C'est très CHIC: A compact password-authenticated key exchange from lattice-based KEM

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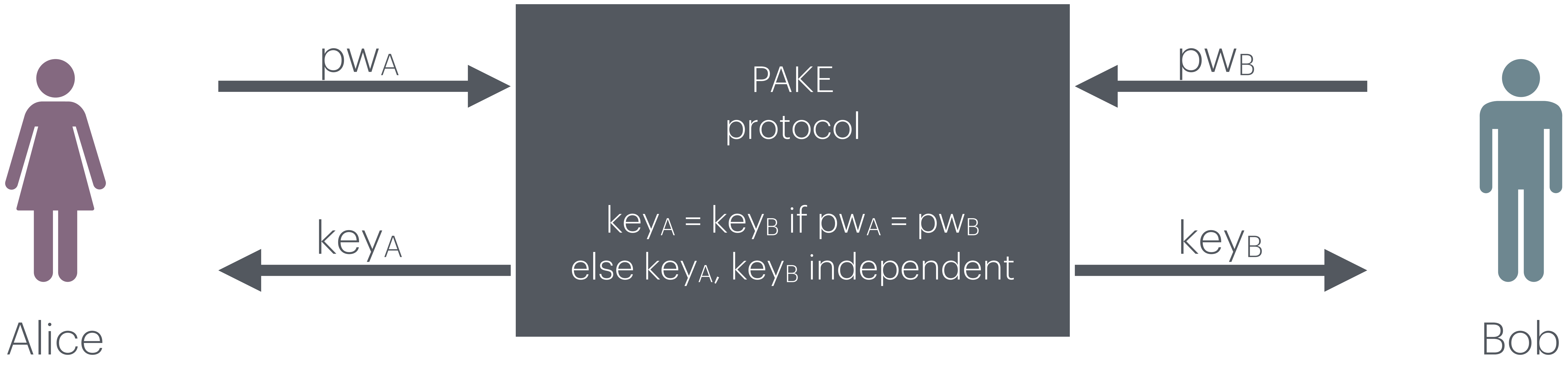
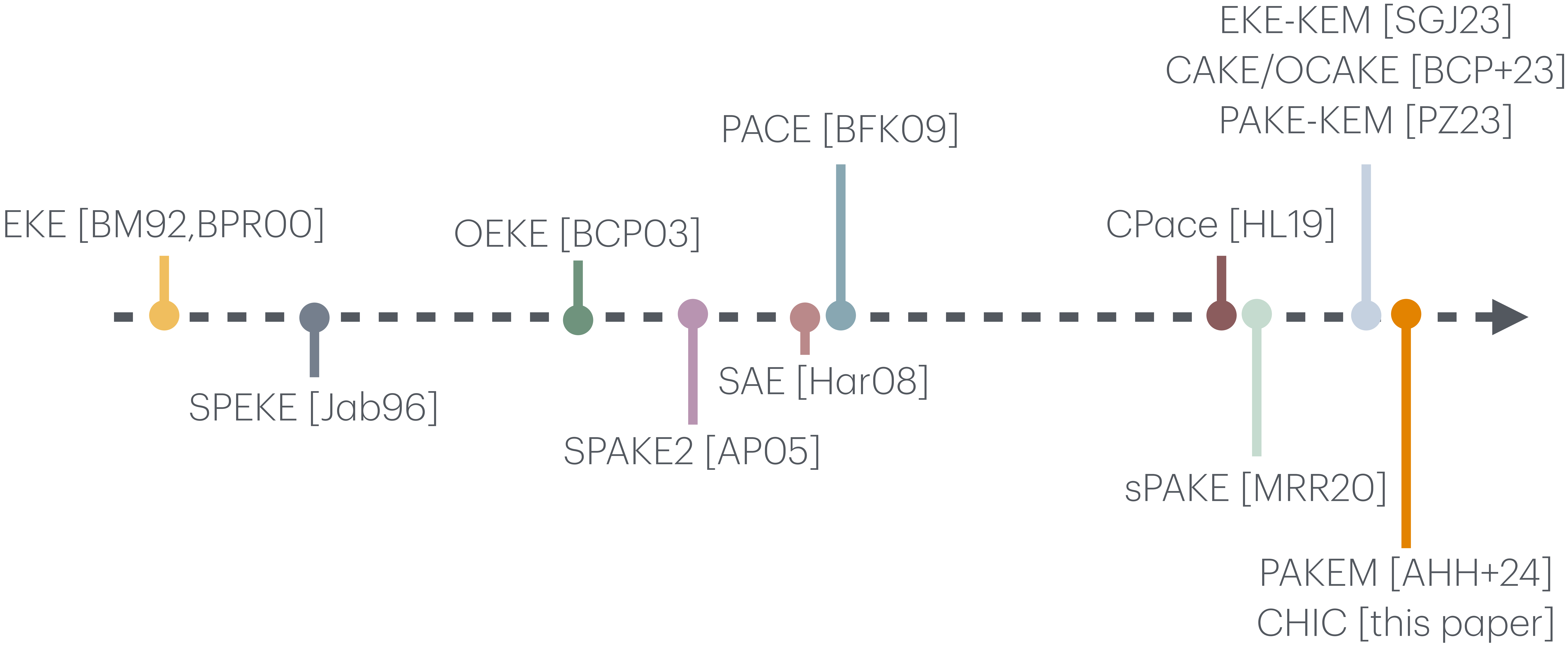
PAKE: Password Authenticated Key Exchange

Protocol



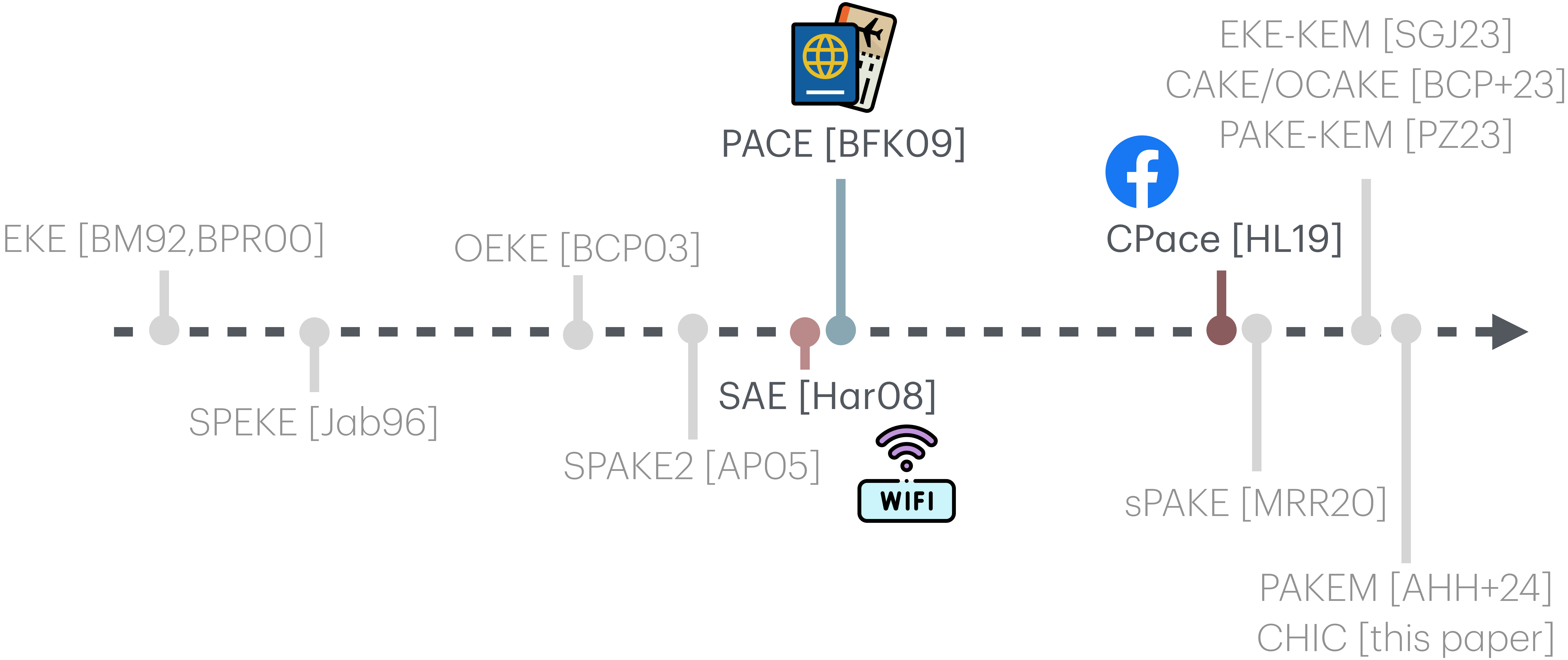
PAKE: Password Authenticated Key Exchange

