# On the Final Round of the NIST Lightweight Cryptography Standardization

Meltem Sönmez Turan
NIST Lightweight Cryptography Team

Security and Implementation of Lightweight Cryptography (SILC)
October 16, 2021 – Zagreb, Croatia

NIST National Institute of Standards and Technology U.S. Department of Commerce

ITL INFORMATION TECHNOLOGY LABORATORY

Background

Evaluation of the Second-round Candidates

Final Round

Next Steps

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# Background

## CONSTRAINED DEVICES

e.g., RFID tags, sensors, IoT devices

## NEW APPLICATIONS

e.g., home automation, healthcare, smart city

## PRIVATE INFORMATION

e.g., Location, health data

## LACK OF CRYPTOGRAPHY STANDARDS

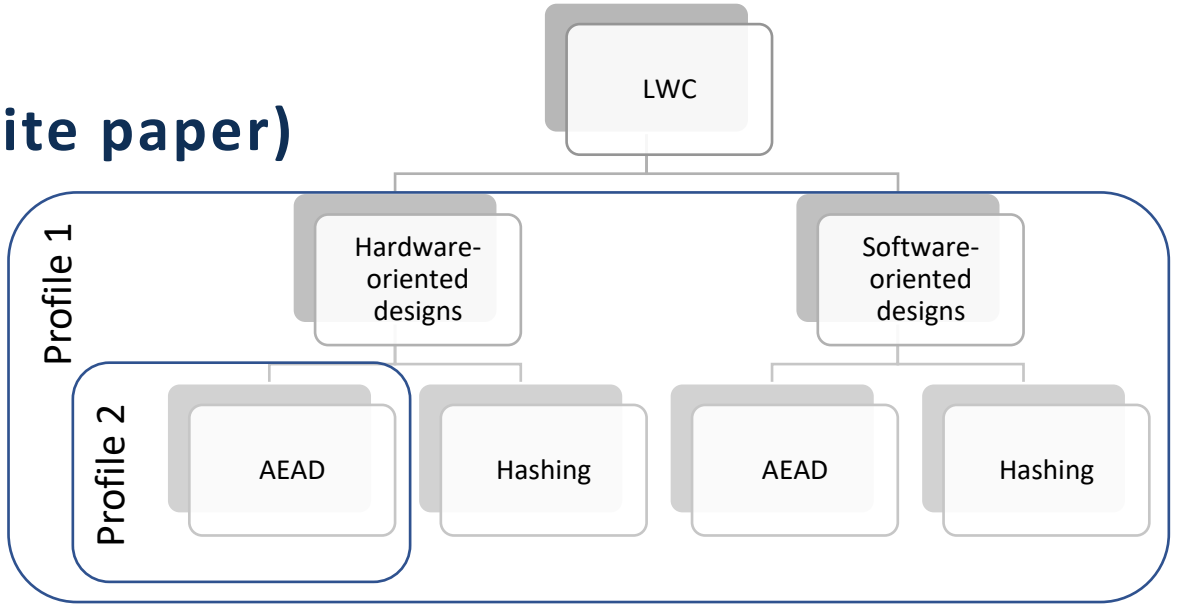
NIST crypto standards are optimized for general-purpose computers

# Early Feedback from Academia & Industry

- Two Lightweight Cryptography Workshops at NIST in July 2015 and October 2016.
- In March 2017, NISTIR 8114 Report on Lightweight Cryptography is published.

**Profiles for Lightweight Cryptography (white paper)**

- Profile I Authenticated Encryption with associated data (AEAD) and hashing for constrained software and hardware environments
- Profile II AEAD for constrained hardware environments



# Example Applications

**Anti-counterfeiting**

- Most RAIN RFID chips have small amount of user memory (typically < 64 bits, some special chips have <2k bits).
- Hardware-oriented primitives with small area

**Healthcare**

- Measuring blood pressure, blood sugar, pulse etc.
- Hardware-oriented primitives by small energy requirements

**Vehicle communication**

- In-vehicle, vehicle-to-vehicle and road-to-vehicle communication, driving assistance systems
- Low latency, high throughput

**Smart Home**

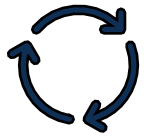
- Electrical home appliances with low-end CPUs
- Software-oriented primitives that consume less CPU time and smaller ROM requirements

## RESEARCH DEVELOPMENTS

e.g., permutation-based designs, simpler key schedules, inherent side channel resistance

## GOAL

Develop new guidelines, recommendations and standards optimized for constrained devices



## PROCESS

Public competition-like process with multiple rounds like AES, SHA3 and PQC standardization.

## SCOPE

**Single profile** Authenticated Encryption and (optional) hashing for constrained software and hardware environments

In August 2018, NIST published the ‘Submission Requirements and Evaluation Criteria for the Lightweight Cryptography Standardization Process’.

**Submission deadline**: February 2019

# Security Requirements

## AEAD

- Confidentiality of the plaintexts (under adaptive chosen-plaintext attacks) + Integrity of the ciphertexts (under adaptive forgery attempts)
- At least 128-bit key
- At least $2^{112}$ computation for attacks (nonce is assumed to be unique under the same key)
- Family of (at most 10) algorithms
  - One **primary member** with key ≥ 128 bits, nonce ≥ 96 bits and tag ≥ 64 bits
  - Limits on the input sizes for the primary member at least $2^{50}$-1 bytes

