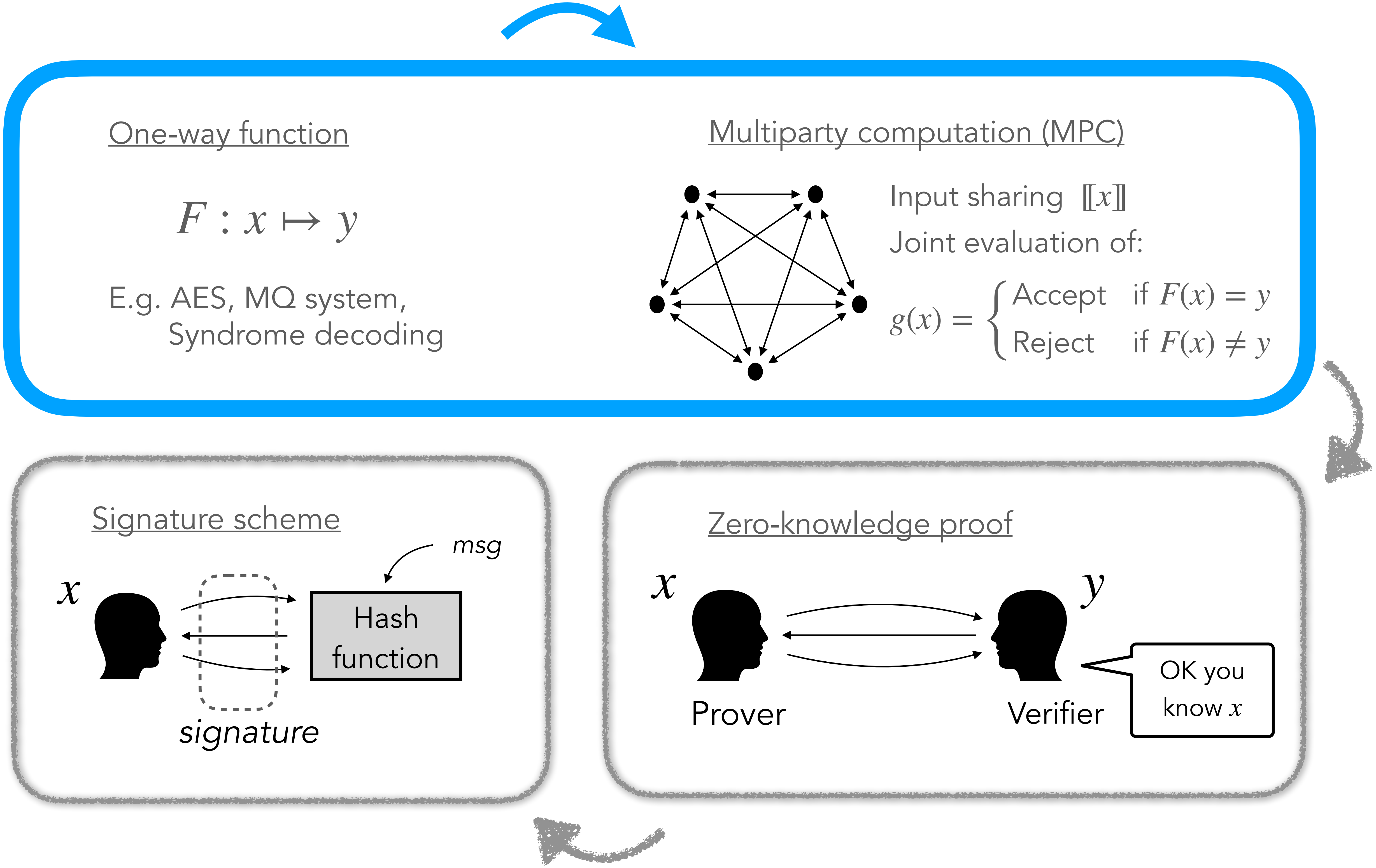
Fiat-Shamir transform



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Signature scheme

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Submitted code-based candidates at NIST call

Syndrome Decoding Problem
in *Hamming* metric

Syndrome Decoding Problem
in *rank* metric

Given a matrix H and a vector y, find x such that $y = Hx$ and

$$\mathrm{wt}_H(x) \leq w$$

$$\mathrm{wt}_R(x) \leq r$$

$(x \in \mathbb{F}_{q^m}^n)$

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The MPC protocol checks that the shared input x satisfies $y = Hx$ and

there exists a degree-w polynomial Q such that

$$\forall i,\ x_i \cdot Q(\gamma_i) = 0.$$

there exists a degree-q^r q-polynomial $L := \sum_{i=0}^{r} L_i X^{q^i}$ such that

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[FJR22] Feneuil T., Joux A., Rivain M. *Syndrome Decoding in the Head: Shorter Signatures from Zero-Knowledge Proofs*. Crypto 2022

[Fen22] Feneuil T. *Building MPCitH-based Signatures from MQ, MinRank, Rank SD and PKP*. ePrint 2022-1512

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SD-in-the-Head (SDitH)

C. Aguilar Melchor, T. Feneuil, N. Gama, S. Gueron, J. Howe, D. Joseph, A. Joux, E. Persichetti, T. Randrianarisoa, M. Rivain, D. Yue.

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RYDE

N. Aragon, M. Bardet, L. Bidoux, J.-J. Chi-Domínguez, V. Dyseryn, T. Feneuil, P. Gaborit, A. Joux, M. Rivain, J.-P. Tillich, A. Vinçotte.

Performances

Shamir's sharing

	Short Instance			Fast Instance		
	$\|\text{sig}\|$	t_{sign}	t_{verify}	$\|\text{sig}\|$	t_{sign}	t_{verify}
SDitH-256	8.3	13.4	12.5	10.1	5.1	1.6
SDitH-251	8.3	22.1	21.2	10.1	4.4	0.6
RYDE	6.0	23.4	20.1	7.4	5.4	4.4

Additive sharing

NIST Category I
Isochronous implementations
Size in kilobytes, timing in Mcycles
@2.60GHz: 1 millisecond $\approx$ *2.6 Mcycles*

Performances

- *How it scales for higher security levels?*

	SDitH			**RYDE**		
	|pk|	***Short***	***Fast***	|pk|	***Short***	***Fast***
Category I	120 B	8.3 KB	10.1 KB	86 B	6.0 KB	7.4 KB
Category III	183 B	19.2 KB	24.9 KB	131 B	12.9 KB	16.4 KB
Category V	234 B	33.4 KB	43.9 KB	188 B	22.8 KB	29.1 KB