Timeline



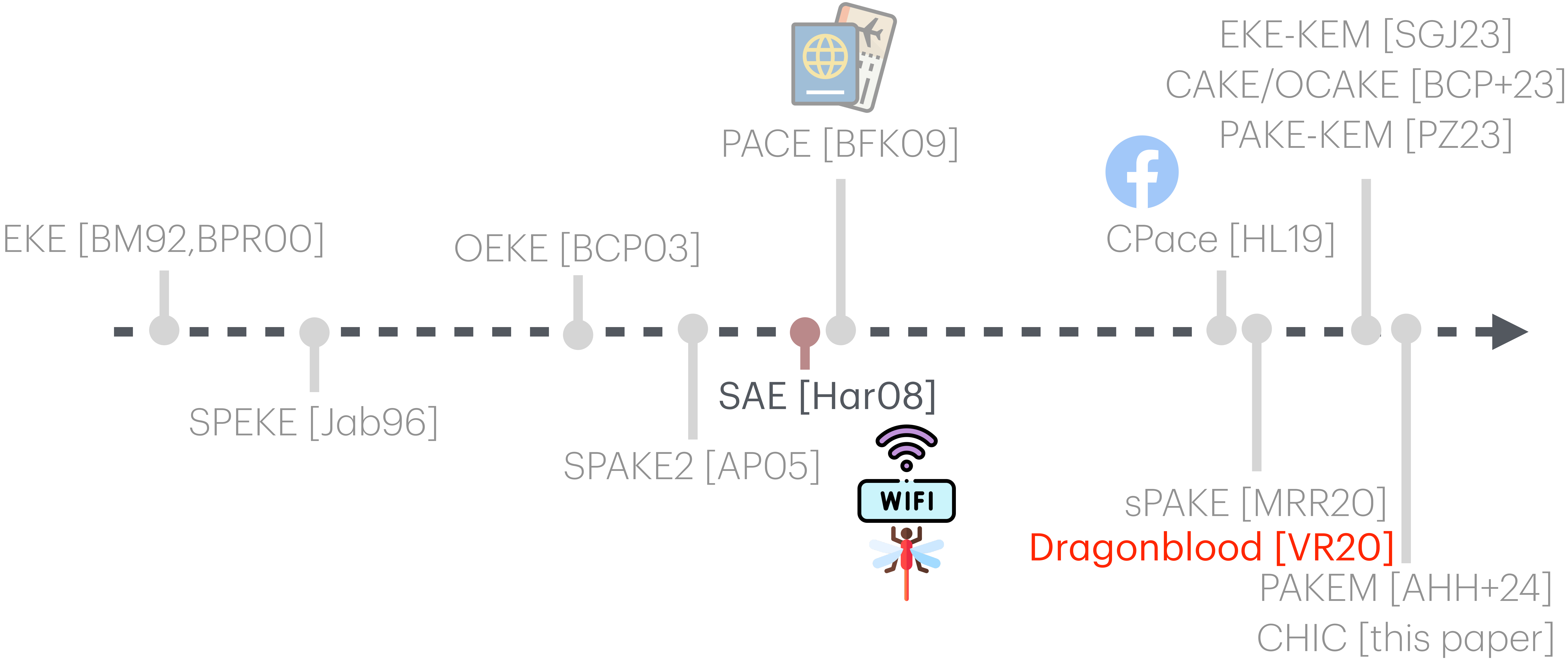
PAKE: Password Authenticated Key Exchange

Real-world adoption of symmetric PAKE protocols



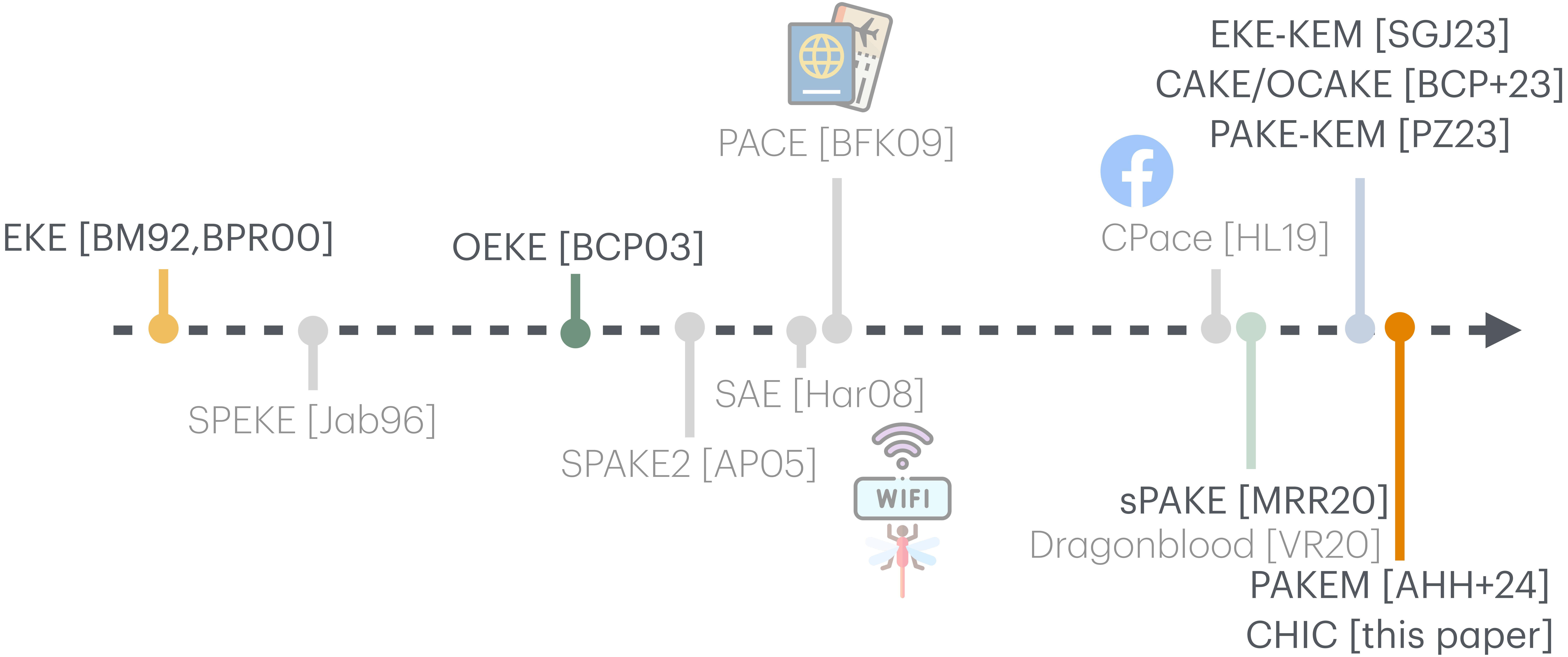
PAKE: Password Authenticated Key Exchange