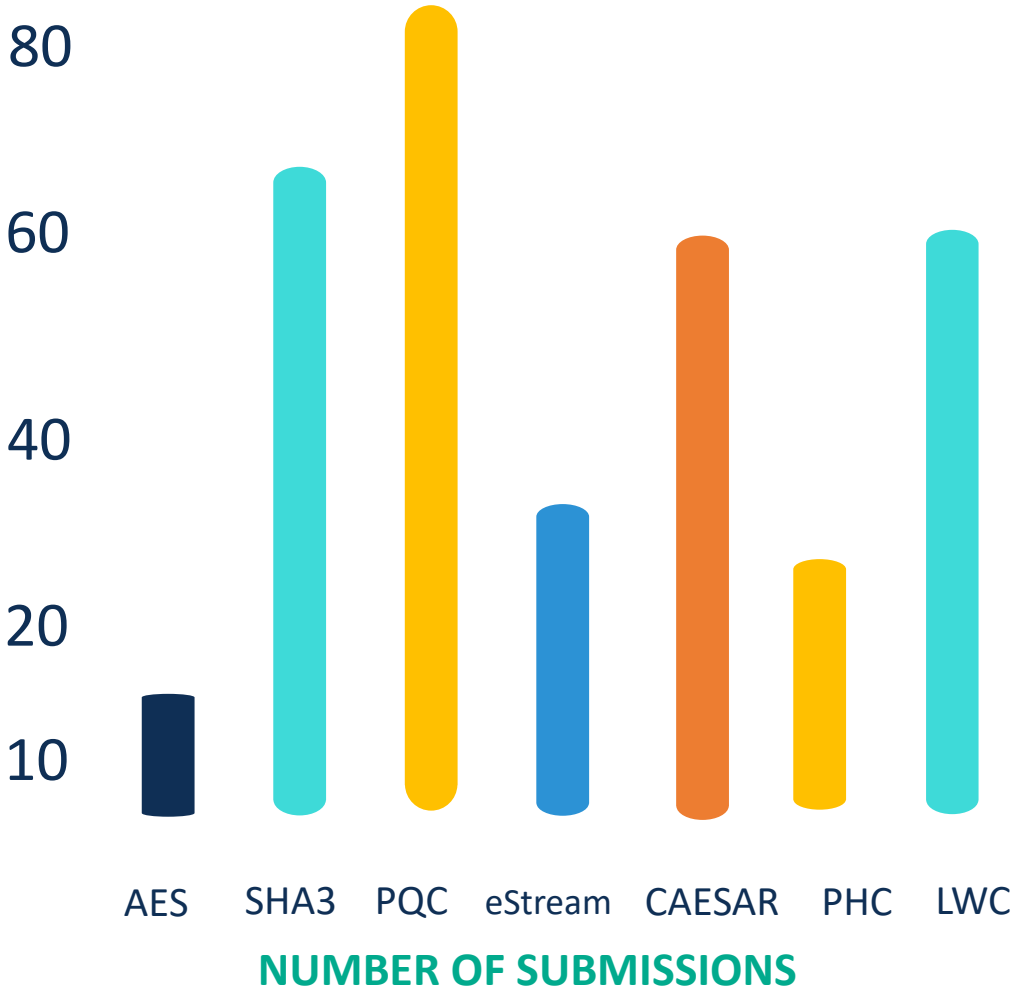
## Hash

- Computationally infeasible to find a collision or a (second) preimage. Resistance to length extension attacks. (Attacks requiring at least $2^{112}$ computations)
- Digest size at least 256 bits
- Family of (at most 10) algorithms
  - One **primary member** has a hash size of 256 bits.
  - Limits on the input sizes for the primary member at least $2^{50}$-1 bytes
- Common design components with the AEAD

# Design and Implementation Requirements

- Perform significantly better in constrained environments (HW and SW platforms) compared to NIST standards.
- Efficient for short messages
- Implementations that lend themselves to countermeasures against side channel attacks, and fault attacks

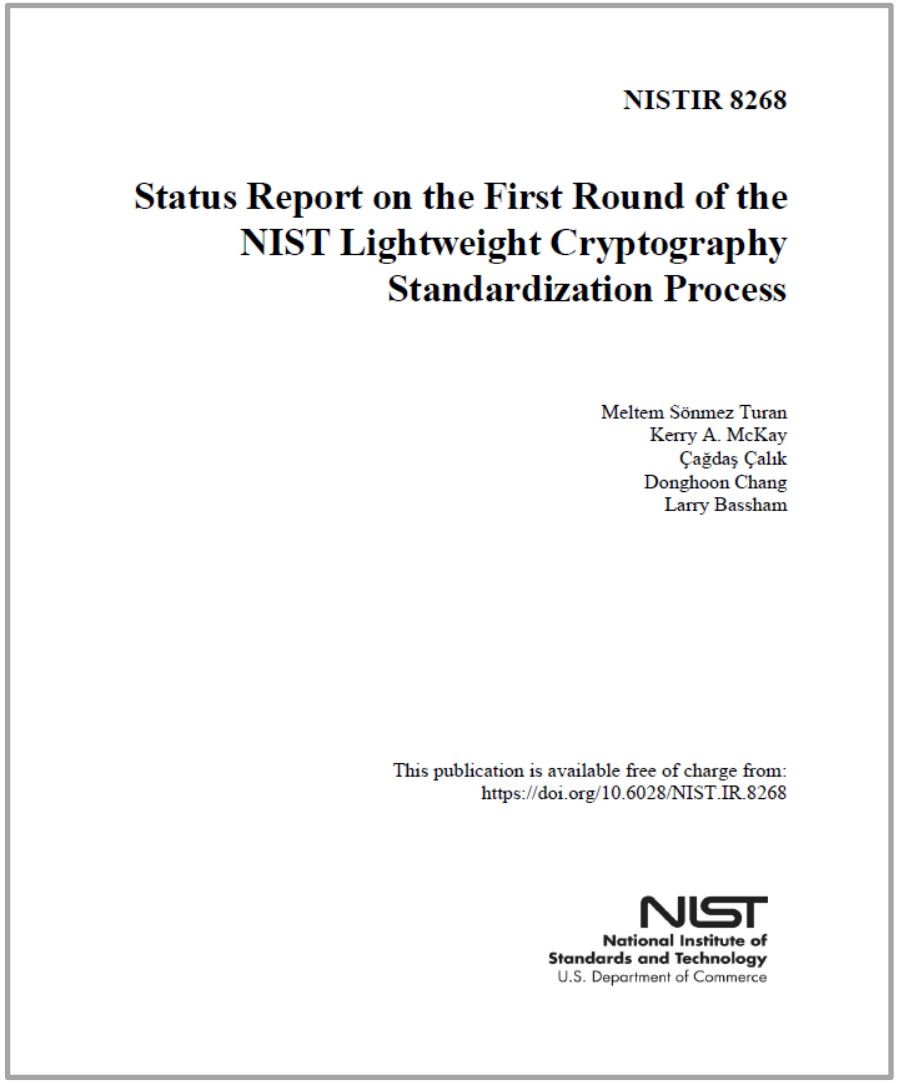
# 56 Round 1 Candidates





# First Round of the Standardization Process

- Approximately 4 months
- Evaluation of the candidates were done based on their security
  - e.g., distinguishing attacks, practical tag forgeries, domain separation issues, new designs with no third-party analysis etc.
- 32 Candidates (out of 56) are selected to move forward to the second round.
- NISTIR 8268 *Status Report on the First Round of the NIST Lightweight Cryptography Standardization Process* (October 2019)



