Multiparty Homomorphic Encryption: from Theory To Practice

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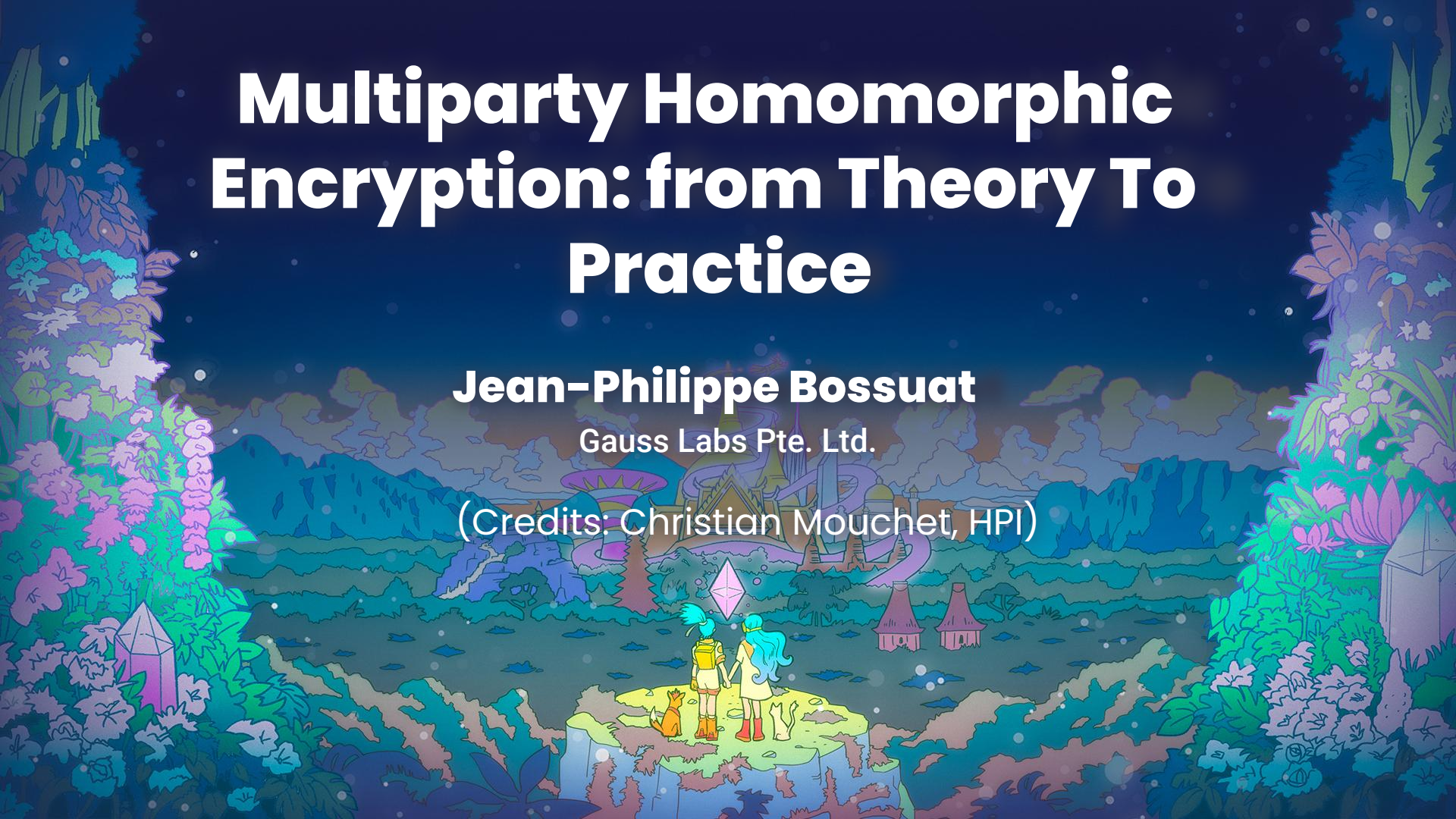
(Credits: Christian Mouchet, HPI)

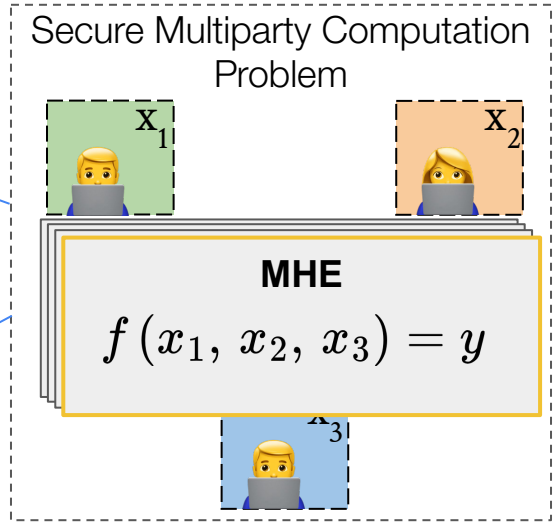


Secure Multiparty Computation

Multiple parties want to **compute** a public function **without disclosing** their inputs.