Real-world attacks

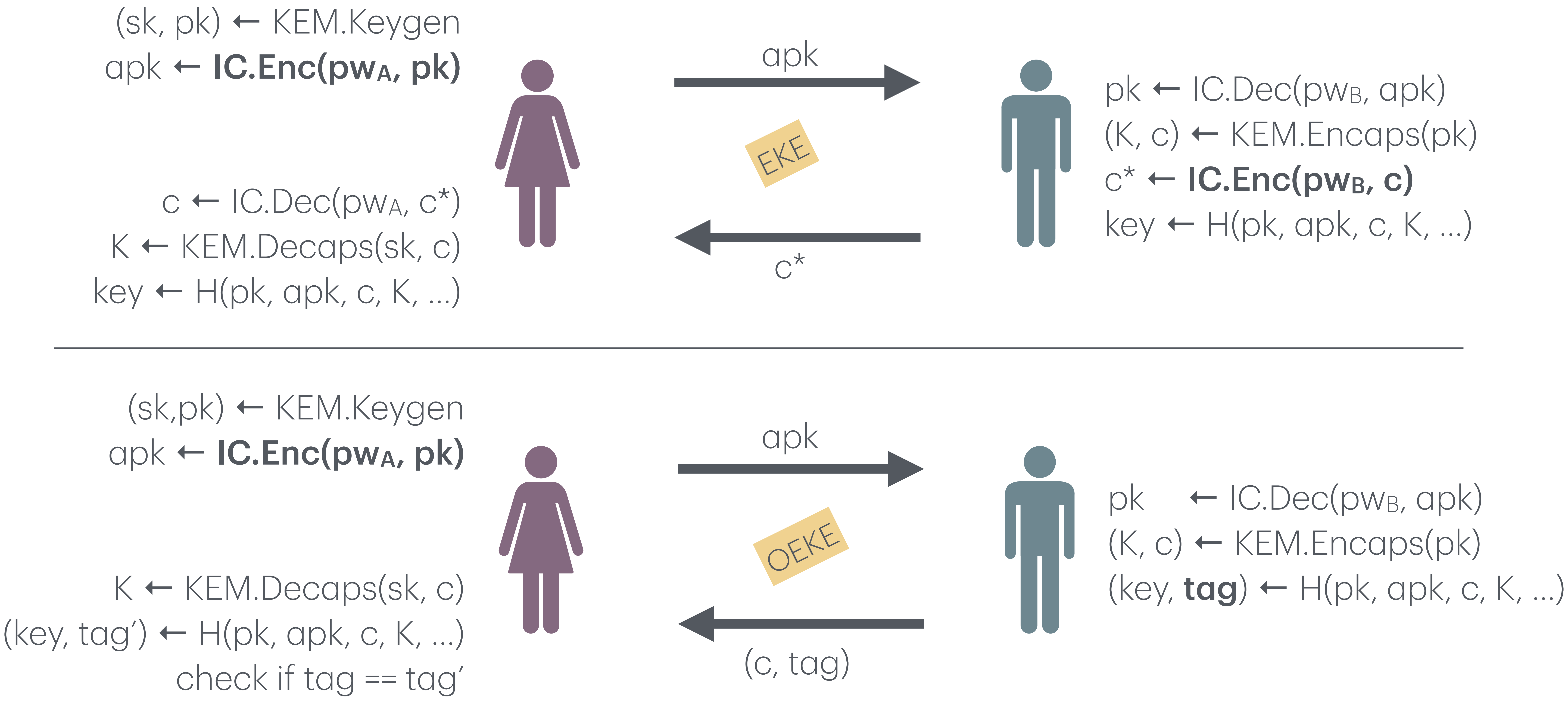


PAKE: Password Authenticated Key Exchange

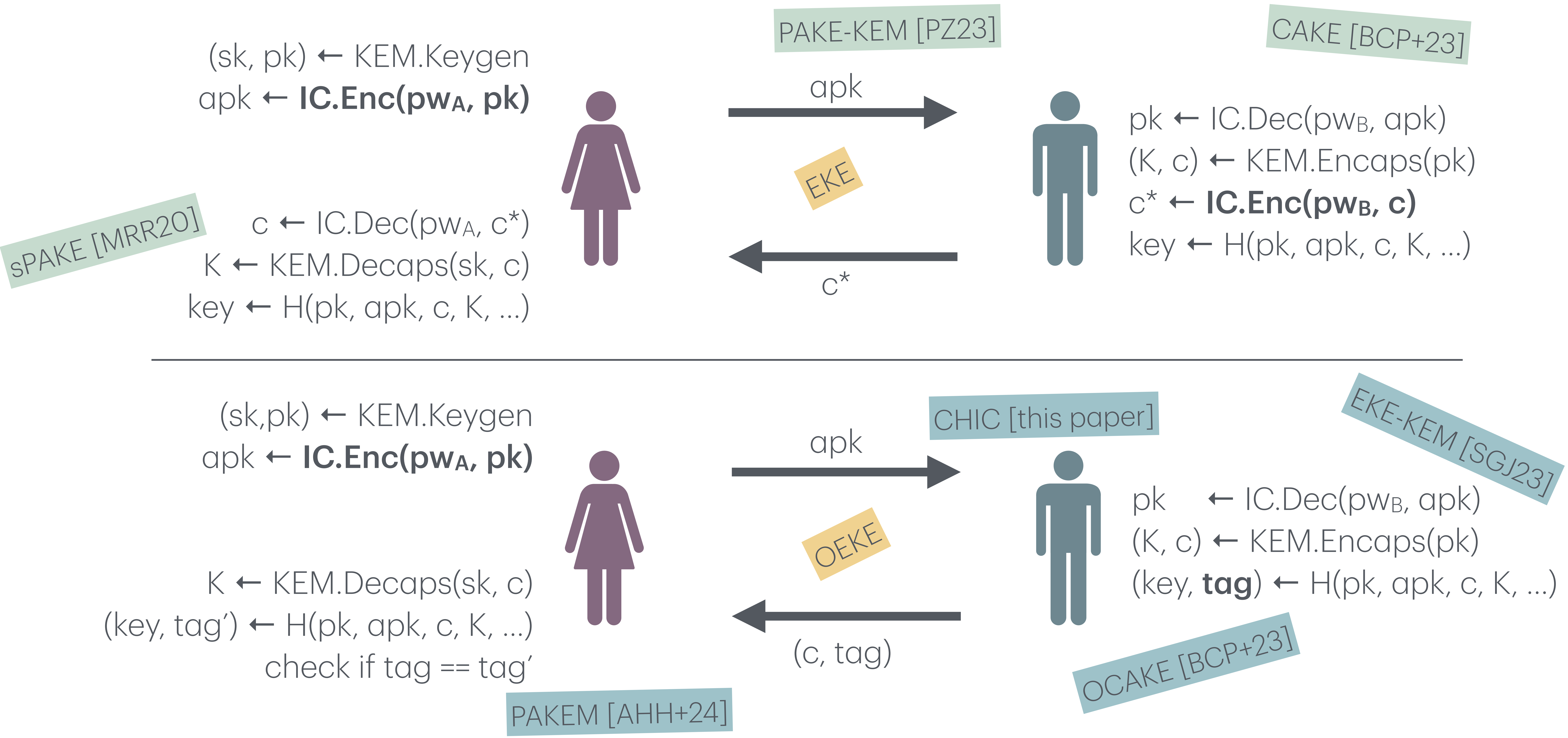
Towards post-quantum security...



EKE and OEKE design patterns



EKE and OEKE design patterns



Challenges in instantiating IC over groups

- Usually, ideal ciphers are instantiated with block ciphers.
- But what if we have an IC over a group?
- The domain of the IC and its instantiation must coincide; otherwise, it becomes trivial for an adversary to mount an offline dictionary attack. The attack proceeds as follows:

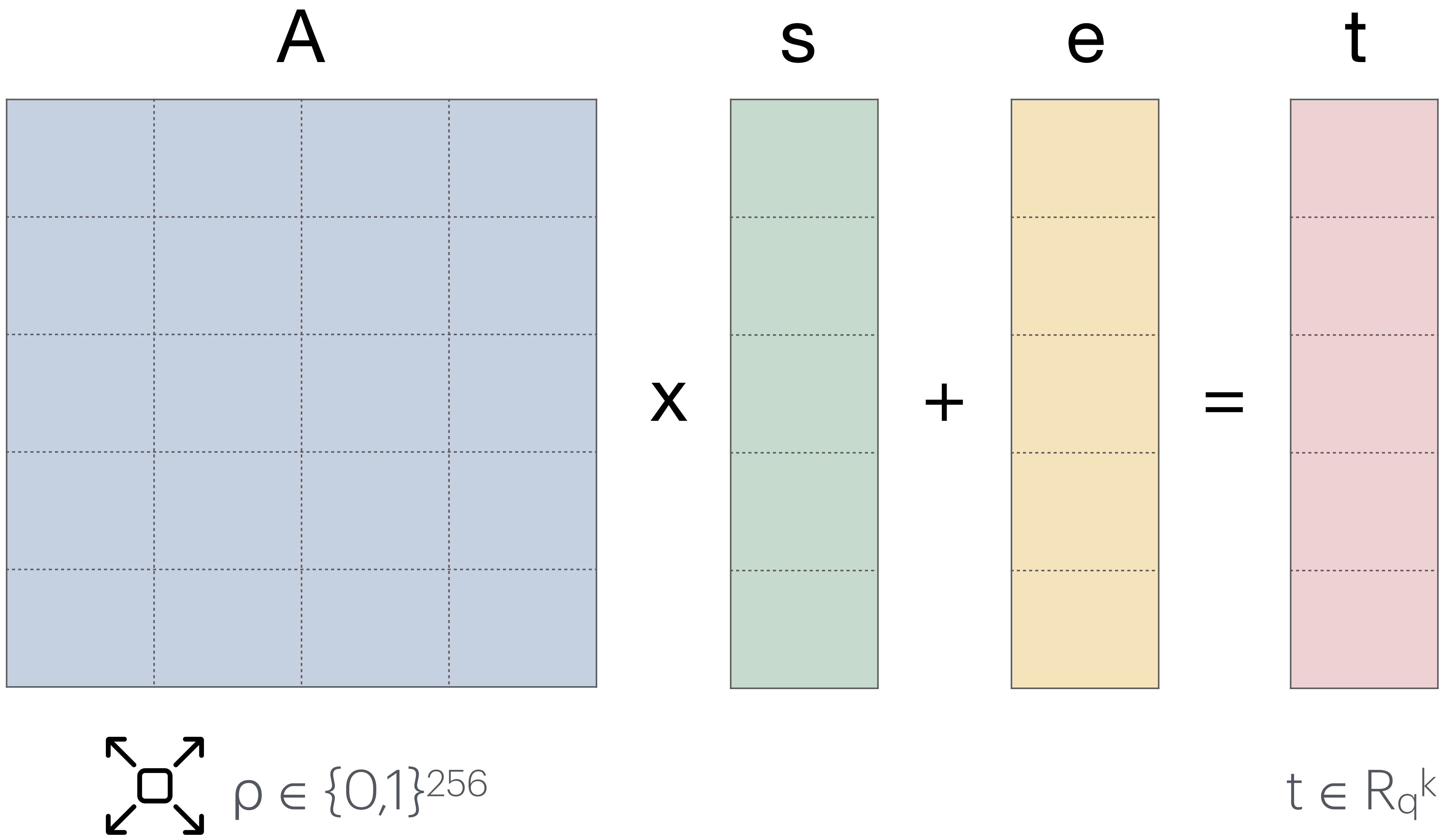
    1. Intercept apk = IC.Enc(pw, pk).