NISTIR 8268

**Status Report on the First Round of the NIST Lightweight Cryptography Standardization Process**

Meltem Sönmez Turan
Kerry A. McKay
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This publication is available free of charge from:
https://doi.org/10.6028/NIST.IR.8268

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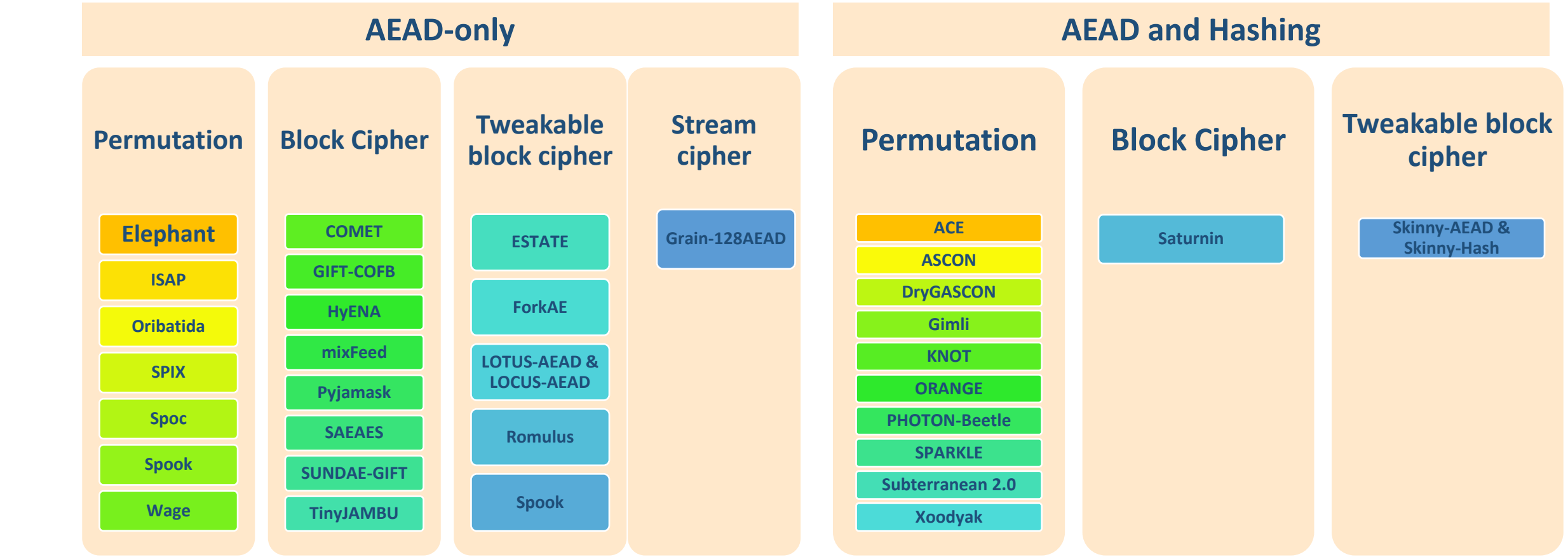
# The Second Round

# Second-Round Candidates

- ACE
- ASCON
- COMET
- DryGascon
- Elephant
- ESTATE
- ForkAE
- GIFT-COFB
- Gimli
- Grain128aead
- HyENA
- ISAP
- KNOT
- LOTUS-LOCUS
- mixFeed
- ORANGE
- Oribatida
- Photon-Beetle
- Pyjamask
- Romulus
- SAEAES
- Saturnin
- Skinny-AEAD
- Sparkle
- SPIX
- SpoC
- Spook
- Subterranean
- Sundae-GIFT
- TinyJambu
- Wage
- Xoodyak