[Functionality]
"Output y"

[Input privacy]
"Without revealing more information about the inputs than what y does"



$\mathcal{P}$

- n parties

$\mathcal{A} \subset \mathcal{P}$

- $n-1$ adversaries
- Passive and static

Multiparty Homomorphic Encryption – Intuition

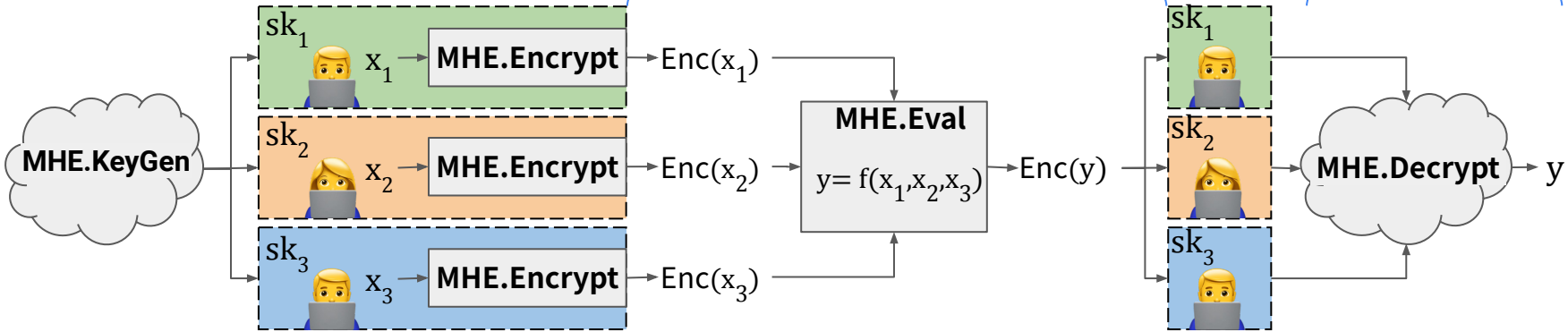
Multiparty Homomorphic Encryption (MHE) extends Homomorphic Encryption (HE) with an **access-structure**.

HE Semantic Security + Access Structure ⇓ Input Privacy

Correctness ⇓ Functionality

MHE Scheme

MHE-based MPC Protocol



Background: Ring Learning with Error (RLWE) [LPR10]

RLWE distribution:

Let:

- $\mathcal{R}_Q = \mathbb{Z}_Q[X]/\left(X^N + 1\right)$ be a polynomials ring of degree N-1 with coefficients $\mathrm{mod}\ Q$,
- χ_Q be the uniform distribution over $\mathcal{R}_Q$
- χ_σ be an error distribution over $\mathcal{R}_Q$ with standard deviation σ
- χ_h be a ternary distribution value over $\mathcal{R}_Q$ with h non zero coefficients

the *ring learning-with-error distribution* over s is defined as:

$$\mathrm{RLWE}_s = (-as + e, a) \quad a \leftarrow \chi_Q \quad s \leftarrow \chi_h \quad e \leftarrow \chi_\sigma$$

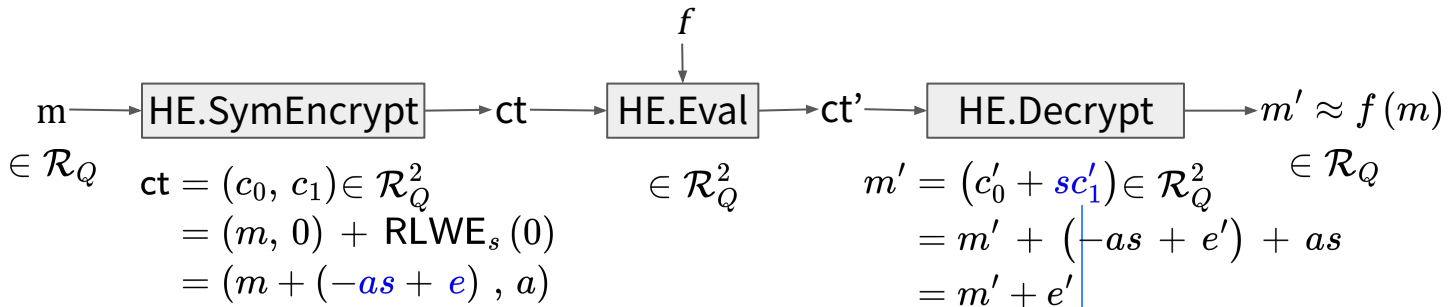
Given a polynomial number of <u>independent</u> samples from the RLWE_s distribution:

- **Search**: find s or e.
- **Decision**: distinguish from $(b \leftarrow \chi_Q, a)$

Background: (Symmetric) HE From RLWE

A simplified RLWE-based HE scheme.

Let $f : \mathcal{R}_Q \to \mathcal{R}_Q$



Scheme's operations are affine functions of the secret-key.

Background: Gadget Ring Learning with Error (GRLWE)

Gadget Ciphertext: $\mathsf{GRLWE}_s(m) = (-\mathbf{a}s + P \cdot m \cdot \mathbf{w} + \mathbf{e}, \mathbf{a}) \in \mathcal{R}_{QP}^{\beta \times 2}$

$$\mathbf{w} = (w_0, w_1, \ldots, w_{\beta-1}) \text{ with } ||w_i|| \leq B \qquad \mathbf{a} = (a_0, a_1, \ldots, a_{\beta-1}) \leftarrow \chi_{QP}^{\beta}$$

$$x = \sum_{i=0}^{\beta-1} w_i^{-1}(x) \cdot w_i \qquad \mathbf{e} = (e_0, e_1, \ldots, e_{\beta-1}) \leftarrow \chi_{\sigma}^{\beta}$$

$$\mathcal{R}_{QP}^{\beta \times 2} \otimes \mathcal{R}_Q \rightarrow \mathcal{R}_Q^2$$