    2. Decrypt apk using a candidate password pw*.

    3. If pk* = IC.Dec(pw*, apk) does not belong to the public key space, then pw* is incorrect.

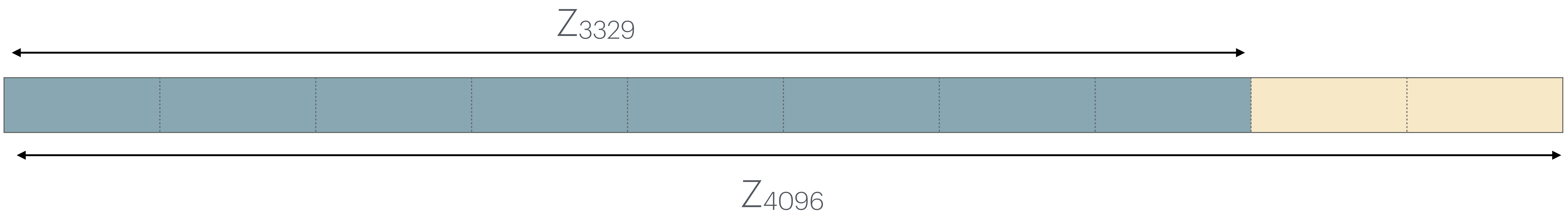
ML-KEM public keys

- Sample $\rho \in \{0,1\}^{256}$
- $A \leftarrow \text{Expand}(\rho) \in R_q^{k*k}$
- $t \leftarrow A * s + e$
- $pk \leftarrow (\rho, t)$

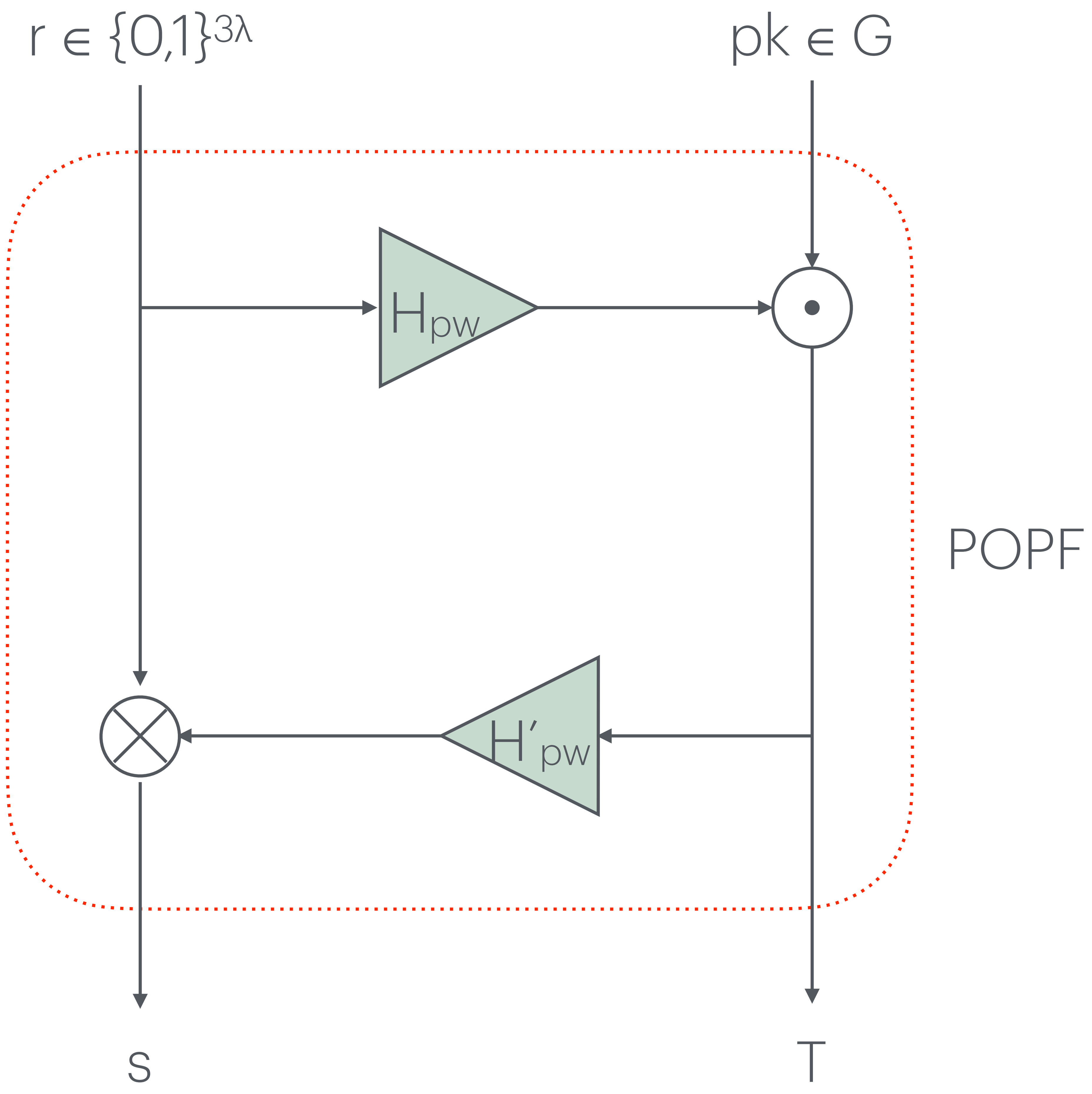


ML-KEM public keys

- R_q is a ring where the elements are polynomials with coefficients in Z_q
- FIPS 203 specifications set $q = 3329$
- $2^{11} < 3329 < 2^{12}$
- To encode a single element in Z_{3329}, we need 12 bits

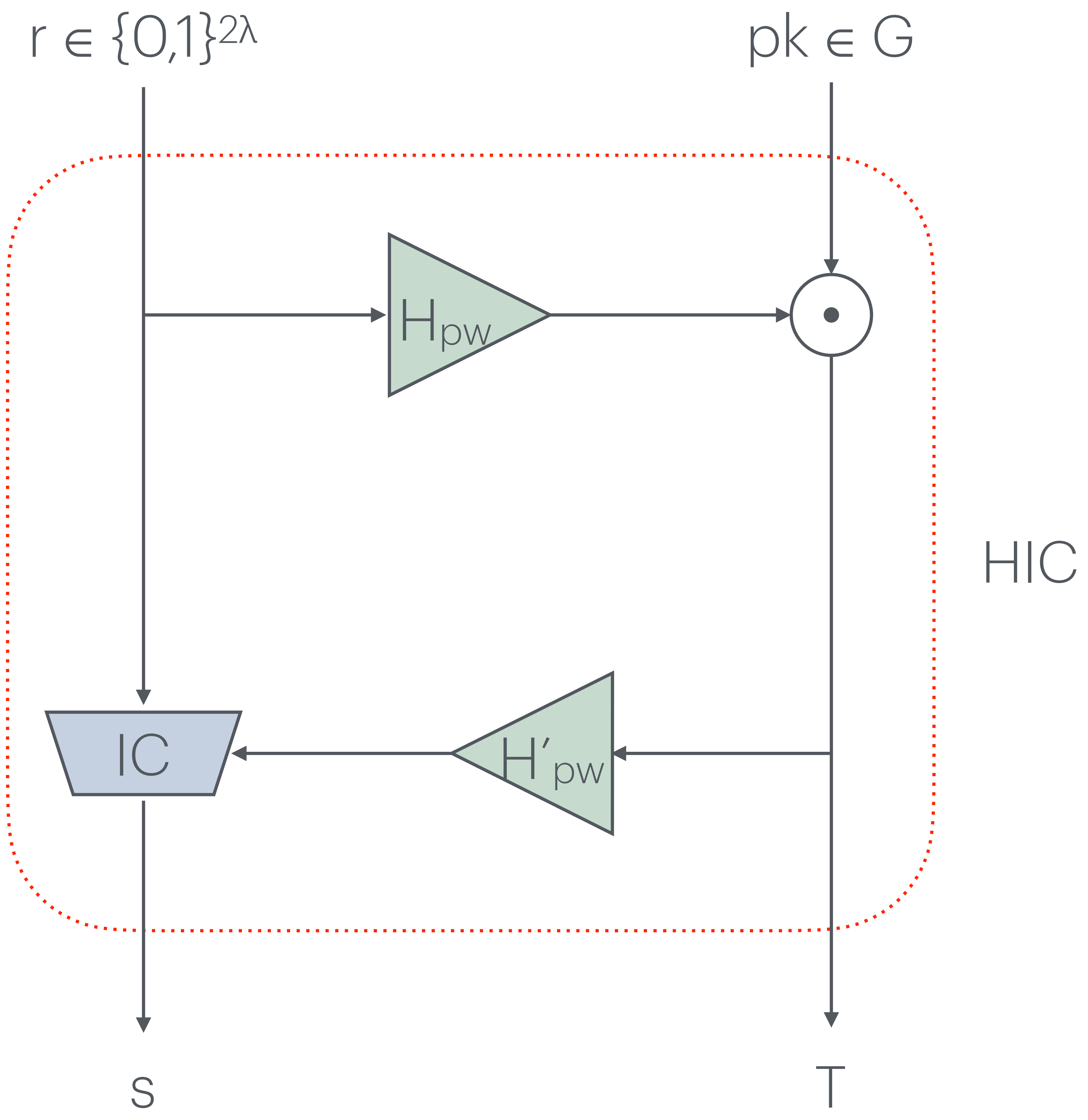


2-round Feistel [MRR20]