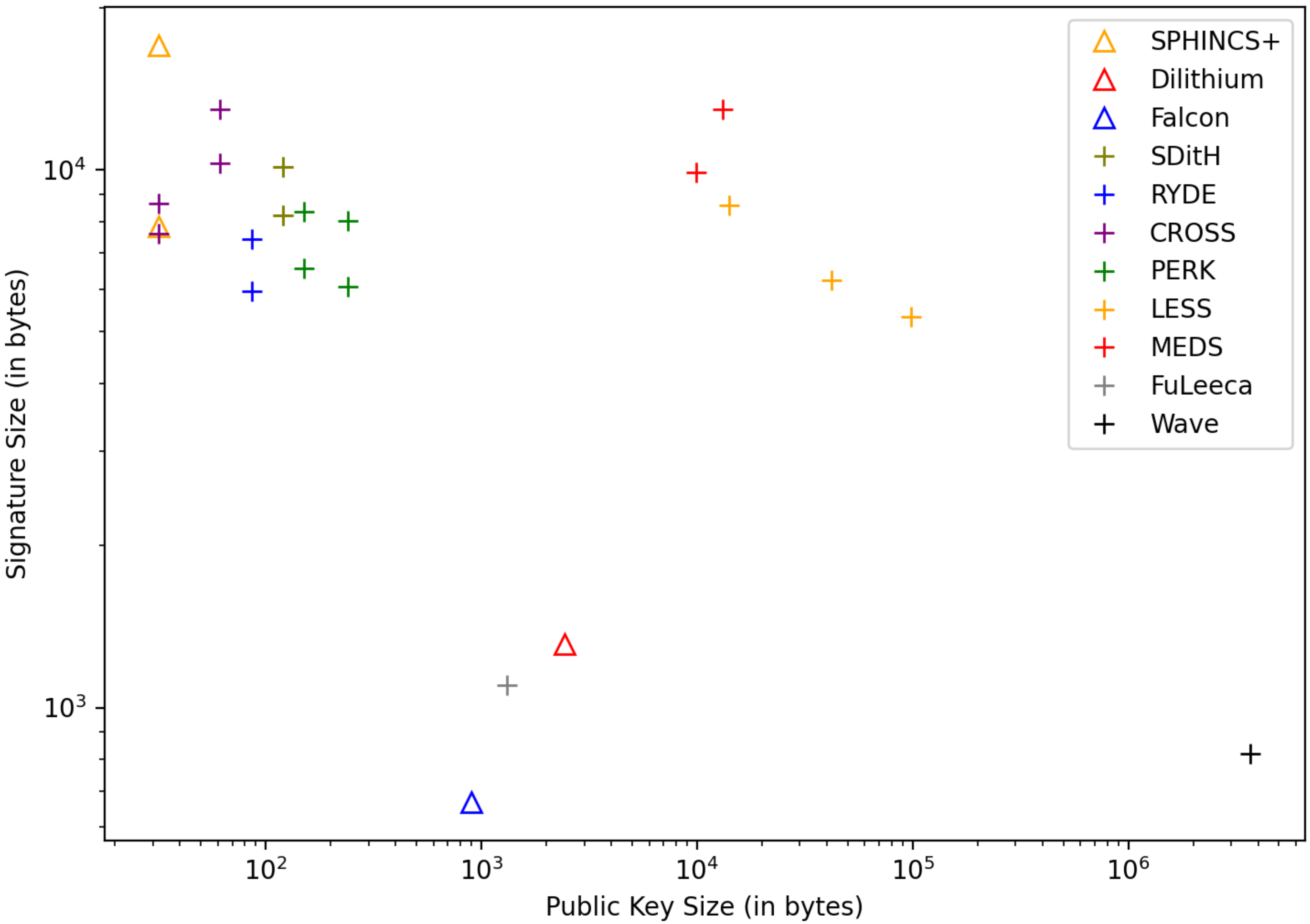
Comparison

NIST Category I
Size in bytes, timing in Mcycles

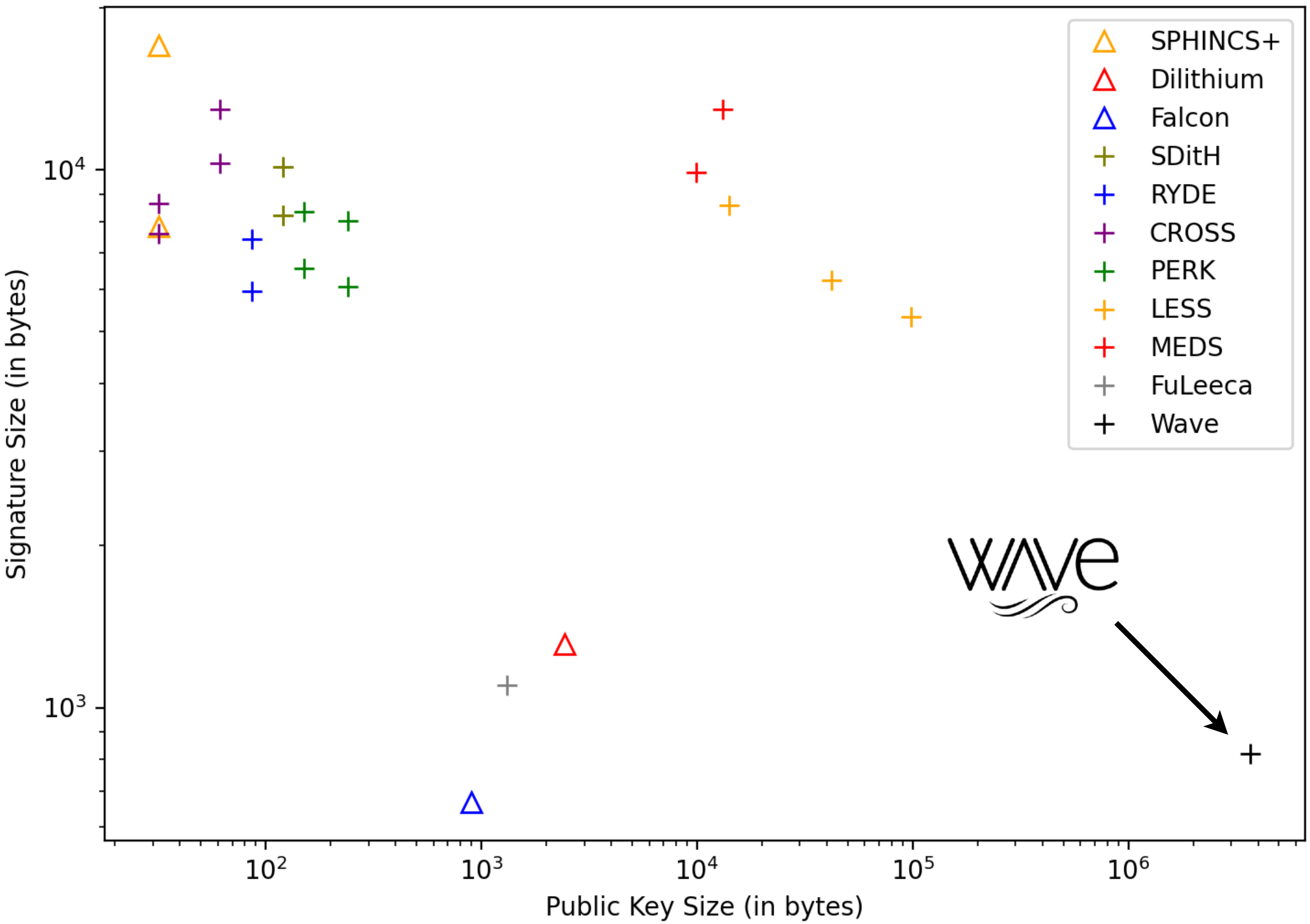
	$\lvert pk\rvert$	$\lvert sig\rvert$	$\lvert sig\rvert+\lvert pk\rvert$	t_{sign}	t_{verify}
SDitH-256-short	120	8241	8361	13.4	12.5
SDitH-251-short	120	8241	8361	22.1	21.2
SDitH-256-fast	120	10117	10237	5.1	1.6
SDitH-251-fast	120	10117	10237	4.4	0.6
RYDE-short	86	5956	6042	23.4	20.1
RYDE-fast	86	7446	7532	5.4	4.4
PERK-short3	150	6560	6710	39	27
PERK-short5	240	6060	6300	36	25
PERK-fast3	150	8350	8500	7.6	5.3
PERK-fast5	240	8030	8270	7.2	5.1
CROSS-fast	61	12944	13005	6.8	3.2
CROSS-small	61	10304	10365	22.0	10.3
CROSS-G-fast	32	8665	8697	3.1	2.1
CROSS-G-small	32	7625	7657	11.0	7.8
LESS-1b	13700	8400	22100	263.6	271.4
LESS-1i	41100	6100	47200	254.3	263.4
LESS-1s	95900	5200	101100	206.6	213.4
MEDS-9923	9923	9896	19819	518.1	515.6
MEDS-13220	13220	12976	26196	88.9	46.0
FuLeeca	1318	1100	2418	1846.8	1.26
Wave-822	3677390	822	3678212	1160	1.23

`https://wave-sign.org/`
`https://www.meds-pqc.org/`
`https://www.less-project.com/`
`https://www.cross-crypto.com/`
`https://pqc-perk.org/`
`https://pqc-ryde.org/`
`https://sdith.org/`
`https://www.ce.cit.tum.de/.../fuleeca/`