# Classification based on Underlying Components



# Classification based on Modes*

## Sequential

**Classical Sponge with Public Permutation**

ACE, ASCON, DryGASCON, Gimli, KNOT, Spix, Spook, Subterranean 2.0, WAGE, Xoodyak

**Modified Sponge with Public Permutation**

ORANGE, Oribatida, PHOTON-Beetle, SPARKLE, SpoC

**Enc-then-Mac**

ISAP, Saturnin

**(T)BC-based Feedback with Rate 1**

COMET, GIFT-COFB, HyENA, mixFeed, Romulus

**Mac-then-Enc**

ESTATE, SUNDAE-GIFT

**Classical Sponge with Secret Permutation**

SAEAES, TinyJAMBU

**Stream Cipher Based**

Grain-128AEAD

## Parallel

ForkAE

LOTUS-AEAD & LOCUS-AEAD

**ΘCB3-based**

SKINNY-AEAD

**OCB3-based**

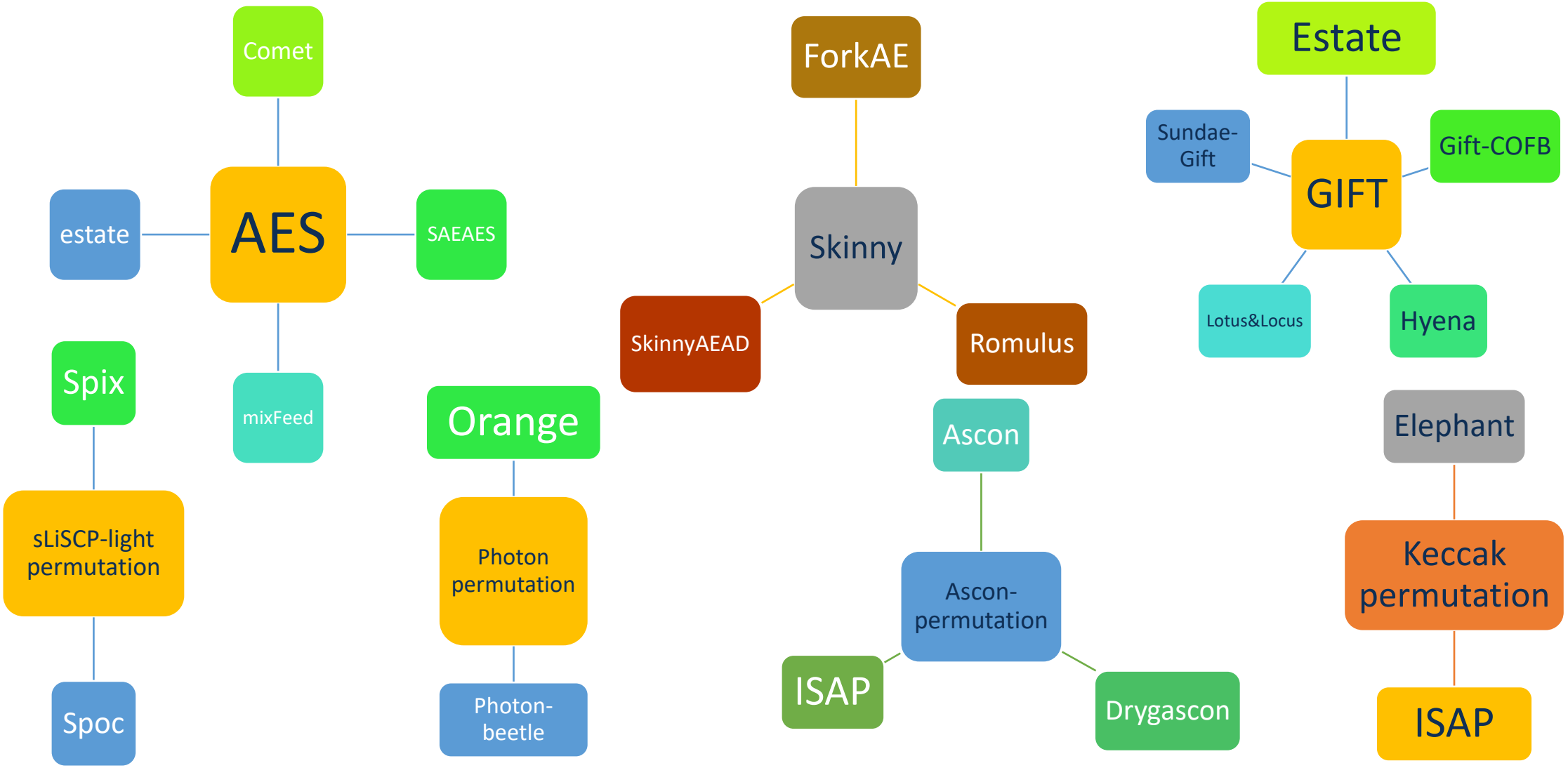
Pyjamask

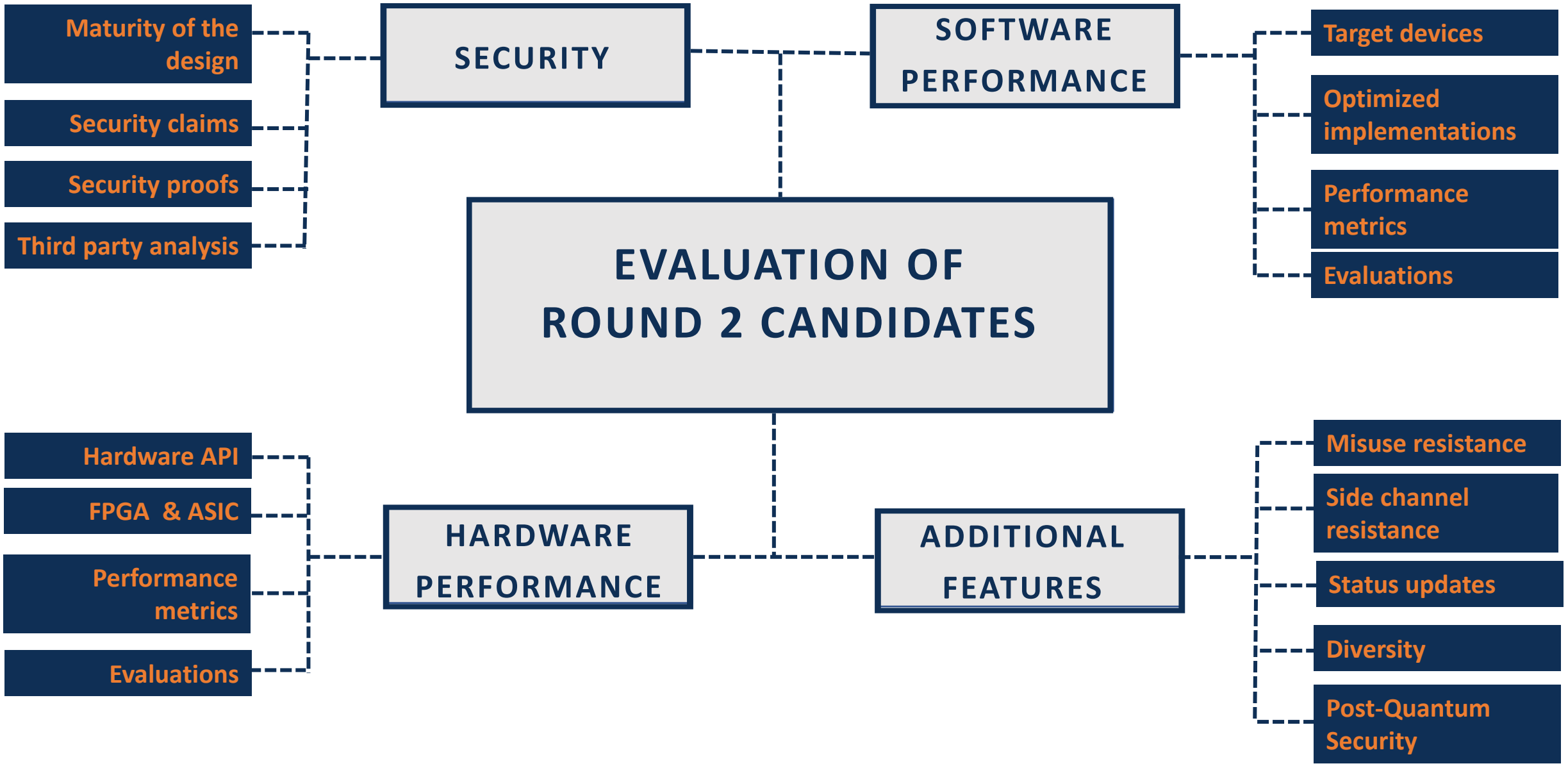
**Enc-then-Mac**

Elephant

* Primary variant only

# Common Building Blocks




EVALUATION OF ROUND 2 CANDIDATES
SECURITY
Maturity of the design
Security claims
Security proofs
Third party analysis
SOFTWARE PERFORMANCE
Target devices
Optimized implementations
Performance metrics
Evaluations
HARDWARE PERFORMANCE
Hardware API
FPGA & ASIC
Performance metrics
Evaluations
ADDITIONAL FEATURES
Misuse resistance
Side channel resistance
Status updates
Diversity
Post-Quantum Security