Gadget Product:

$$\begin{aligned}
\mathsf{GRLWE}_s(m_0) \otimes m_1 &= \left\lceil P^{-1} \cdot \left\langle \mathbf{w}^{-1}(m_1), \mathsf{GRLWE}_s(m_0) \right\rangle \right\rfloor \\
&= \left\lceil P^{-1} \cdot \sum_{i=0}^{\beta-1} w_i^{-1}(m_1) \cdot (-a_i s + P \cdot m_0 \cdot w_i + e_i, a_i) \right\rfloor \\
&= (-bs + m_0 m_1 + e', b) \\
&= \mathsf{RLWE}_s(m_0 m_1)
\end{aligned}$$

$$\sigma_{e'} \approx \sqrt{\frac{N\beta}{12}} B \sigma_e$$

Secret-key operations are affine functions of the secret key

All operations affine functions of the secret-key: $(-as + e) + x$

Setup phase:

Public Encryption Key Generation: $\mathsf{RLWE}_s(0) = (-as + e, a)$

Public Rotation Key Generation for $\mathsf{rot}_k(\cdot)$: $\mathsf{GRLWE}_s(\pi_k(s)) = (-s\mathbf{a} + \mathbf{e} + \pi_k(s) \cdot \mathbf{w}, \mathbf{a})$

Public Relinearization Key Generation: $\mathsf{GRLWE}_s(s^2) = (-s\mathbf{a} + \mathbf{e} + P \cdot s^2 \cdot \mathbf{w}, \mathbf{a})$

Compute phase:

Decrypt: $sc_1 + e + c_0$

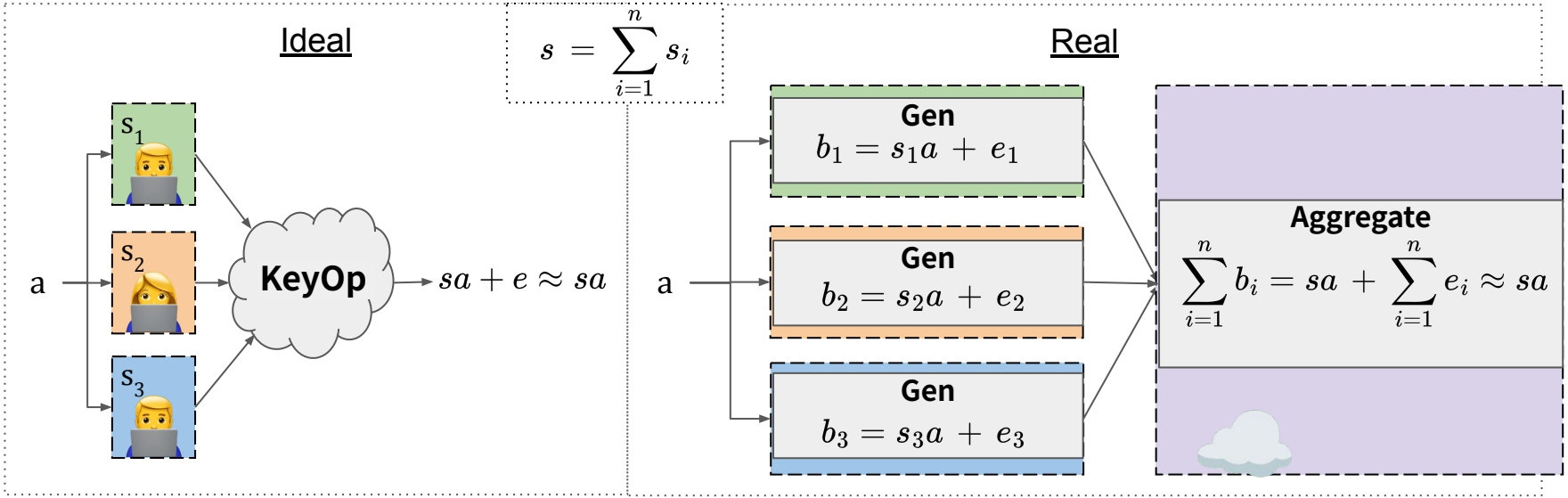
Re-encrypt: $((s - s') \cdot c_1 + e + c_0, c_1)$

Issue: not linear

MHE Scheme Construction – Secret-key Operations

Affine secret-key operations can be implemented as single-round protocols (Generalizing [AJLT+12][MTBH+21]).

→ We refer to these protocols as having **P**ublic **A**ggregatable **T**ranscripts (**PAT**)