Comparison


Signature Size (in bytes)
Public Key Size (in bytes)
10^3
10^4
10^2
10^3
10^4
10^5
10^6
△ SPHINCS+
△ Dilithium
△ Falcon
+ SDitH
+ RYDE
+ CROSS
+ PERK
+ LESS
+ MEDS
+ FuLeeca
+ Wave

Comparison



SPHINCS+
Dilithium
Falcon
SDitH
RYDE
CROSS
PERK
LESS
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WAVE
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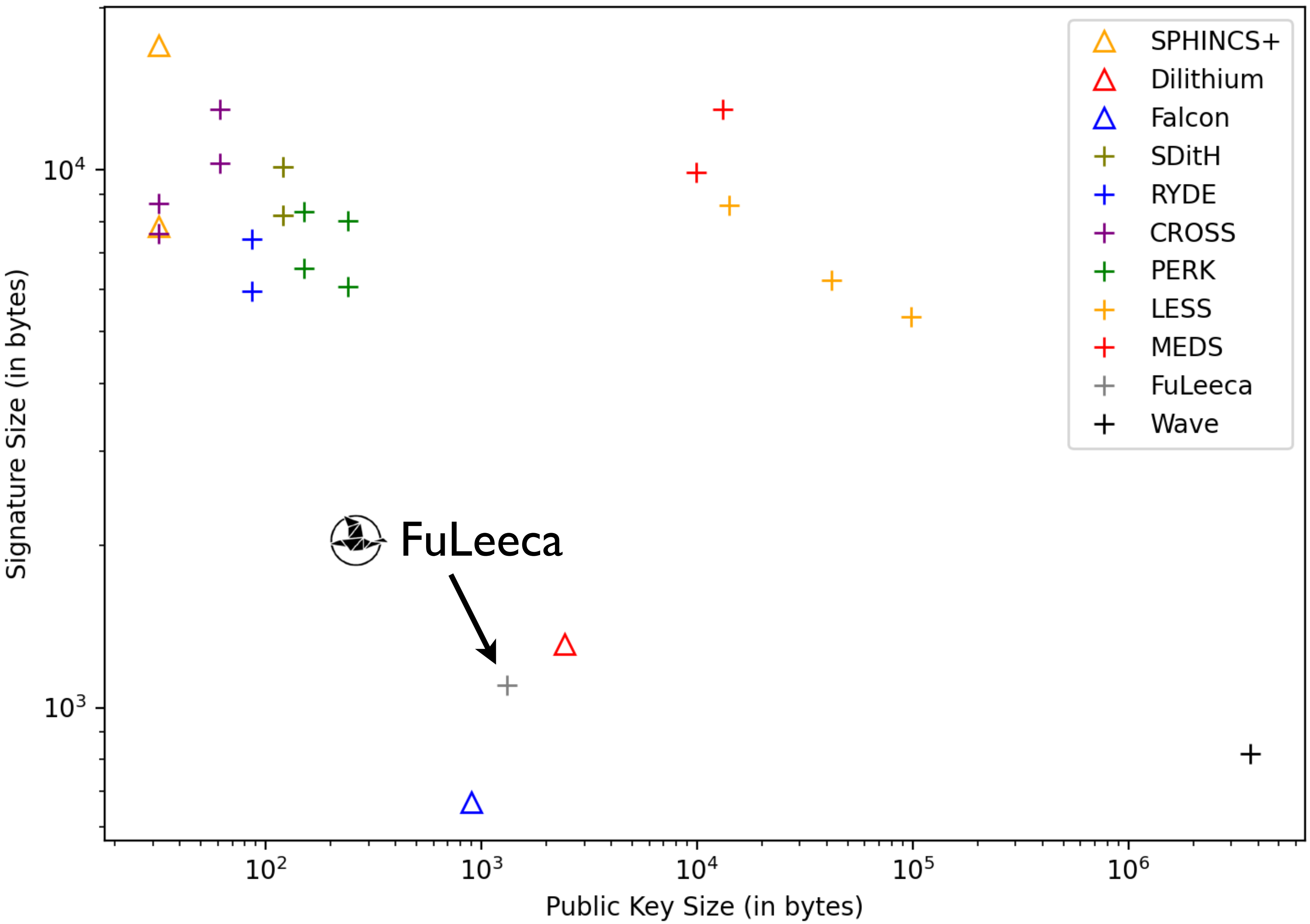
Comparison