# Software Benchmarking

**Microcontroller benchmarking by NIST LWC Team**

**Devices:**
- 8-bit AVR
- 32-bit ARM Cortex M0+, M4
- MIPS32 M4K
- Tensilica L106

**Metrics:**
- Code size
- Speed

**Microcontroller benchmarking by Renner et al.**

**Devices:**
- 8-bit AVR
- 32-bit ARM Cortex M3, M7
- Tensilica Xtensa LX6
- RISC-V

**Metrics:**
- Size
- RAM usage

**Microcontroller benchmarking by Weatherly**

**Devices:**
- AVR
- ARM Cortex-M3
- Tensilica Xtensa LX6

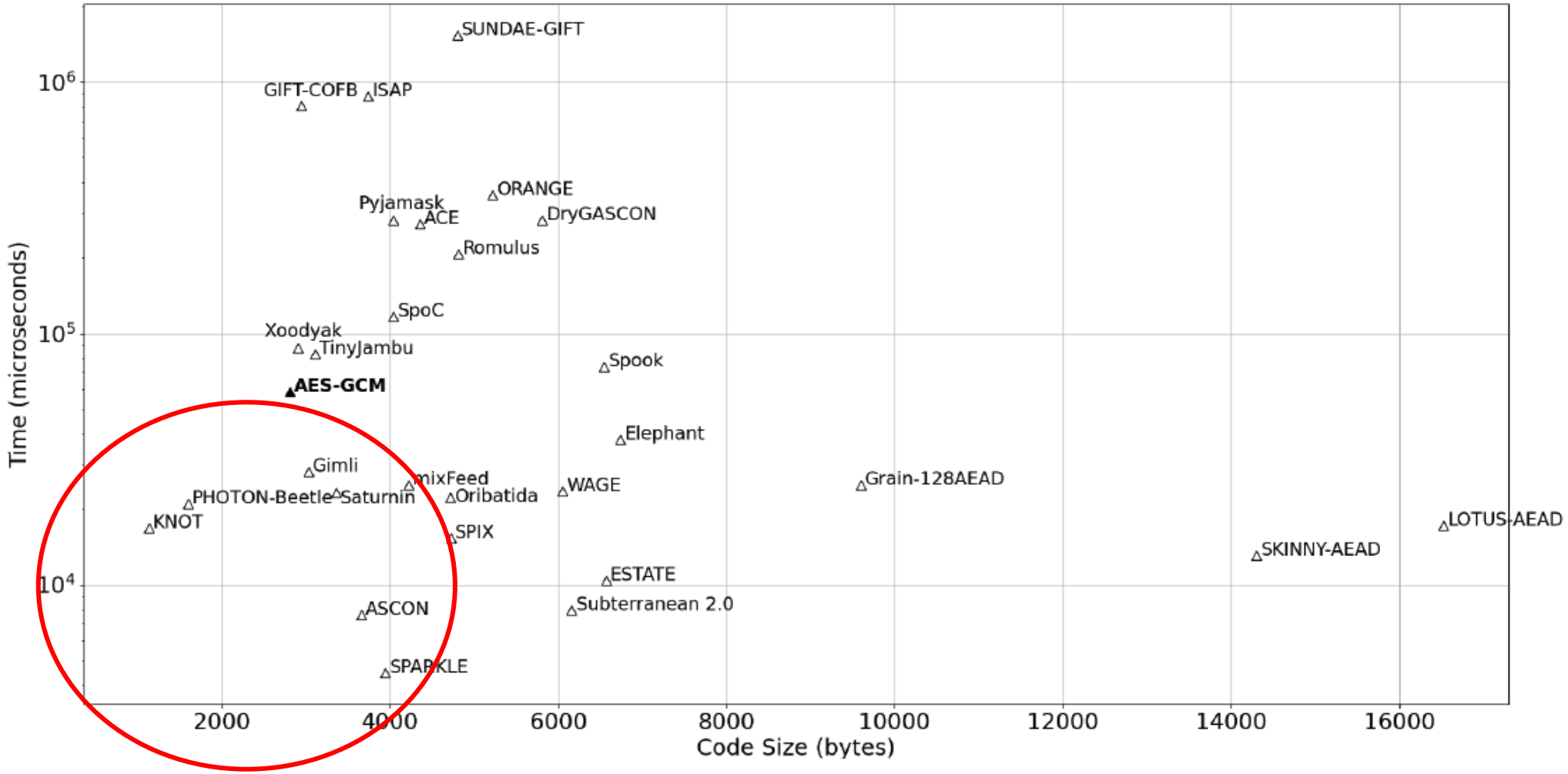
**Metrics:**
- Speed

**eBACS (ECRYPT Benchmarking of Cryptographic Systems) by Lange and Bernstein**

**Devices:**
- Many systems covering ARM, AMD, Intel, PPC, RISC V, and MIPS architectures

**Metrics:**
- Speed