Helper-Assisted, MHE-based MPC

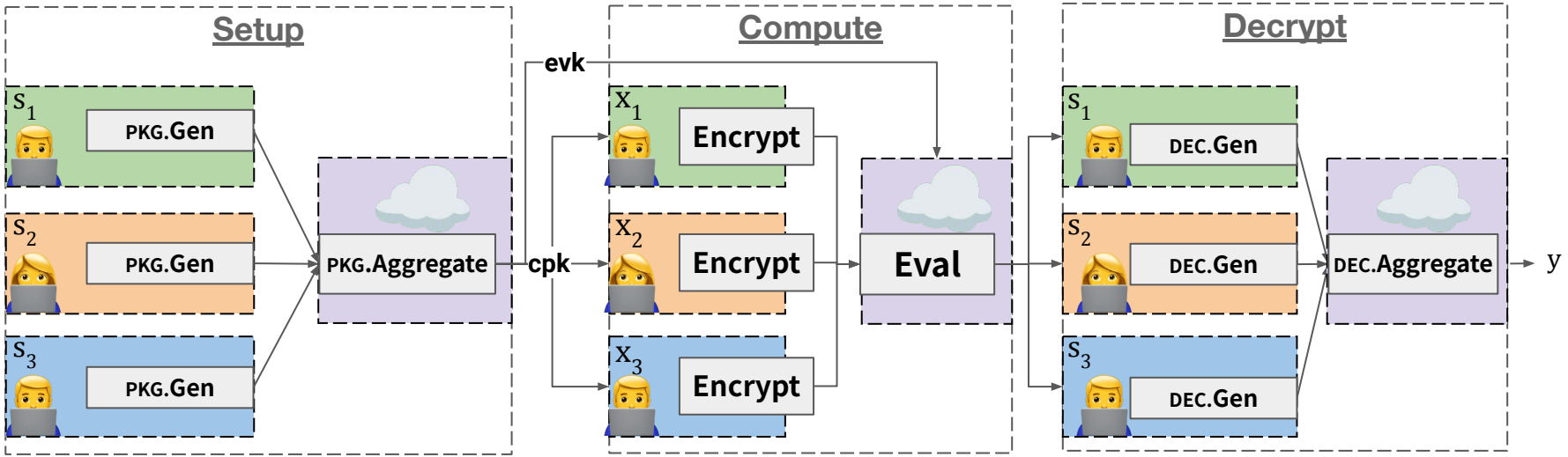
The MHE-based MPC protocol has many practical advantages. [MTBH+21]

One-time setup
- ✓ Amortizable cost
- ✓ Session-like paradigm

Low communication complexity
- ✓ **2 (because of RIk) + 2 rounds**
- ✓ Non-interactive Eval

Public Transcript
- ✓ Delegated public share aggregation
- ✓ Sublinear MPC

Delegated evaluation
- ✓ In classic passive-adversary setting



Implementation

Both the N-out-of-N- and the T-out-of-N-threshold scheme are implemented in Lattigo [M**B**TH20]

- (Threshold-) BGV, BFV, CKKS, FHEW
- (Single-party) SOTA CKKS bootstrapping
- Standalone, modular math & crypto layers

- **100% Open-source** (Apache 2.0 licence)
- 100% written in Go
- Full suite of unit-test and benchmarks

https://github.com/tuneinsight/lattigo

Systematically used by the winners of the **iDASH Privacy & Security Workshop: Secure Genome Analysis Competition**

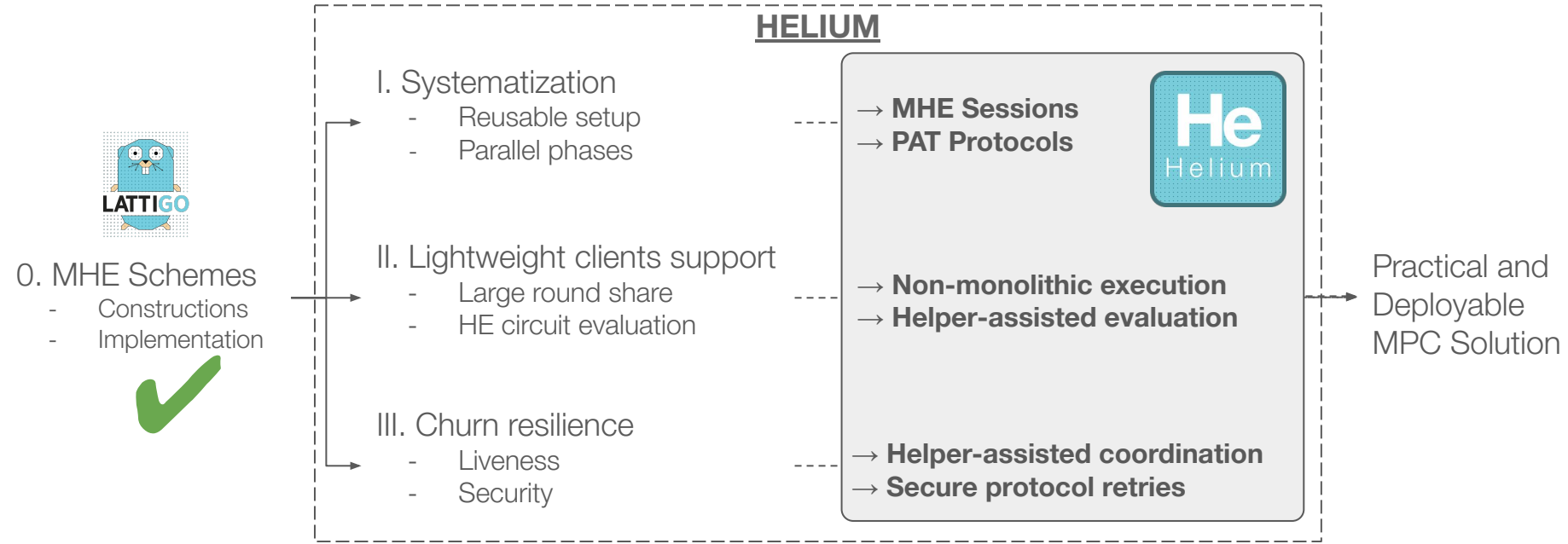
➢ I (github/Pro7ech) and another team tied for first place in the 2024 competition, we both used Lattigo