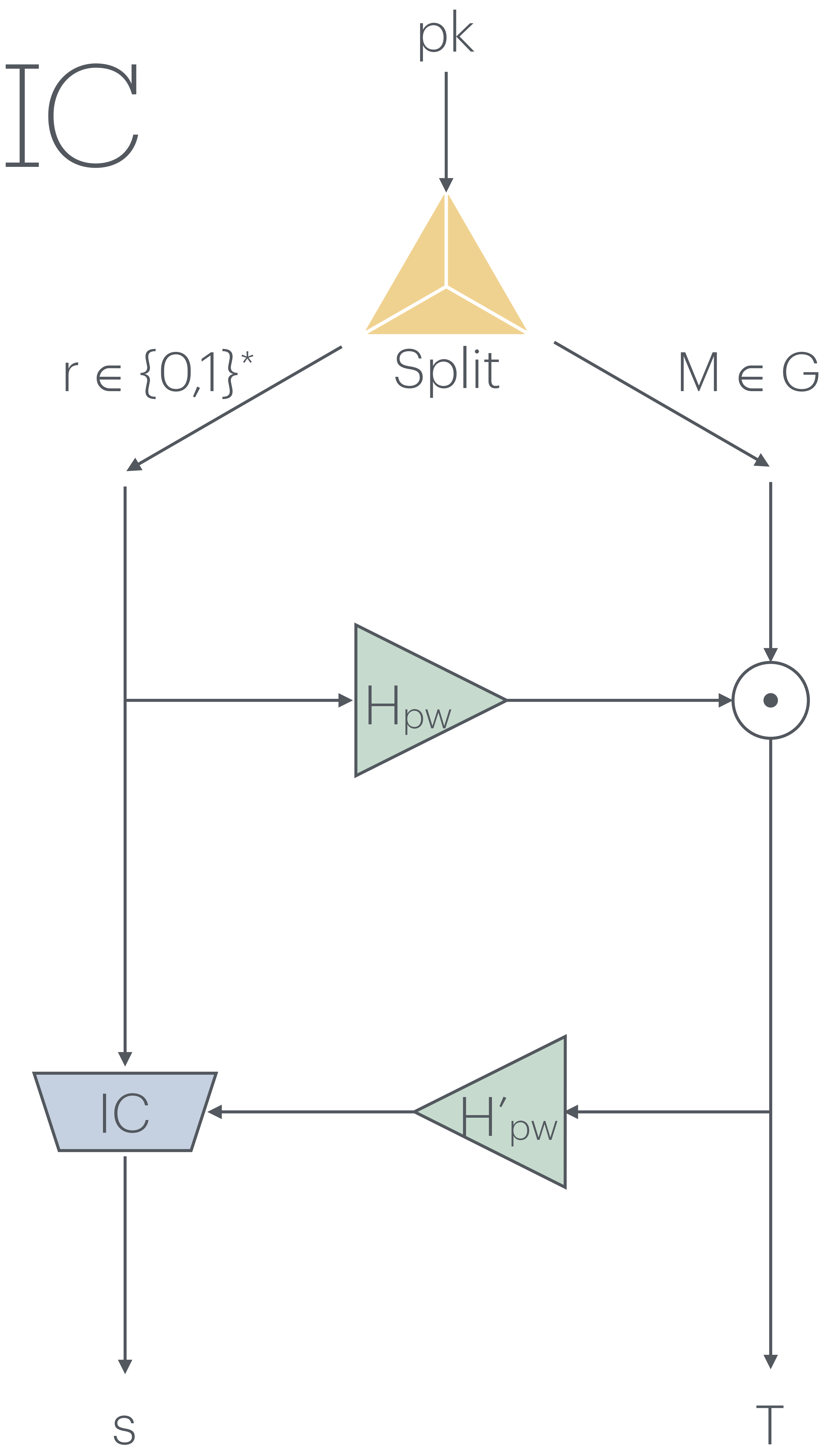
- Password-encrypt with a 2-round Feistel (2F).
- Public key on the right wire; random coins on the left wire.
- Ciphertext expands pk.
- Only one hash onto group needed instead of IC over the group.
- Modular approach with game-based definition POPF. However, 2F permits some malleability and POPF is insufficient for (O)EKE constructions.

A modified 2-round Feistel [SGJ23]



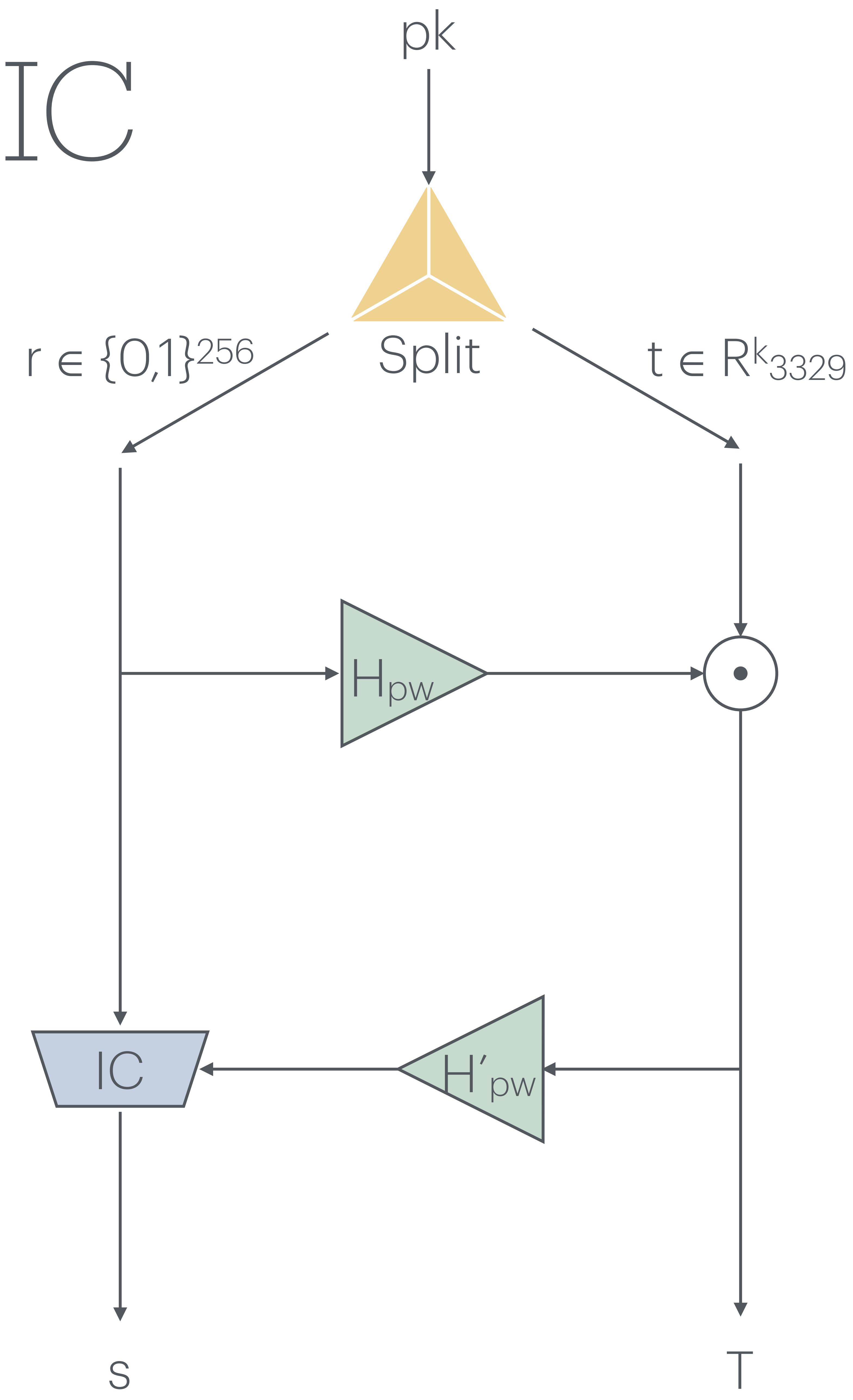
- Replace XOR operation with IC to avoid malleability
- IC over bit strings — easy to instantiate
- Modular approach with UC definition: Half-Ideal Cipher (HIC)
- Why "half-ideal"? The s-part is random.