# Results – Software Benchmarking



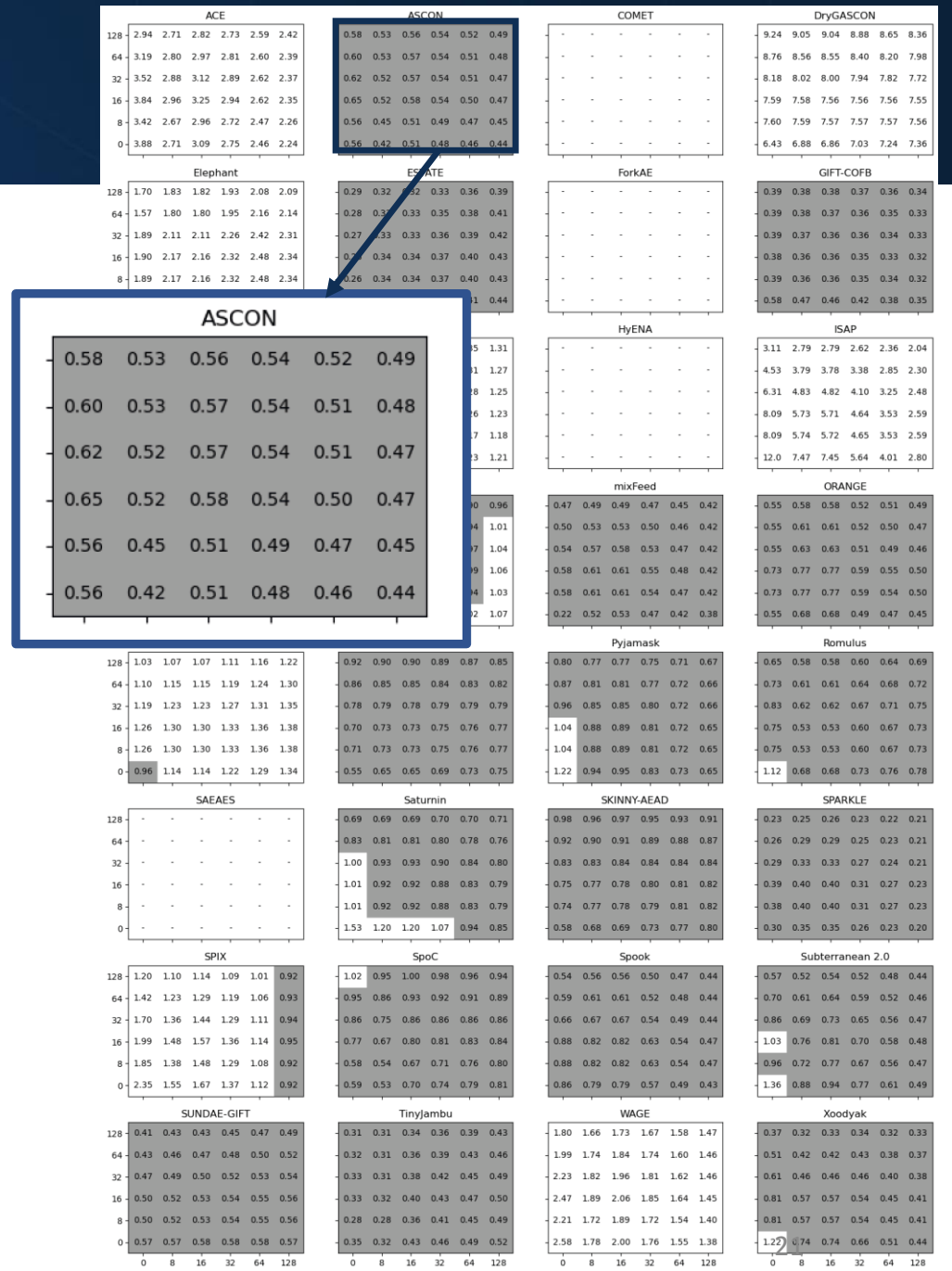

Code size vs. speed results of the smallest primary AEAD variants - 16-byte message and 16-byte AD on ATmega328P

# Results – Software Benchmarking

Relative timings for each candidate are shown by a matrix of values, where

- rows = message lengths (0 bytes – 128 bytes),
- columns = AD lengths (0 bytes – 128 bytes).

$$\textbf{Metric} = \frac{\text{Execution time of the candidate}}{\text{Execution time of AES-GCM}}$$



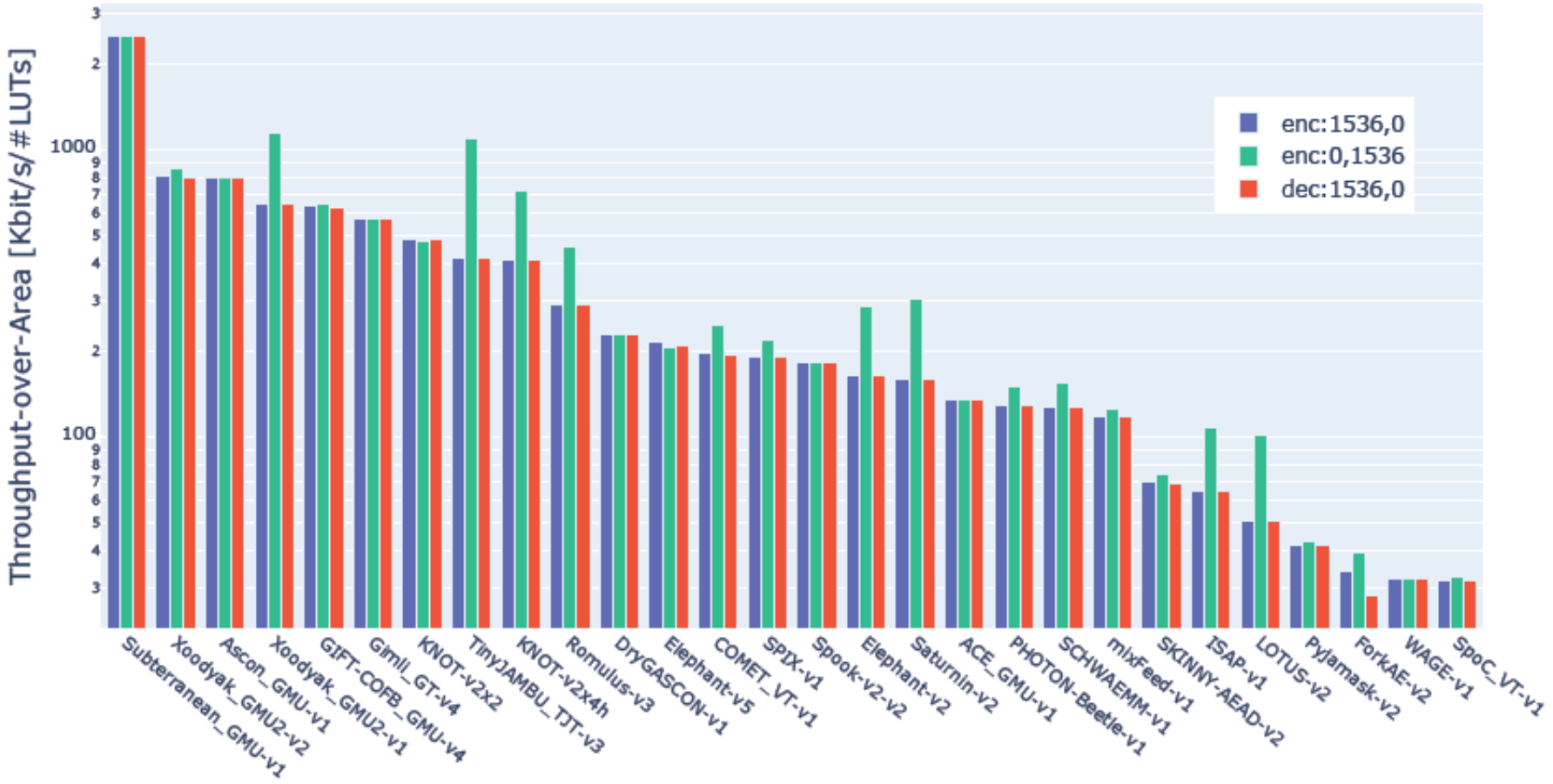

**Result:**

Ascon, Estate, Gimli,  Knot, Lotus-AEAD, mixFeed, Orange, Photon-Beetle, Pyjamask, Romulus, Saturnin, Skinny-AEAD, Sparkle, Spoc, Spook, Subterranean, SUNDAE-GIFT, TinyJambu, Xoodyak perform better than AES-GCM on ATmega328P.