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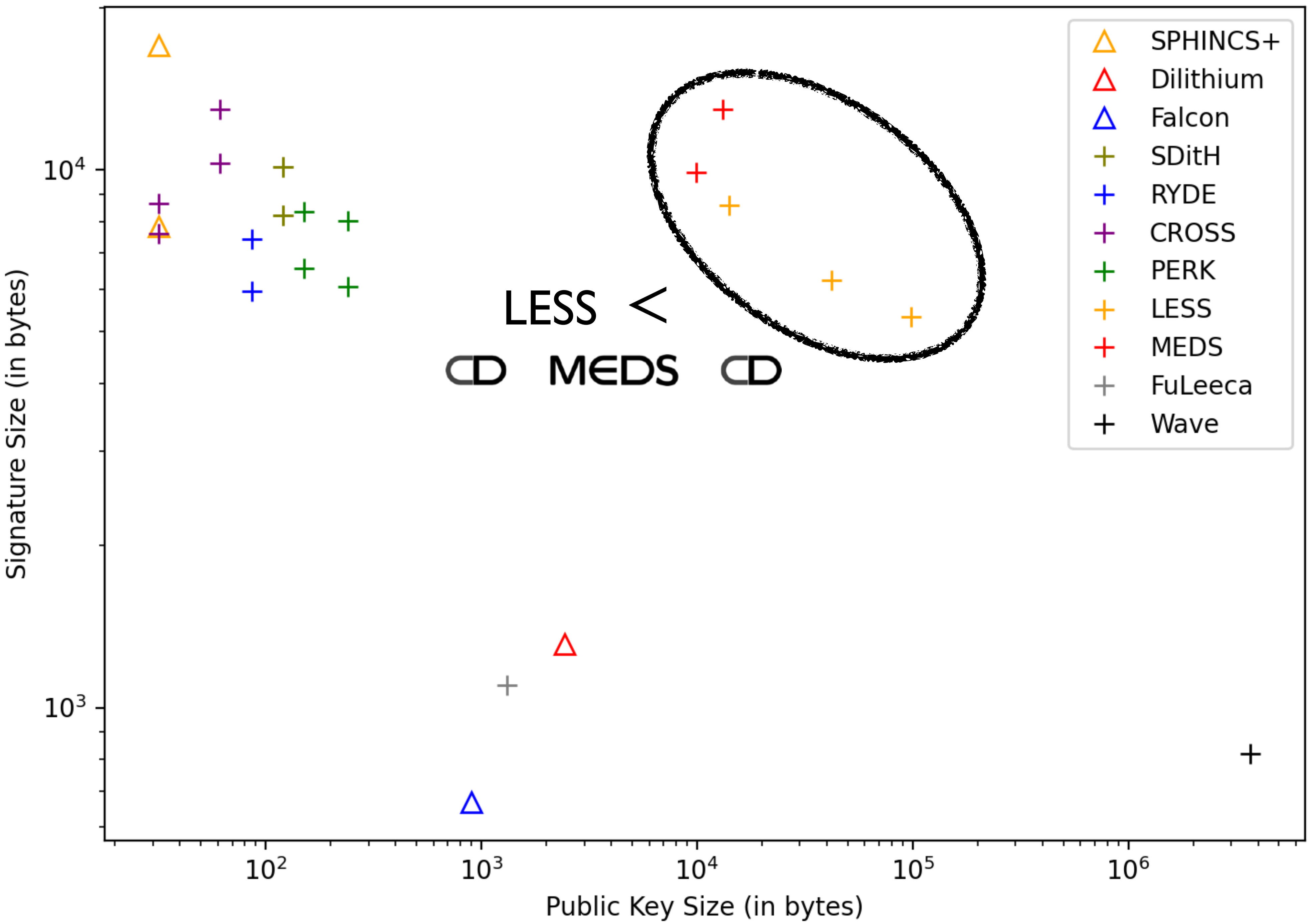
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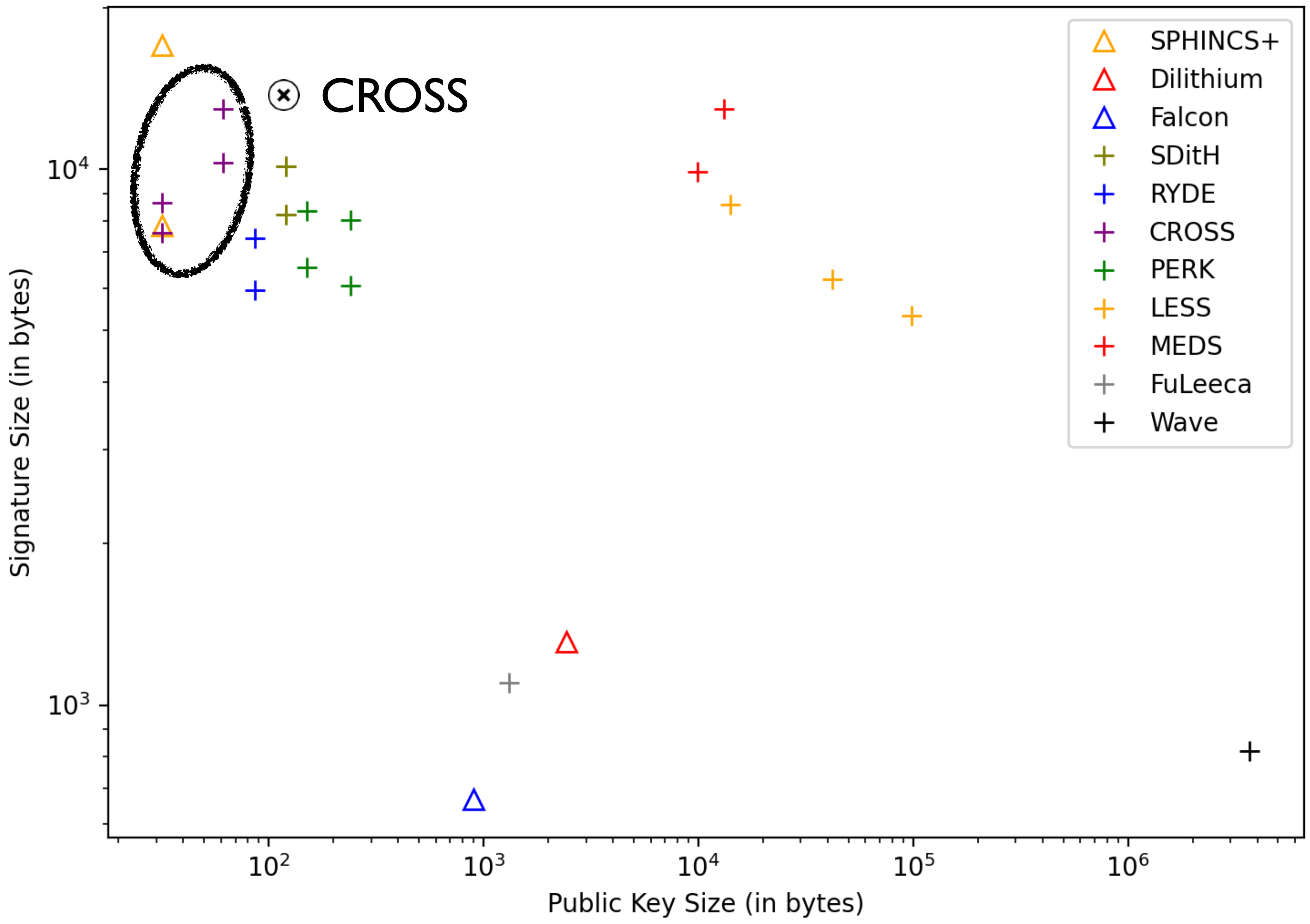