Compact HIC



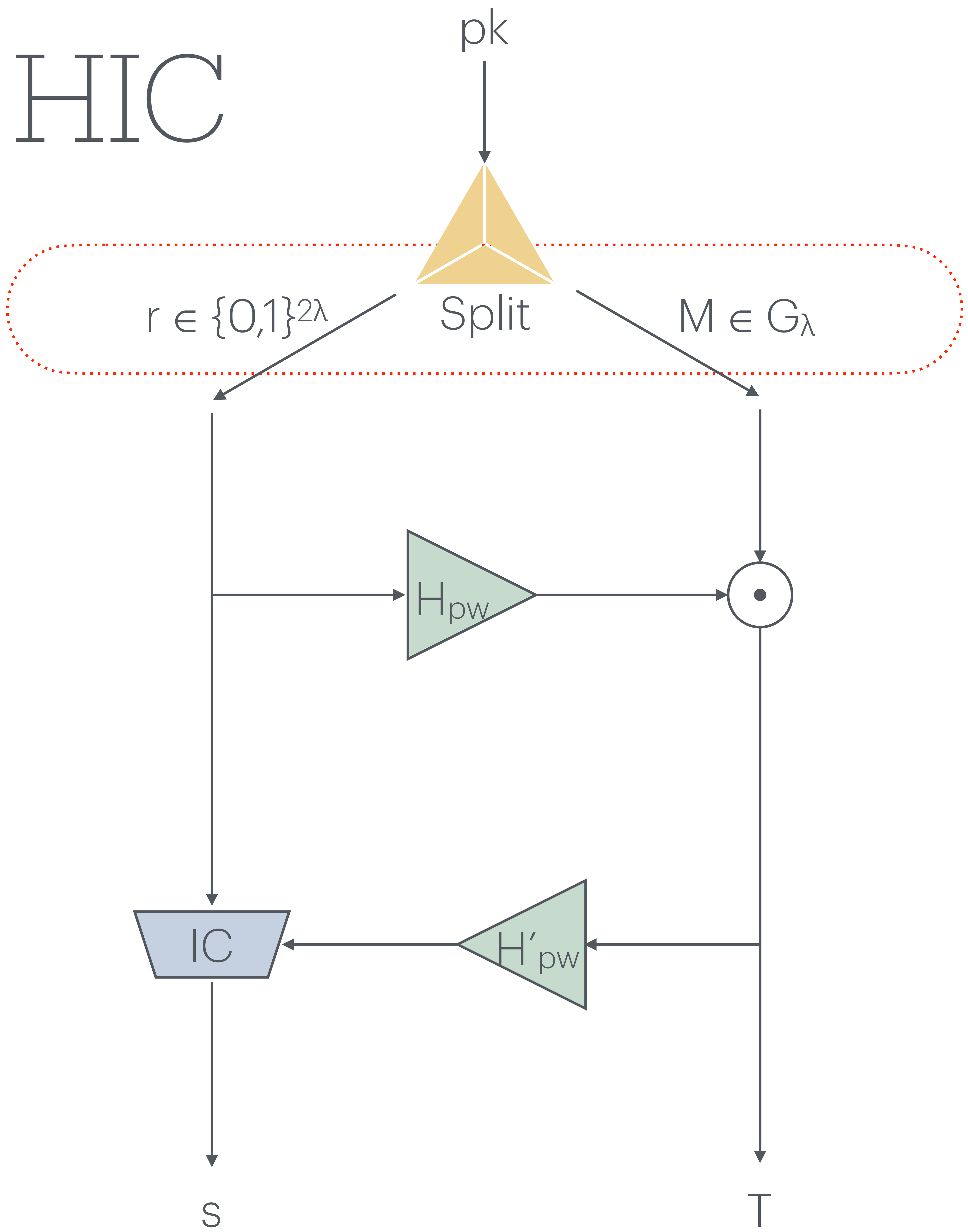
- Can we split the public and feed both wires of the 2F?

Compact HIC



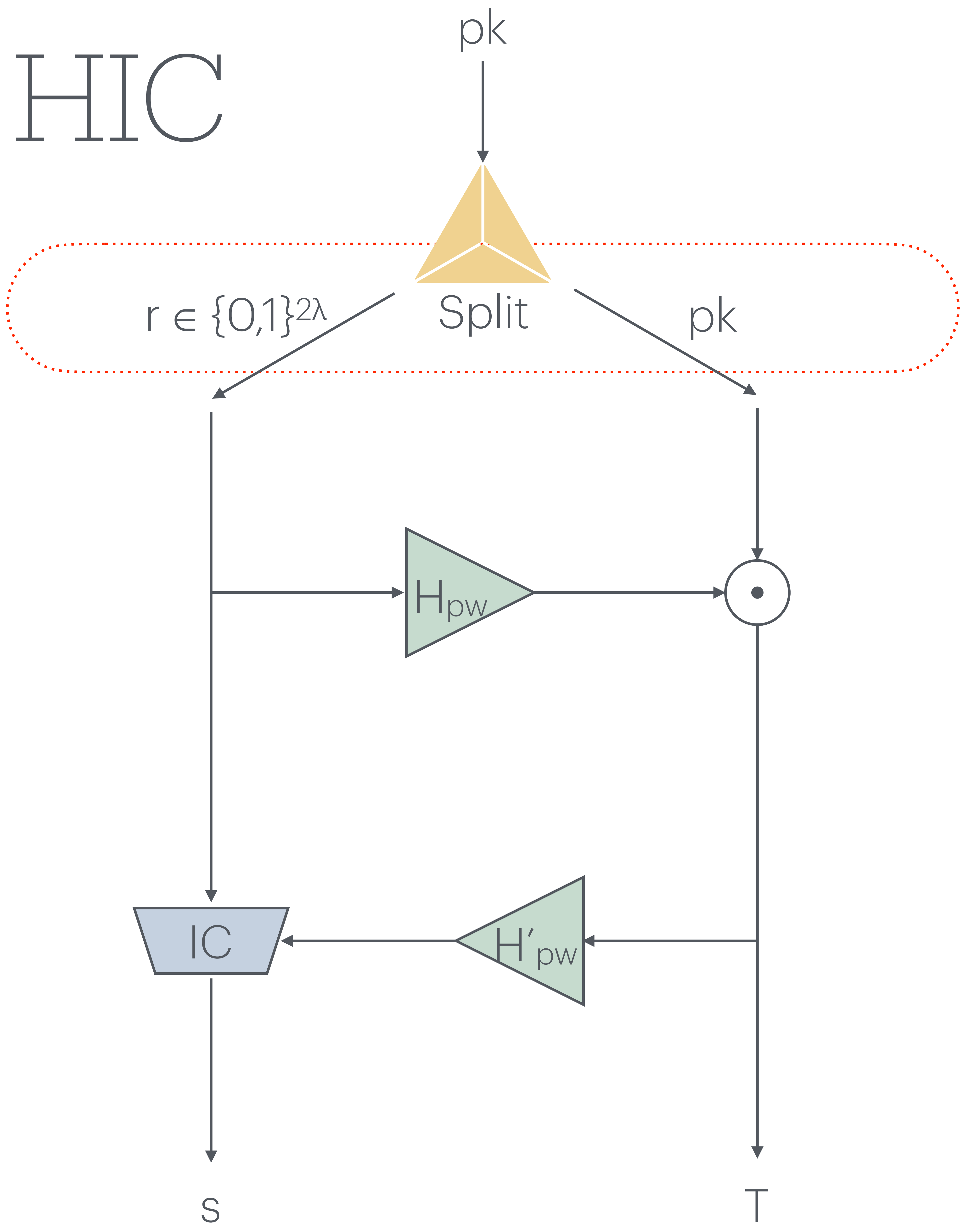
- In particular, we are interested in the trivial breakdown of ML-KEM public keys.
- Compact: avoids ciphertext expansion!
- Effectively, de-randomizes HIC.