# Hardware Benchmarking

| *Initiative* | *Platforms* | *Metrics* |
|---|---|---|
| GMU CERG group | Xilinx Artix-7<br>Intel Cyclone 10 LP<br>Lattice Semiconductor ECP5 | Resource utilization (LUT or LE, flip-flops)<br>Maximum clock frequency (MHz)<br>Throughput (Mbits/s)<br>Energy per bit (nJ/bit) |
| Khairallah et al. | TSMC 65nm<br>FDSOI 28nm | Area ($\mu m^2$ and GE)<br>Clock period (ns)<br>Power (mW)<br>Energy (mJ) |
| Aagaard and Zidarič | ST Micro 65nm<br>TSMC 65nm<br>ST Micro 90nm<br>TSMC 90nm<br>ARM/IBM 130nm | Throughput (bits per cycle)<br>Area (GE)<br>Energy (nJ)<br>Area×Energy (GE×nJ)<br>Clock Speed (GHz) |

# Results – Hardware Benchmarking




Throughput-over-Area for Authenticated Encryption and Decryption of 1536-byte messages at 75MHz by GMU

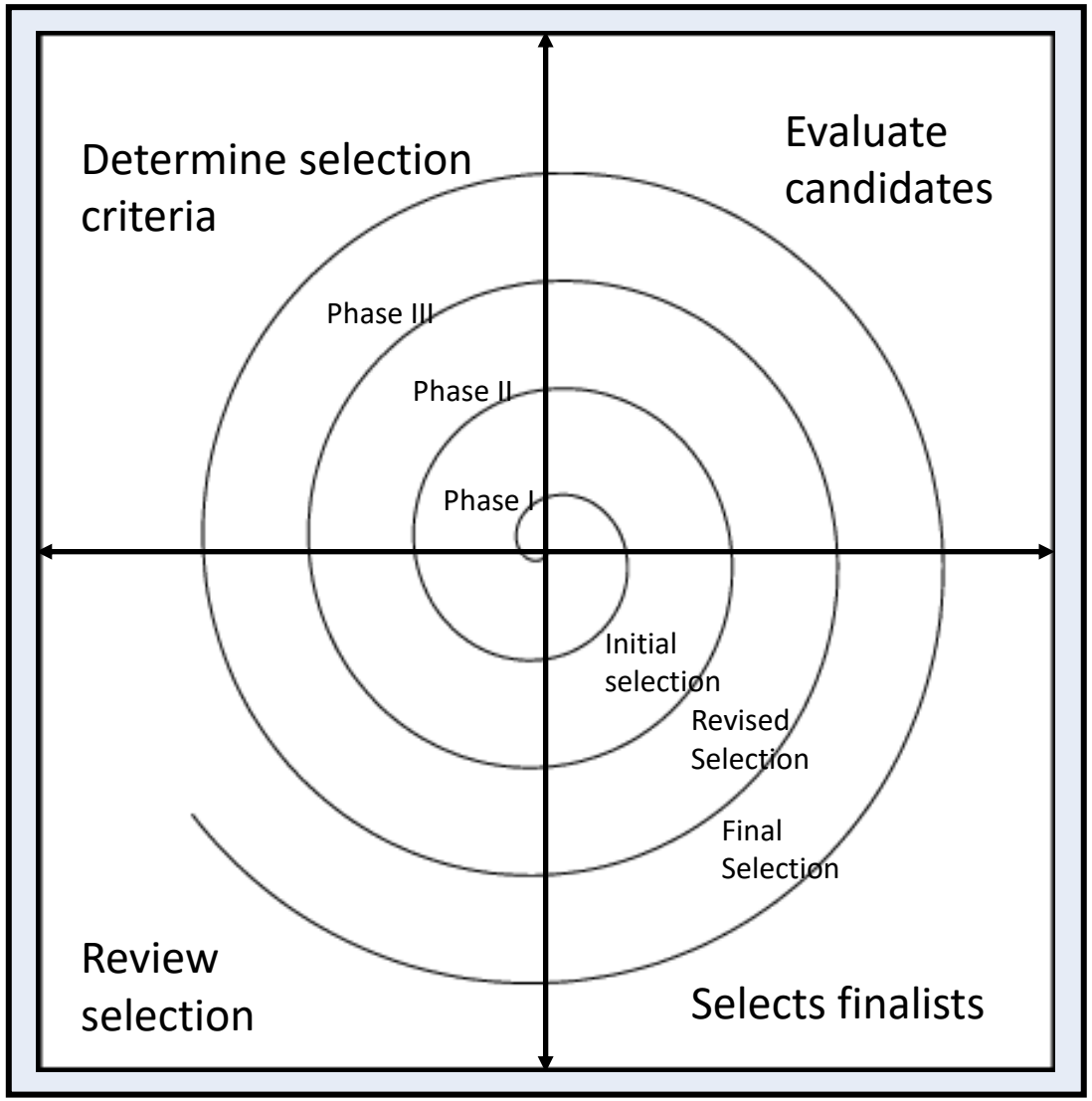
# Additional Features

- Nonce is assumed to be unique. Misuse resistance is a plus.
- Post quantum security is not included in the call.
  - Most symmetric-key algorithms are believed to be secure against quantum threats. Best generic attack: Grover's algorithm (quadratic speedup over exhaustive search)
  - Ascon, Gimli, Saturnin address the issue in their specification
  - Six candidates with large key sizes: DryGascon, Knot, SAEAES, Sparkle, Spook, TinyJambu.
- *Complexity of recovering the key from the internal state* is not mentioned in the call.
  - Keyed initialization and finalization makes it hard to recover the key.
- Status updates and the tweak plans were also considered.
  - e.g., Increasing/decreasing number of rounds, new functionality, internal changes
- Diversity of the finalists + current NIST standards

# Challenges of Evaluation

- **Large number of candidates:**
  - 32 family of algorithms (89 AEAD, 19 hash variants). Evaluation mostly done on *primary variants.*
- **Limited resources:**
  - Mostly relies on third-party analysis.
  - Not all algorithms get the same attention.
- The industry need is not clear.
  - too specific vs. too broad
- **Assigning weights for different criteria:**
  - Different security claims (nonce misuse, RUP security, side channel resistance, etc.), different functionality (AEAD, hash, XOF etc.), attacks with different complexities