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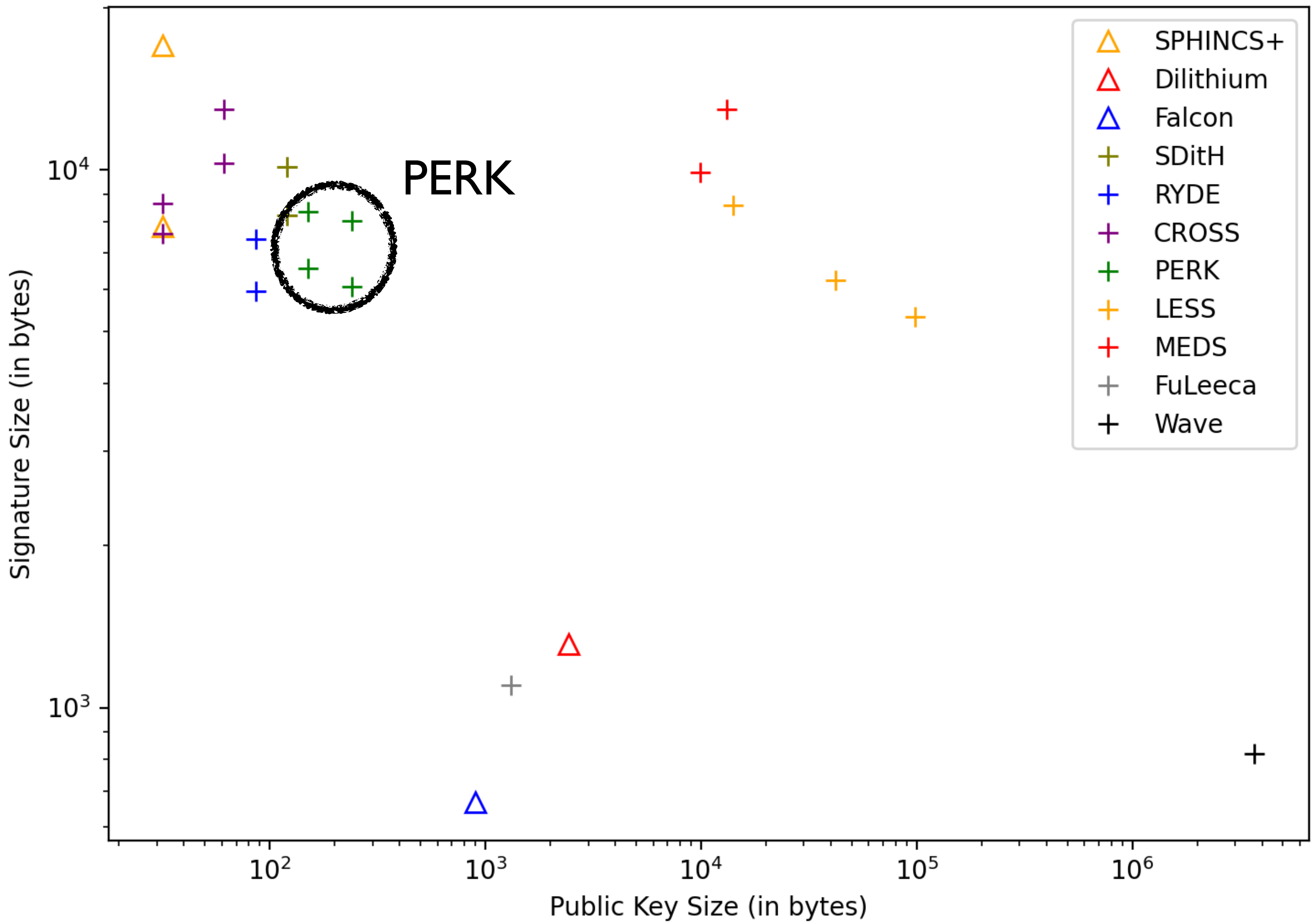
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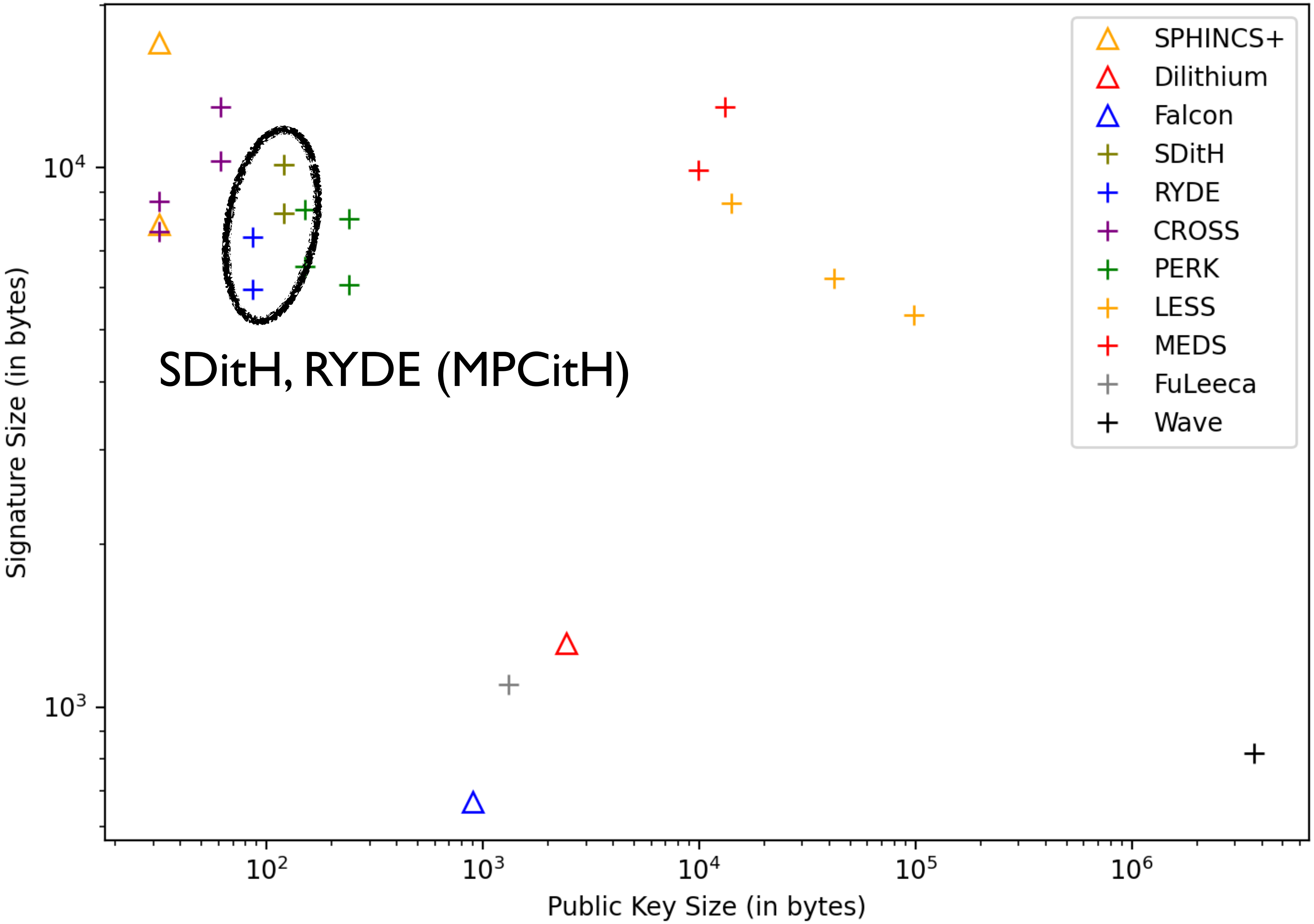
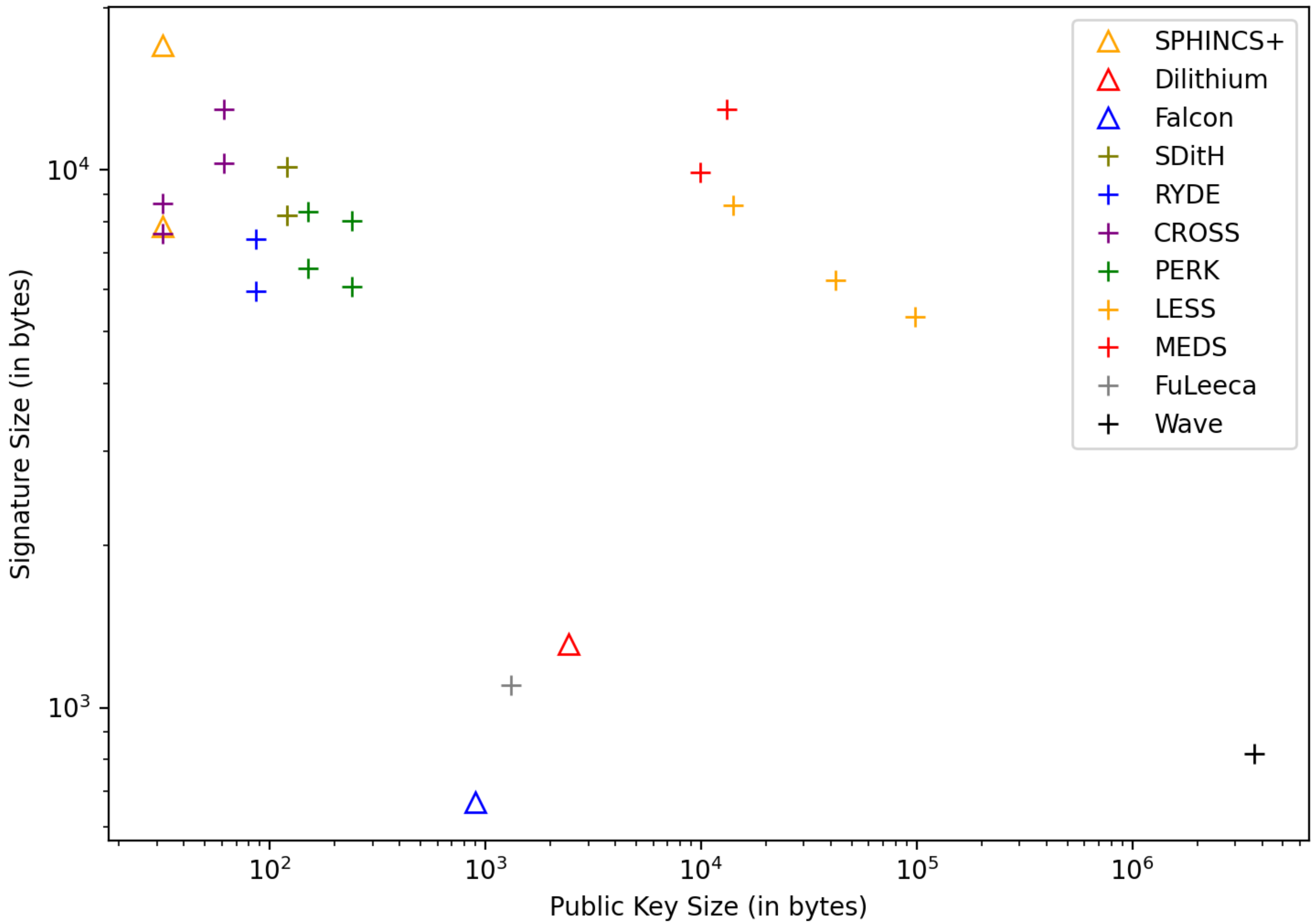