Practical Challenges of MHE-based MPC

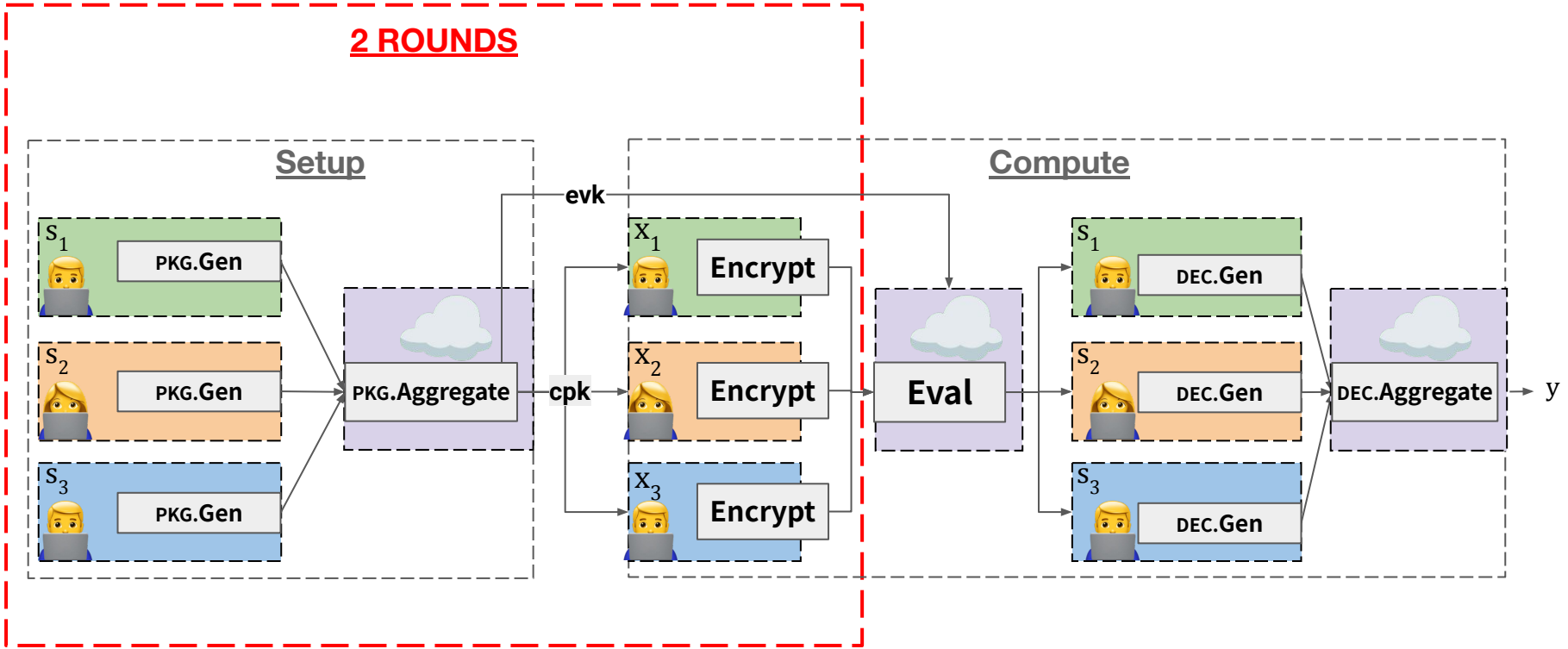
Christian Mouchet, Sylvain Chatel, Apostolos Pyrgelis, Carmela Troncoso, ***Helium: Scalable MPC among Lightweight Participants and under Churn***, ACM SIGSAC, 2024

…, but the way to practice is full of challenges.