# Evaluation strategy



# Selecting the Finalist

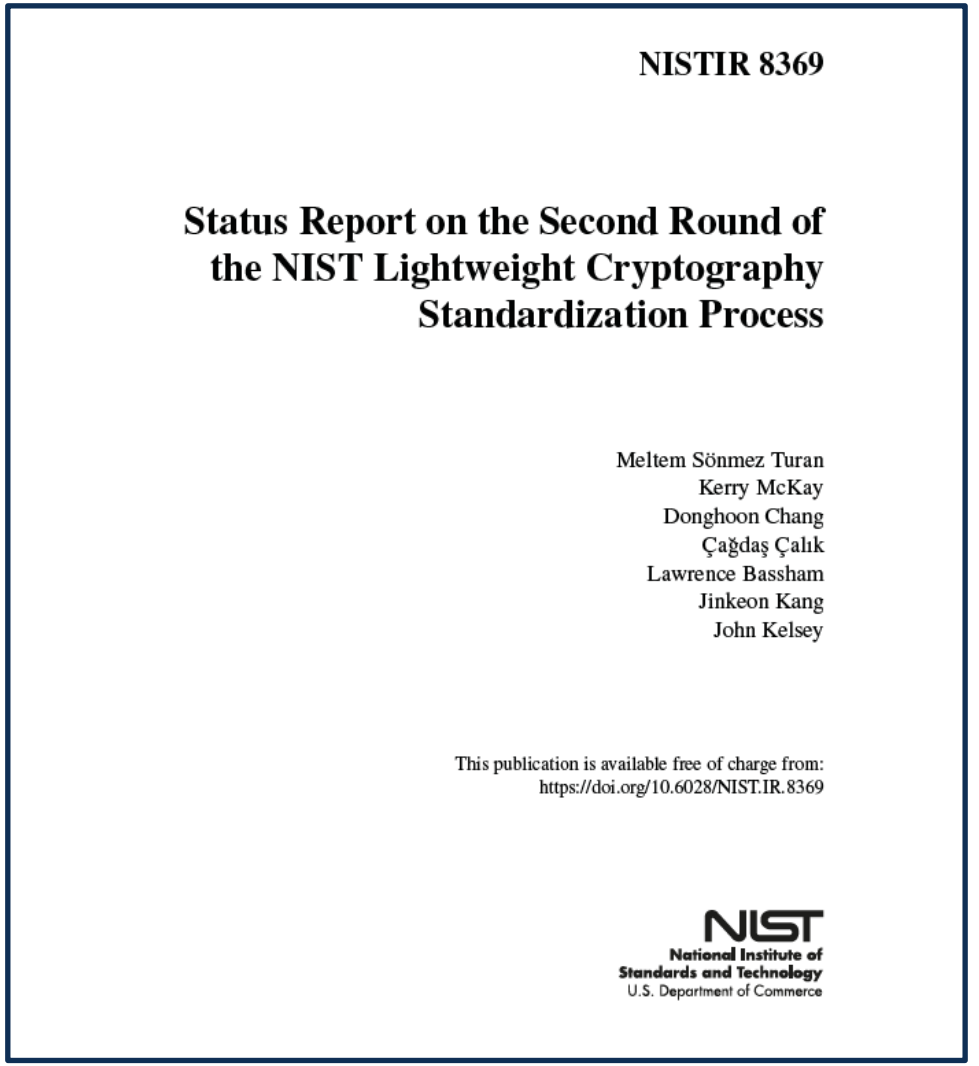
- Evaluation of the second-round candidates took around 20 months (from Aug. 2019 to March 2021).

Two workshops

- Nov. 2019 – Third LWC Workshop
- Oct. 2020 – Fourth LWC Workshop (virtual)

In March 2021, NIST announced 10 **finalists**:

| | | | | |
|---|---|---|---|---|
| **ASCON** | **Elephant** | **GIFT-COFB** | **Grain-128aead** | **ISAP** |
| **Photon-Beetle** | **Romulus** | **Sparkle** | **TinyJambu** | **Xoodyak** |



NISTIR 8369

Status Report on the Second Round of the NIST Lightweight Cryptography Standardization Process

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| Finalist | Building Block | Mode | #variants | Key size | Nonce size | Tag size |
|---|---|---|---|---|---|---|
| Ascon | Permutation | Monkey dublex | 3 aead<br>4 hash | 128-160 | 128 | 128 |
| Elephant | Permutation | Enc-then-MAC | 3 aead | 128 | 96 | 64-128 |
| Gift-COFB | Block cipher | Combined feedback | 1 aead | 128 | 128 | 128 |
| Grain-128aead | Stream cipher | - | 1 aead | 128 | 96 | 64 |
| ISAP | Permutation | Enc-then-MAC | 4 aead | 128 | 128 | 128 |
| Photon-beetle | Permutation | Combined feedback | 2 aead<br>1 hash | 128 | 128 | 128 |
| Romulus | Tweakable BC | Mac-then-Enc | 3 aead<br>1 hash | 128 | 128 | 128 |
| Sparkle | Permutation | Duplex | 4 aead<br>2 hash | 128-256 | 128-256 | 128 |
| TinyJambu | Keyed Permutation | Duplex | 3 aead | 128-256 | 96 | 64 |
| Xoodyak | Permutation | Cyclist | 1 aead<br>1 hash | 128 | 128 | 128 |

# Next Steps

- Evaluation of the finalists
- Fifth Lightweight Cryptography Workshop(~May 9-11, 2022)
- Selection of the winner(s) and publication of the report
- Standardization

# Timeline


1st Workshop
2nd Workshop
NISTIR 8114
Submission due
Round 1
Round 2
NISTIR 8268
3rd Workshop
4th workshop
Round 3
NISTIR 8369
5th Workshop
End of Round 3
July 2015
October 2016
March 2017
February 2019
April 2019
August 2019
October 2019
November 2019
October 2020
March 2021
July 2021
Spring 2022
Summer 2022

# Thanks!

**CONTACT NIST TEAM**

lightweight-crypto@nist.gov

**PUBLIC FORUM**

lwc-forum@list.nist.gov

**GITHUB**

https://github.com/usnistgov/Lightweight-Cryptography-Benchmarking

**WEBSITE**

https://csrc.nist.gov/Projects/lightweight-cryptography

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