SDitH, RYDE (MPCitH)

Comparison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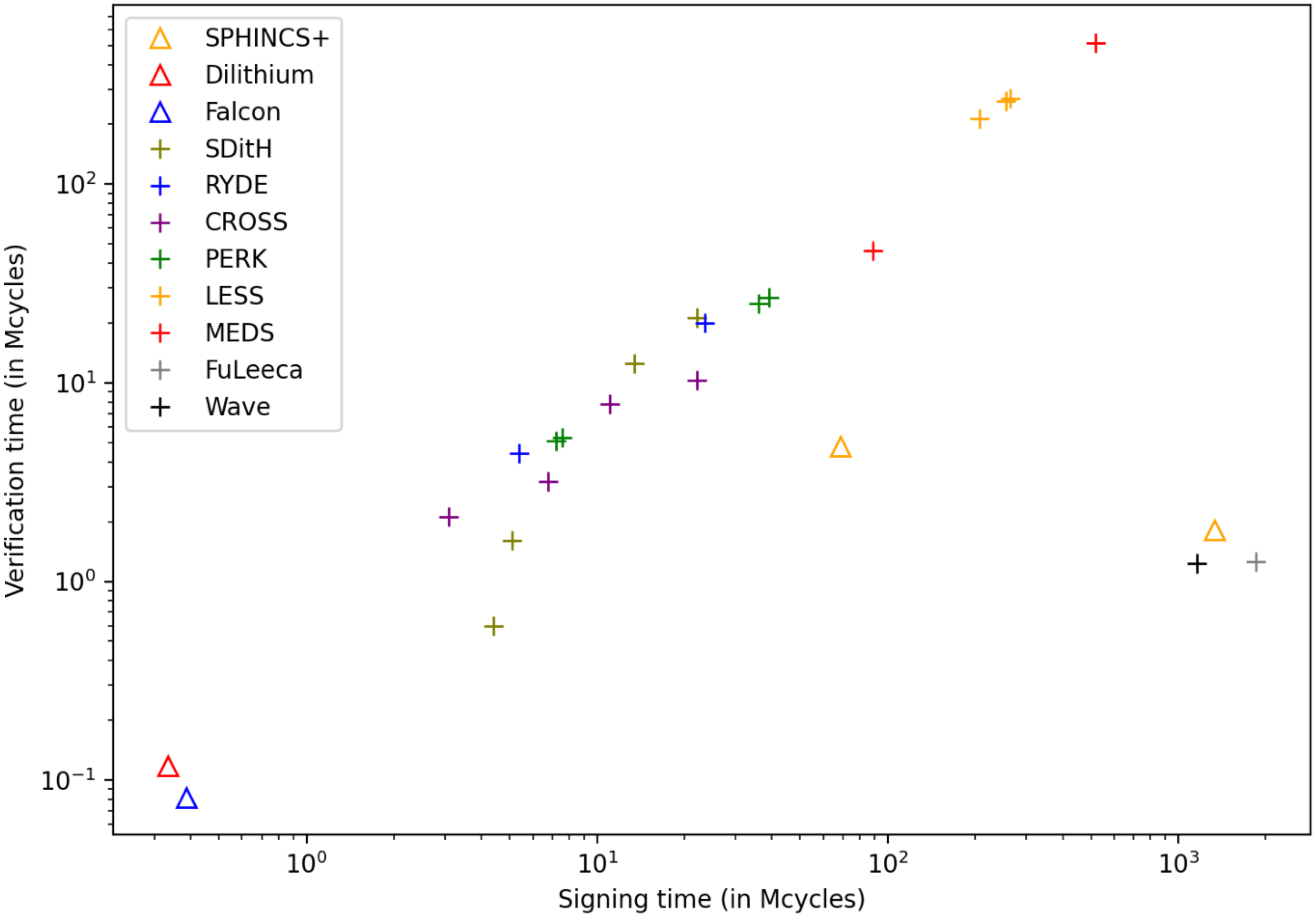
Comparison

Optimized implementations are not available for all these signature schemes. These numbers will change in the coming months.



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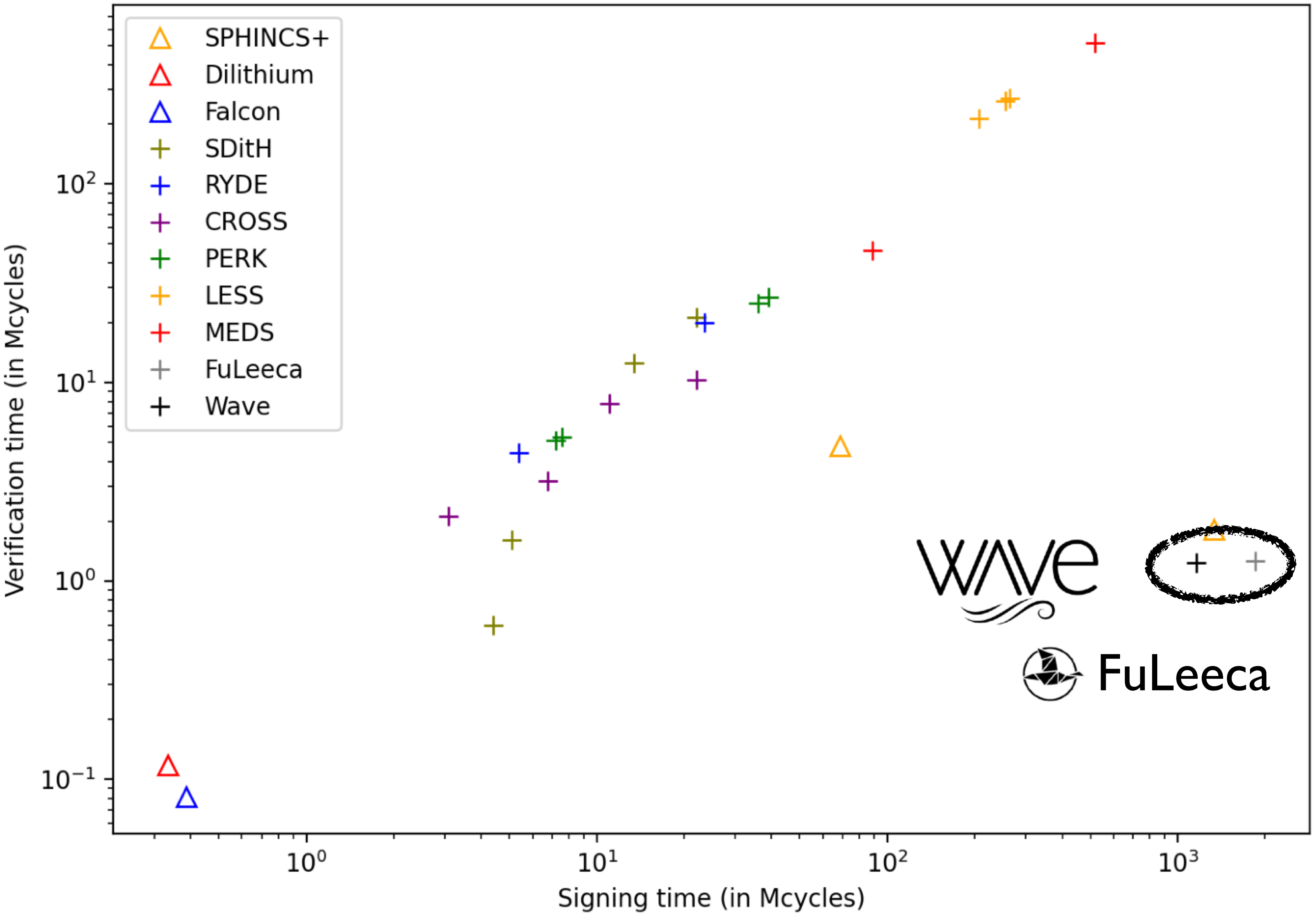