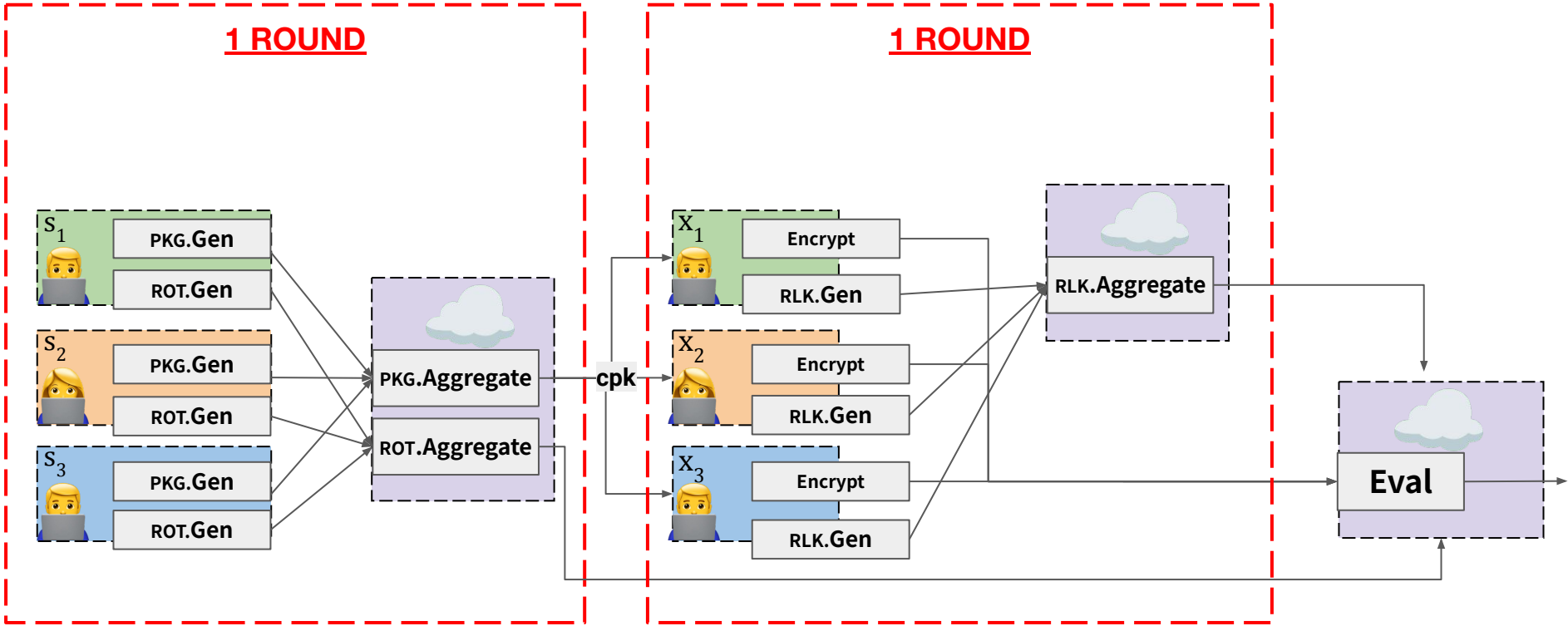
https://github.com/ChristianMct/helium



Toward Non-Interactive Setup & Encryption



Toward Non-Interactive Full Setup & Encryption



Toward Non-Interactive Full Setup & Encryption

$$\mathsf{Pk} = \mathsf{RLWE}_s(0) = \sum_{i=1}^{n} \mathsf{RLWE}_{s_i}(0)$$

$$\mathsf{Rot}_k = \mathsf{GRLWE}_s(\pi_k(s)) = \sum_{i=1}^{n} \mathsf{GRLWE}_{s_i}(\pi_k(s_i))$$

$$\mathsf{Rlk} = \mathsf{GRLWE}_s(s^2) = \sum_{i=1}^{n} \mathsf{GRLWE}_{\mathsf{pk}}(0) + (0,\ s_i\mathbf{w})$$

Rlk requires Pk to be generated!

Toward Non-Interactive Full Setup & Encryption

It would be really great if we could reduce the setup & encryption to a single PAT

Condition: A predetermined set of parties $\mathcal{P}$ and inputs

Enables:

- Each $\mathcal{P}_i \in \mathcal{P}$ sends a single **PAT** to the server $\mathcal{S}$
- $\mathcal{S}$ can chose any $\mathcal{P}' \subseteq \mathcal{P}$, aggregate the associated **PAT**s to produce the evaluation keys and ciphertexts and can run an arbitrary circuit
- Decryption only requires the collaboration of $\mathcal{P}' \subseteq \mathcal{P}$

Toward Non-Interactive Full Setup & Encryption

Rlk is important both for relinearization (ciphertext compactness) and expanding GRLWE ciphertexts to RGSW ciphertexts (used in FHEW bootstrapping)

Looking more at the structure of **Rlk**:

$$\mathsf{Rlk} = \sum_{i=1}^{n} \mathsf{GRLWE}_{\mathsf{pk}}\left(0\right) + \left(0,\ s_i \mathbf{w}\right)$$

Decryption implicitly multiplies the second component by *s*

$$= \sum_{i=1}^{n} \mathsf{GRLWE}_{s_i}\left(s s_i\right)$$

$$= \mathsf{GRLWE}_{s}\left(s \sum_{i=1}^{n} s_i\right)$$

Toward Non-Interactive Full Setup & Encryption

We propose 1 - round PAT protocols Key Dependent Message (KDM) RLWE and GRLWE ciphertexts

$$\mathsf{RLWE}_s\left(s\sum_{i=1}^{n} m_i\right) \quad \mathsf{GRLWE}_s\left(s\sum_{i=1}^{n} m_i\right)$$

1-Round PAT Protocol for $\mathsf{RLWE}_s(\mathsf{sm})$

From two RLWE and one GRLWE ciphertexts we can homomorphically generate a KDM RLWE ciphertext