Compact HIC



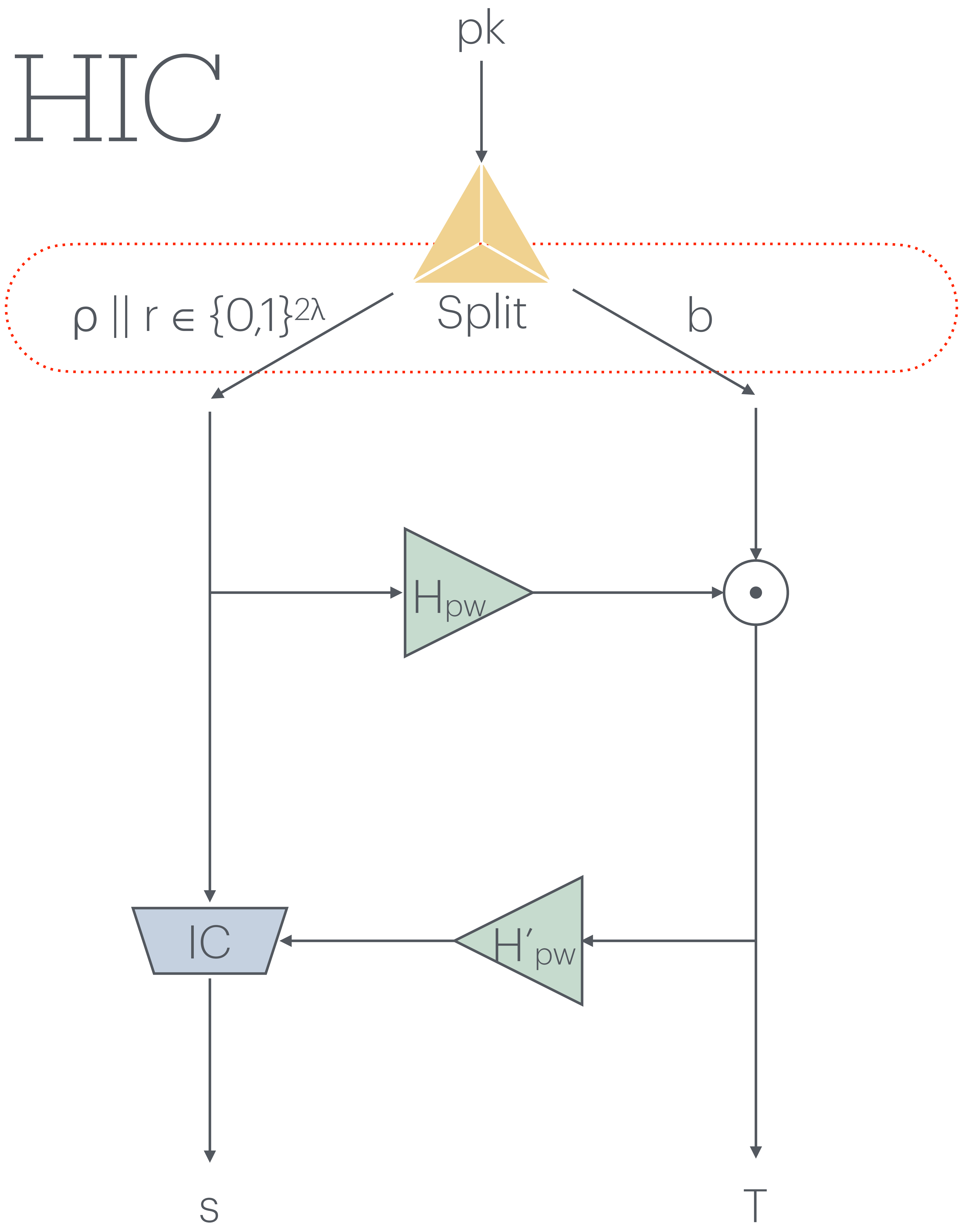
- In general, (O)EKE constructions require public keys to be uniformly distributed.
- HIC requires uniform r.
- We can combine both requirements into a single definition w.r.t. function Split.
- Experiment UNI-PK:
  $(\_, pk_0) \leftarrow$ Keygen
  $(r_0, M_0) \leftarrow Split(pk_0)$
  $(r_1, M_1) \leftarrow \{0,1\}^{2\lambda} \times G_\lambda$
  $b \leftarrow \{0,1\}$
  $b' \leftarrow A(r_b, M_b)$
  return $b == b'$

Compact HIC



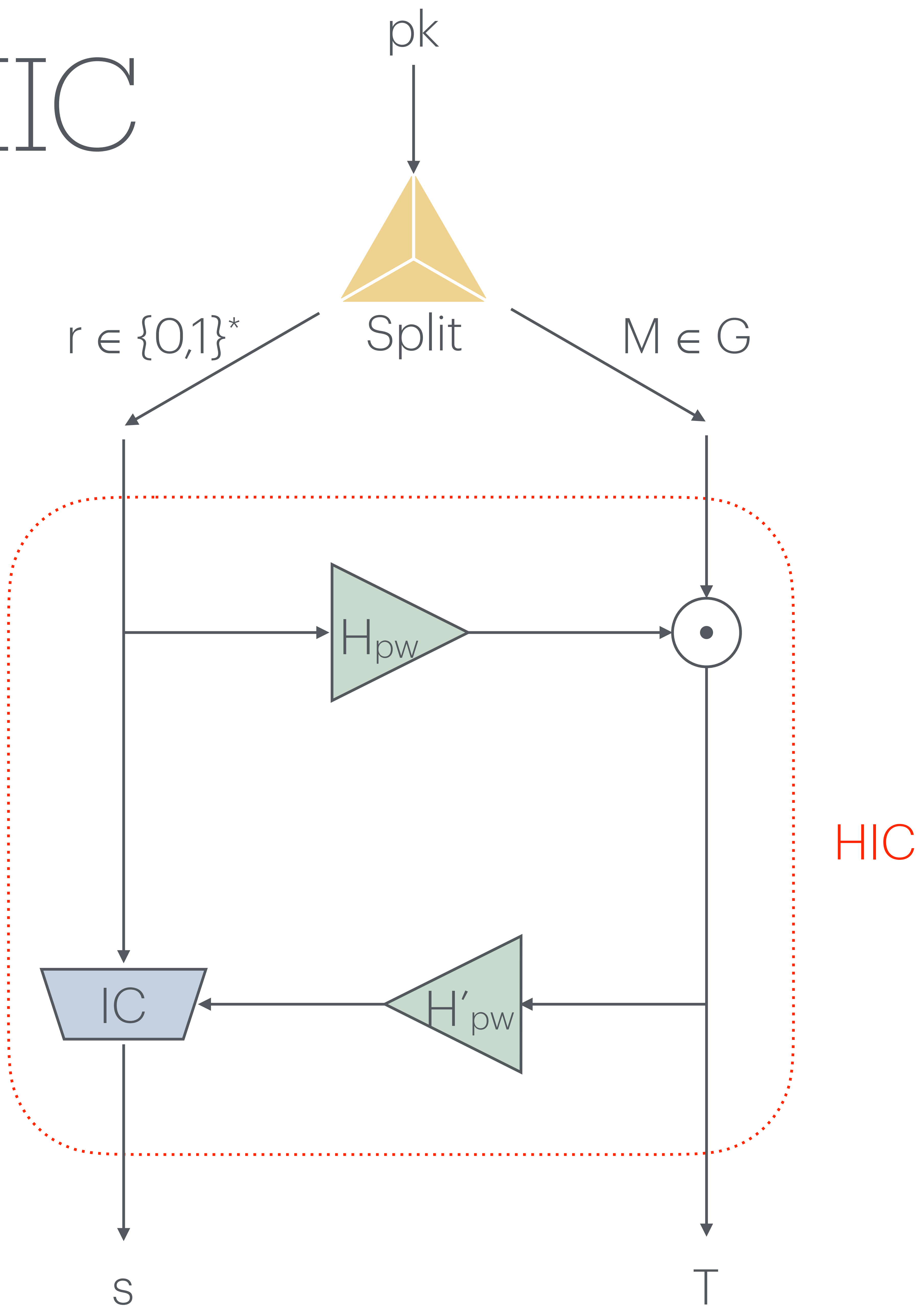
- The randomized identity Split recovers standard public key uniformity (also know as *fuzziness* [BCP+23]).
- Leads back to the HIC construction [SGJ23].

Compact HIC



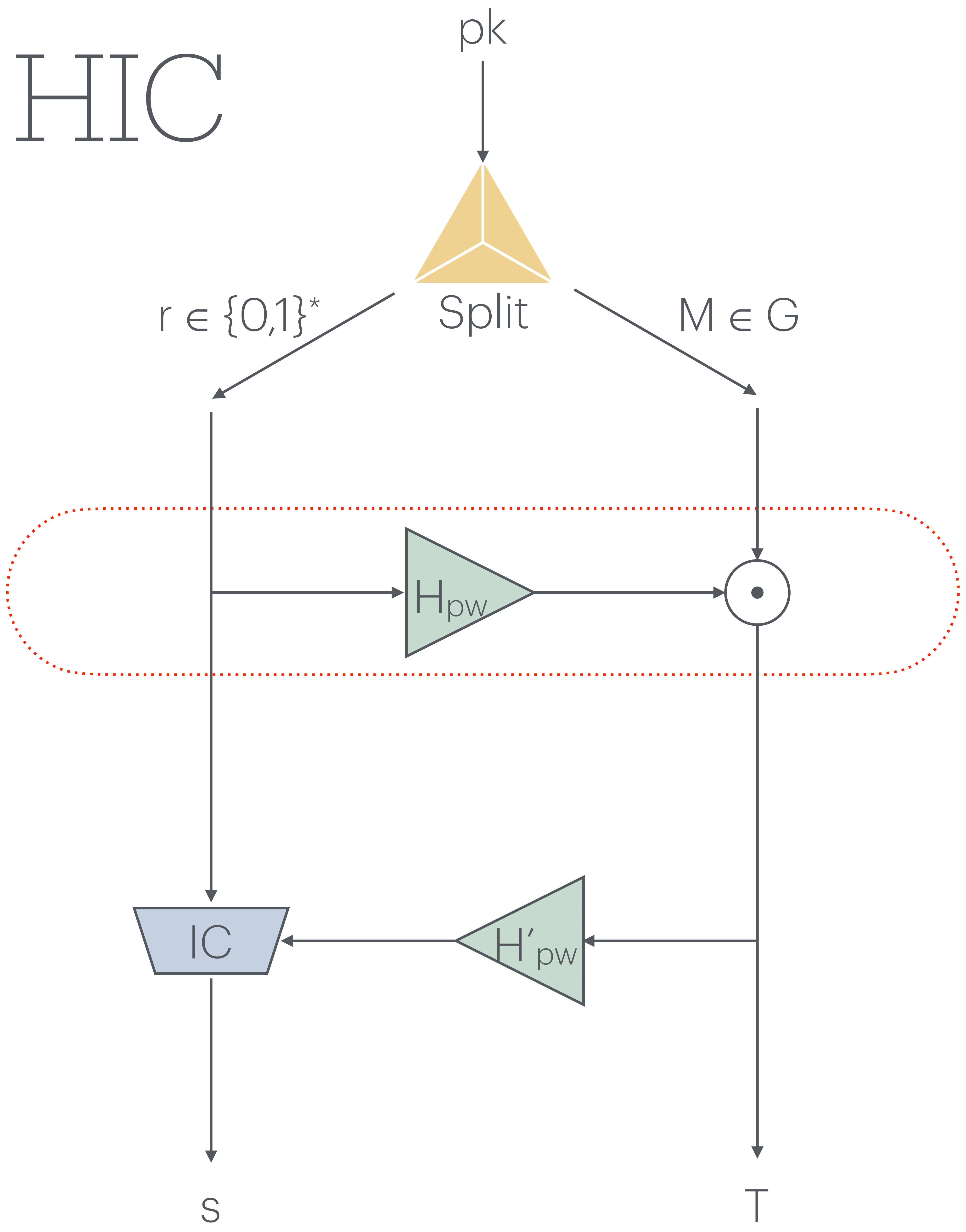
- FrodoKEM determines seed $\rho \in \{0,1\}^{128}$.
- A Randomized Split can easily extend FrodoKEM keys by appending random bits to ρ, ensuring it reaches the required length.
- This approach requires no modifications to FrodoKEM.