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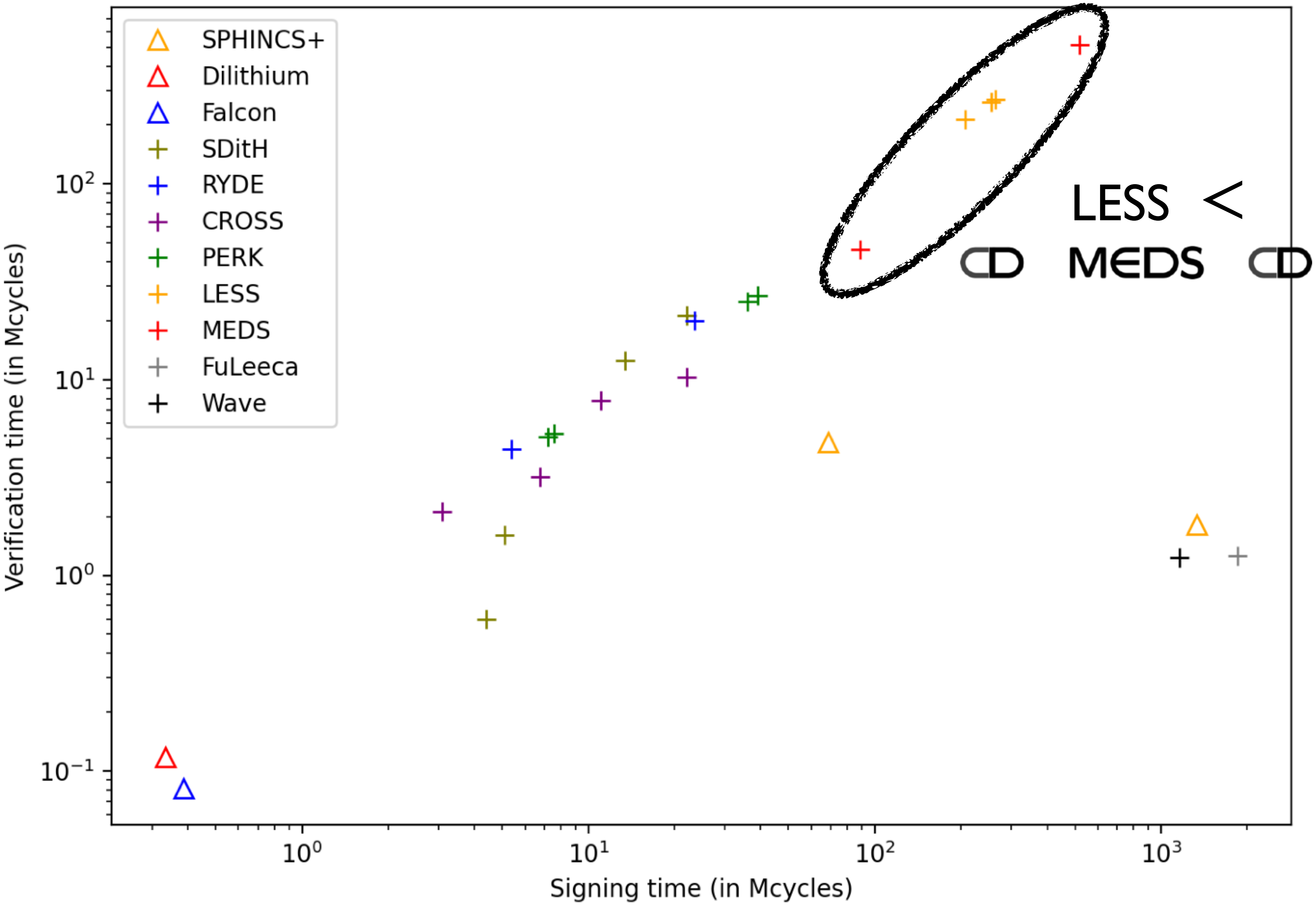

LESS <

MEDS

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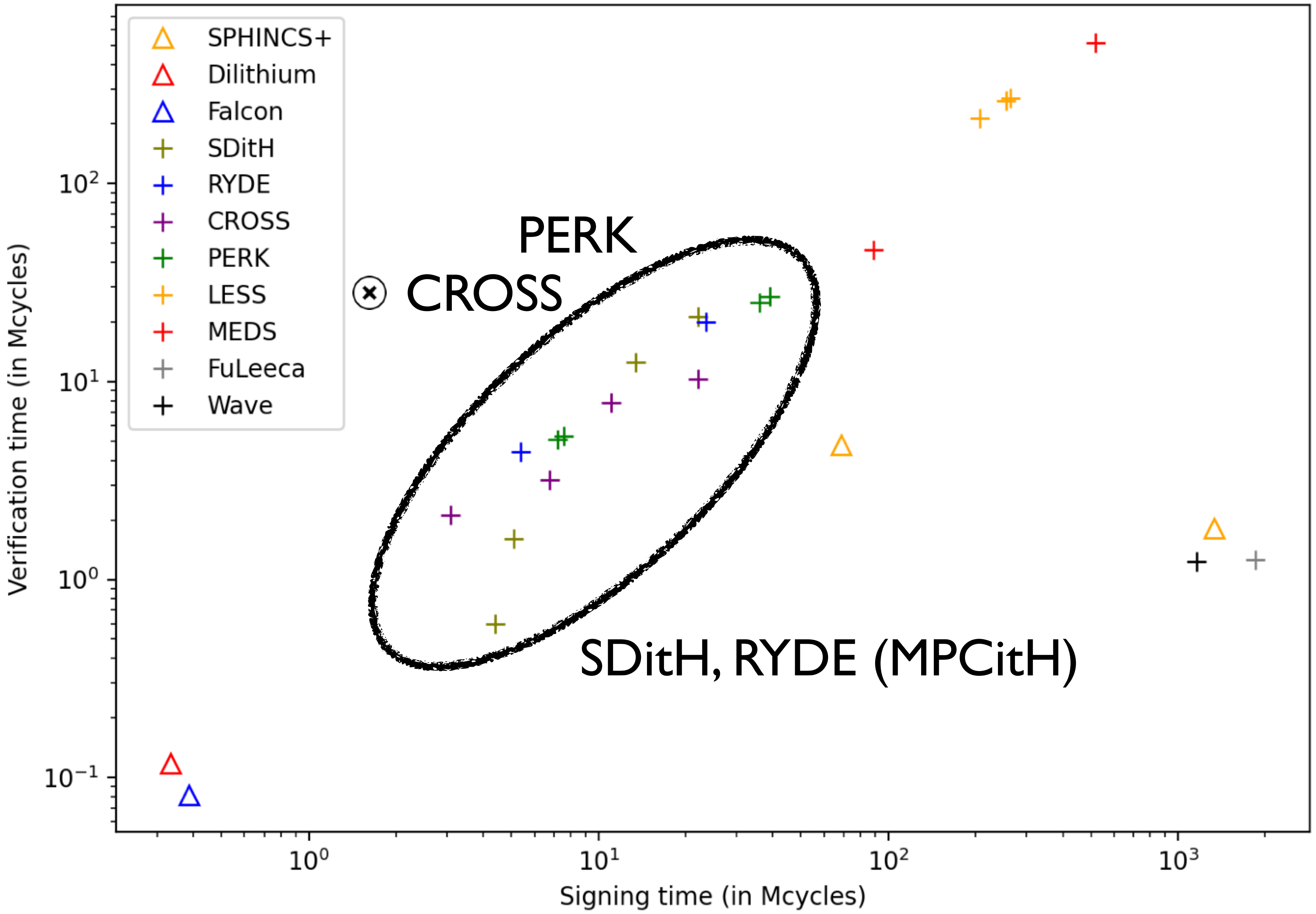