$$s = \sum_{i=1}^{n} s_i$$

$$u = \sum_{i=1}^{n} u_i$$

$$m = \sum_{i=1}^{n} m_i$$

Affine in *s*, *u* and *m*

$$\mathsf{RLWE}_u(m) = (0, -au + m + e_0)$$

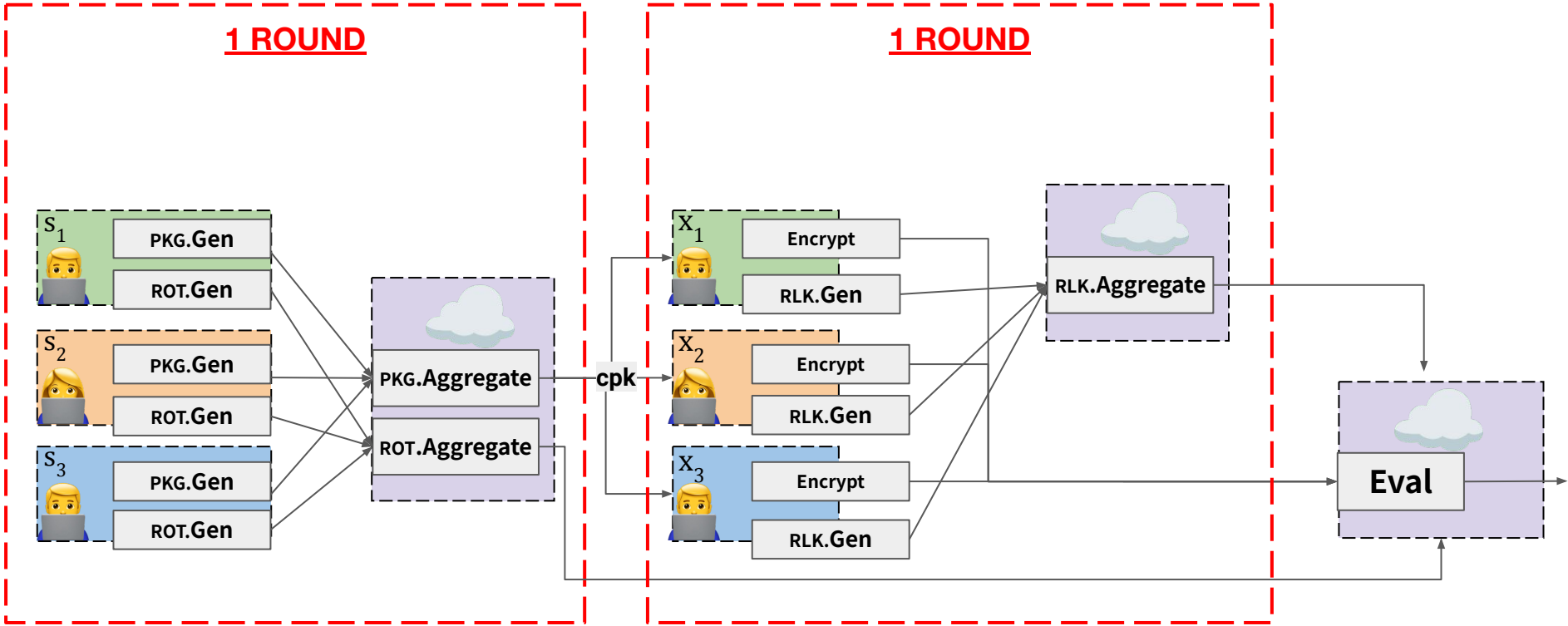
$$\mathsf{RLWE}_s(0) = (as + e_1)$$

$$\mathsf{GRLWE}_s(-u) = (-\mathbf{b}s - P \cdot u \cdot \mathbf{w} + \mathbf{e}_2, \mathbf{b})$$

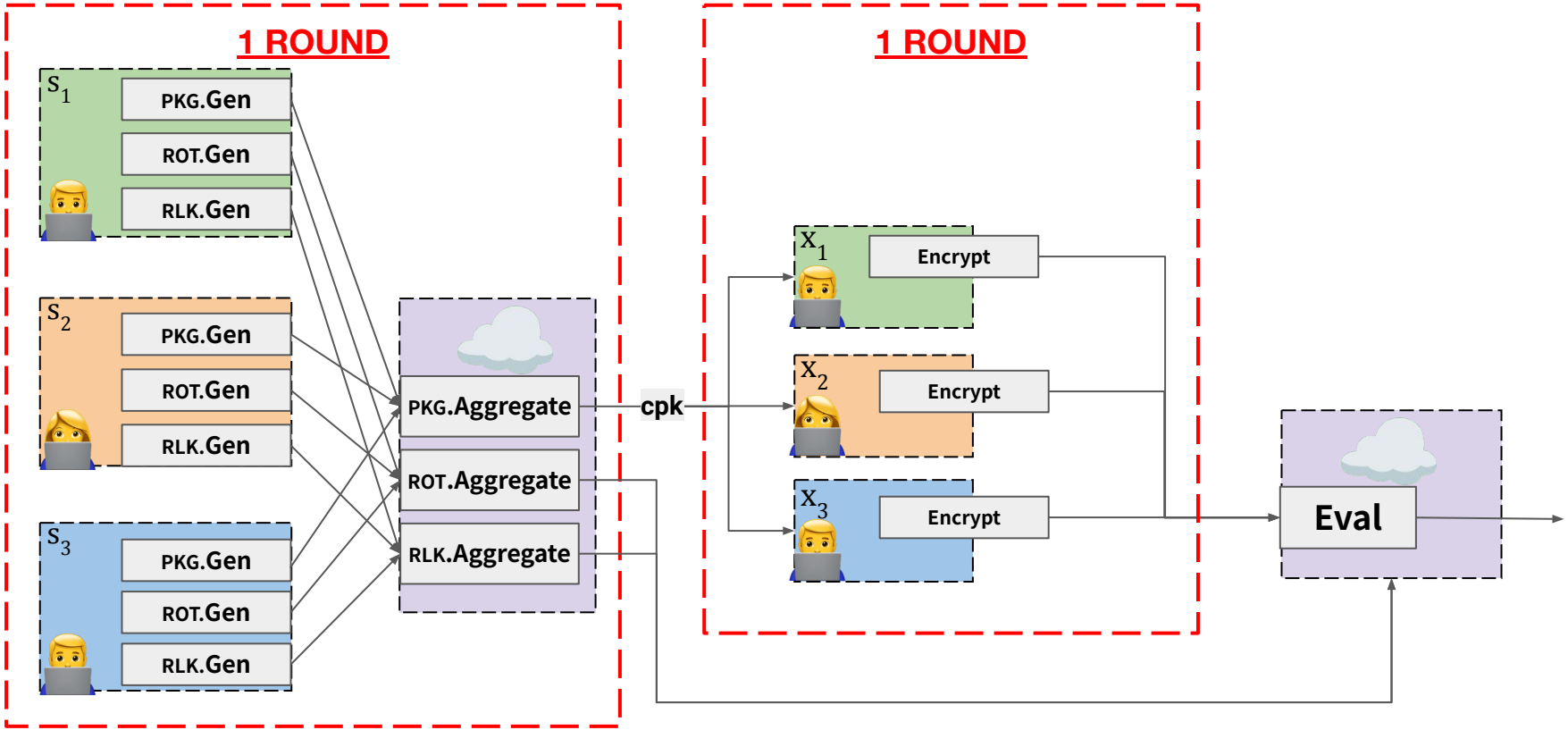
$$\mathsf{RLWE}_s(ms) = (-cs + e', c + m + e'')$$