Compact HIC



- F_{HIC} features honest interfaces accessible by the environment Z, but no control over randomness r is provided.
- Unfortunately, we lose the modular HIC abstraction.
- Solution: Direct proof.

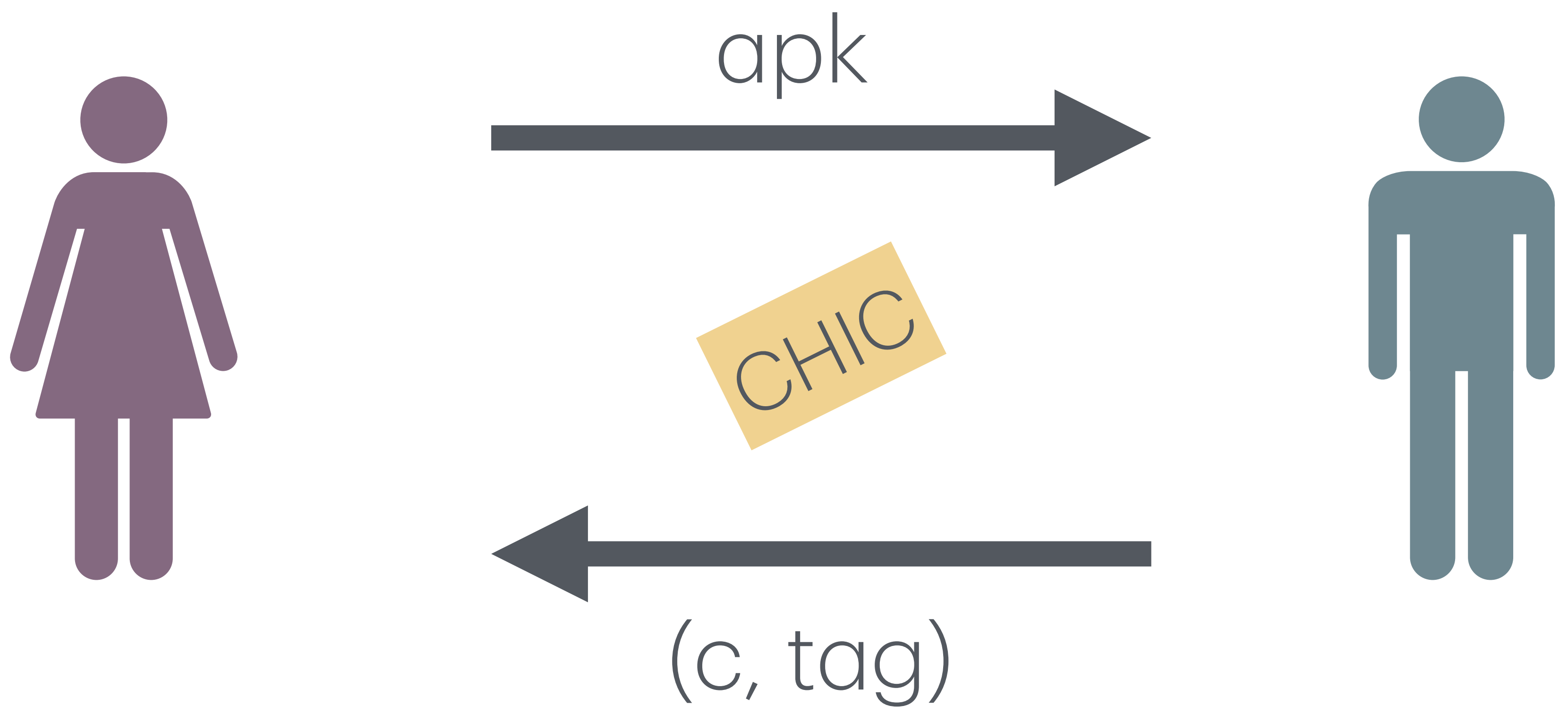
Compact HIC



- How to instantiate hash-onto-group H?
  - ★ FrodoKEM makes it easy because it uses power-of-two modulus. Simply use an eXtendable Output Function (XOF).
  - ★ For ML-KEM we reuse the rejection sampling procedure used to expand ρ into a matrix A of polynomial coefficient modulus 3329.

The CHIC protocol

(sk, pk) ← KEM.Keygen
(r, M) ← Split(pk)
(s, T) ← $m2F_{pw}$(r, M)
apk ← (s, T)



(s, T) ← apk
(r, M) ← $m2F^{-1}_{pw}$(s, T)
pk ← $Split^{-1}$(r, M)
(K, c) ← KEM.Encaps(pk)
(key, tag) ← H(pk, apk, c, K, ...)

K ← KEM.Decaps(sk, c)
(key, tag') ← H(pk, apk, c, K, ...)
check if tag == tag'

Requirements from KEM

CHIC UC-realizes F_{PAKE} [CHK05] in the RO and IC model provided that KEM has the following properties:

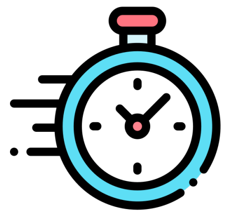
- **One-wayness of ciphertexts**: OW-CPA, but OW-PCA leads to tighter reduction.
- **Anonymity of ciphertexts**: ANO-PCA. Actively-secure KEM is necessary.
- **Uniformity of public keys**: UNI-PK.

Benchmarks

Experimental results in microseconds. Comparison of execution times of CHIC participants (two initiator stages and responder single stage) with respect to key exchange using only a CPA or CCA Kyber KEM.

	CPA KEM			CCA KEM			CHIC		
	Keygen	Enc	Dec	Keygen	Enc	Dec	Start	Resp	End
Kyber512	25	29	9	45	49	12	70	74	14
Kyber768	28	36	41	49	59	65	75	85	93
Kyber1024	36	56	53	61	87	83	89	123	117

Final remarks / future work

On timing-attacks 

- The rejection-sampling of ML-KEM is not constant-time, meaning Keygen is not constant-time.

- Timing attacks potentially affect any ML-KEM to PAKE compiler, regardless of how we instantiate the hash onto group H.

- FIPS 203 allows to limit the number of iterations of SampleNTT to 280, with a probability of failure of 2^{-261}.

- We are exploring how to implement a constant-time Keygen algorithm for ML-KEM and use it to instantiate the hash-to-group operation.

Final remarks / future work

On IC-256-256

- AES has only been standardized only with a 128-bit block size. However, our proofs requires avoiding collisions across different block cipher keys. Therefore, we need to instantiate the IC with a block cipher with 256-bit size blocks and 256-bit length keys.

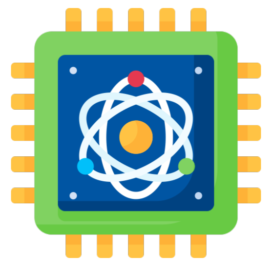
- To meet this requirement, we used Rijndael-256-256. If AES must be used, domain extenders can provide a solution [CDMS10].

- NIST is currently considering standardizing Rijndael-256-256 [edu.lu/pdmd3].

NIST

Final remarks / future work

On quantum adversaries



- The current proof is in the RO and IC model.
- However, a *harvest-now-decrypt-later* attack is ineffective against CHIC because the ciphertexts are post-quantum secure.

Thank you for your attention