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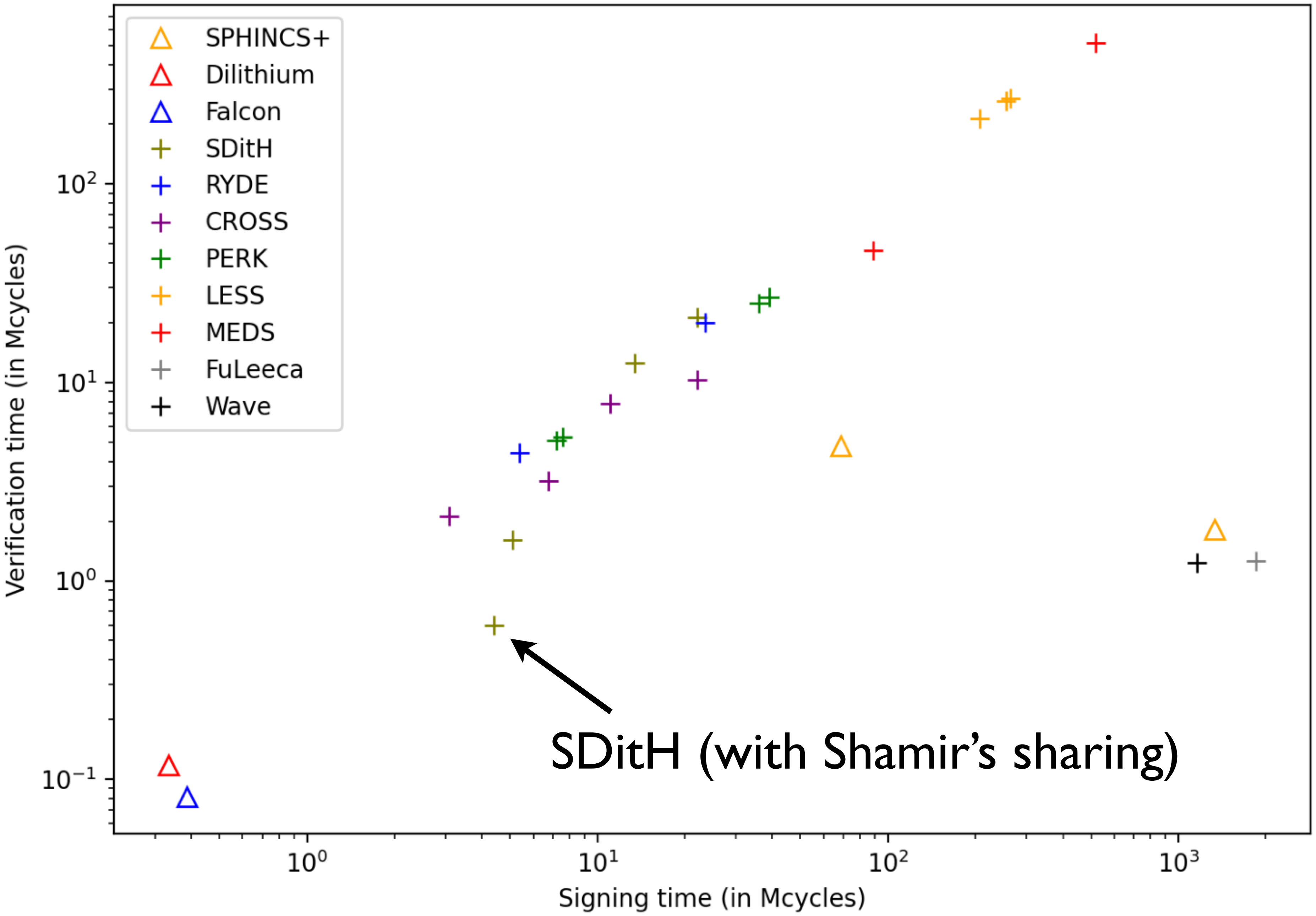

SDitH (with Shamir’s sharing)

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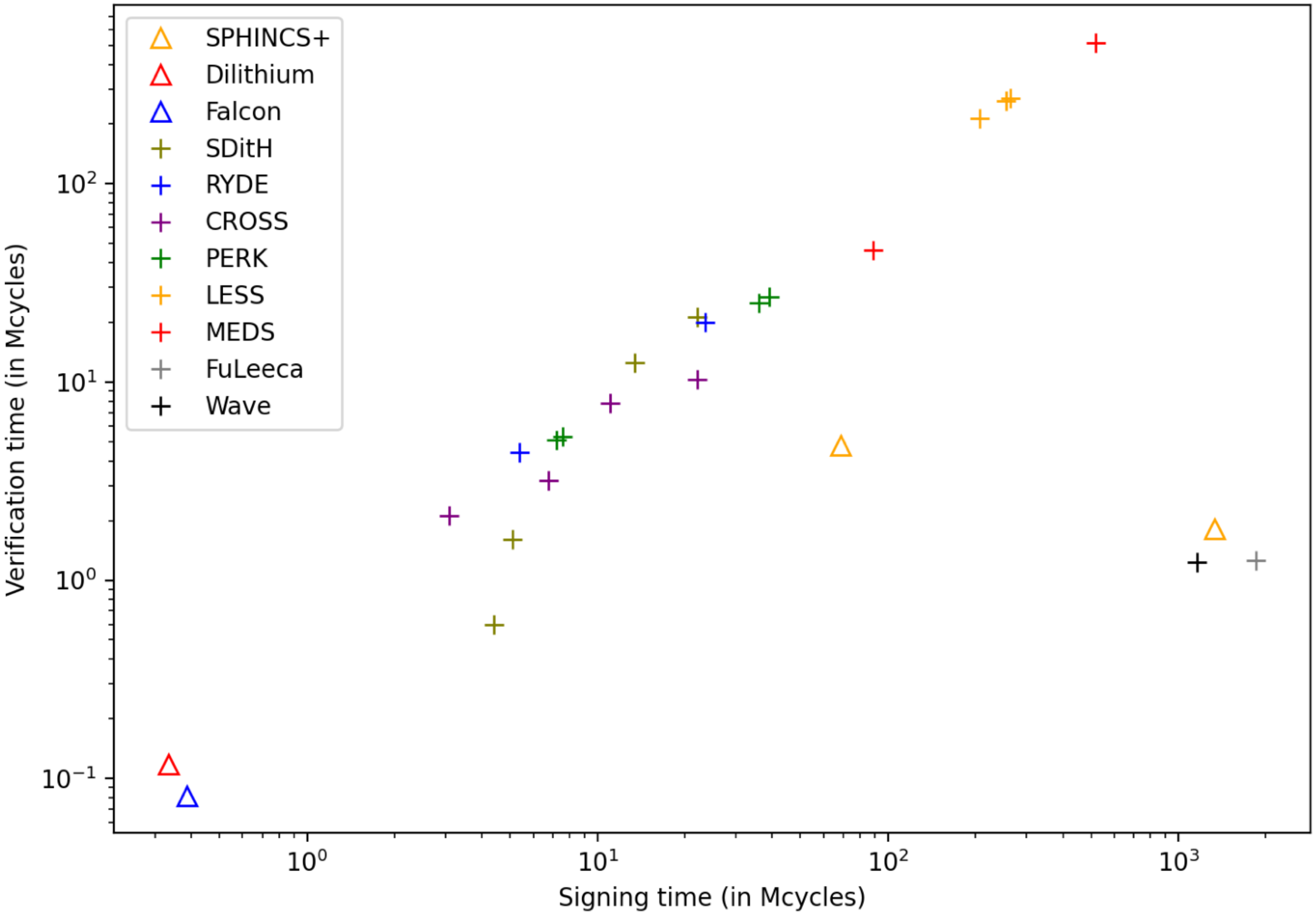

Advantages and limitations

- Limitations
  - Relatively ***slow*** *(few milliseconds)*
    - Greedy use of symmetric cryptography
  - Relatively ***large*** signatures (*5-10 KB for L1*)
  - ***Quadratic*** growth in the security level

- Advantages
  - ***Conservative*** hardness assumption:
    - Old problems, no structure, no trapdoor
  - ***Small*** (public) keys
  - Highly ***parallelizable***
  - ***Good*** public key + signature size
  - Adaptive and ***tunable*** parameters

Conclusion

- MPC-in-the-Head
  - Very versatile and tunable
  - Can be applied on any one-way function
  - A practical tool to build *conservative* signature schemes
    - *No structure* in the security assumption

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  - *Low-threshold-based MPCitH*: new approach, could lead to follow-up works

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- Remark:
  - Can be applied to one-way functions from other research fields: multivariate quadratic problem, MinRank problem, …

Conclusion

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Website: `https://sdith.org/`
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RYDE

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Website: `https://pqc-ryde.org/`
Email: `team@pqc-ryde.org`