Ephemeral secrete *u* is needed because public randomness *a* is reused across RLWE samples (a.k.a multi-secret RLWE)

Toward Non-Interactive Full Setup & Encryption



Toward Non-Interactive Full Setup & Encryption



Toward Non-Interactive Setup & Encryption

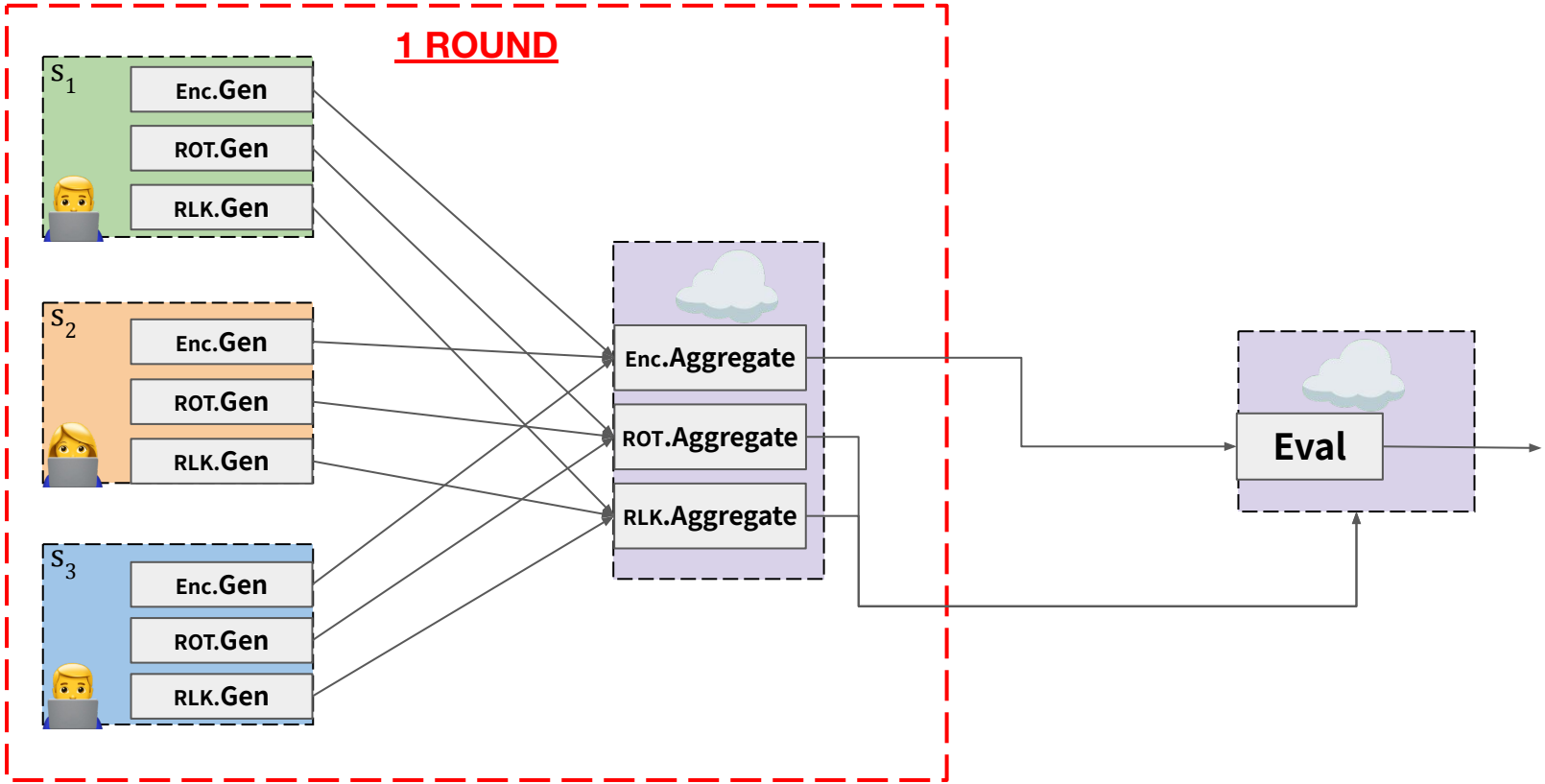
- Allocating 1-round for encryption is ok if we want flexibility on the circuit inputs
- But if the original inputs are fixed (e.g. a game state or bank account) we can include it in the setup PAT

1-Round PAT for Encryption

$$\mathsf{Enc}_{\mathsf{pk}}(m) = \mathsf{Enc}_{s_i}(m) + \sum_{j \neq i} \mathsf{Enc}_{s_j}(0)$$

- However requires O(n) communication per ciphertext per party

Toward Non-Interactive Full Setup & Encryption



1-Round PAT Full Setup & Encryption Implementation

Pro7ech's Lattigo Fork:

- Based on Lattigo v5.0.2
- Over 30k changes
- New functionalities, primitives, protocols, QoL, refactored backend, bug fixes, etc…

https://github.com/Pro7ech/lattigo

Gauss Labs Phantom Zone:

- Rust based FHE-MPC focused library
- Evaluate arbitrary functions on a set of private inputs owned by different parties
- High level of abstraction, focused for ease of use

https://github.com/gausslabs/phantom-zone

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“Number rules the universe.”

— Pythagoras

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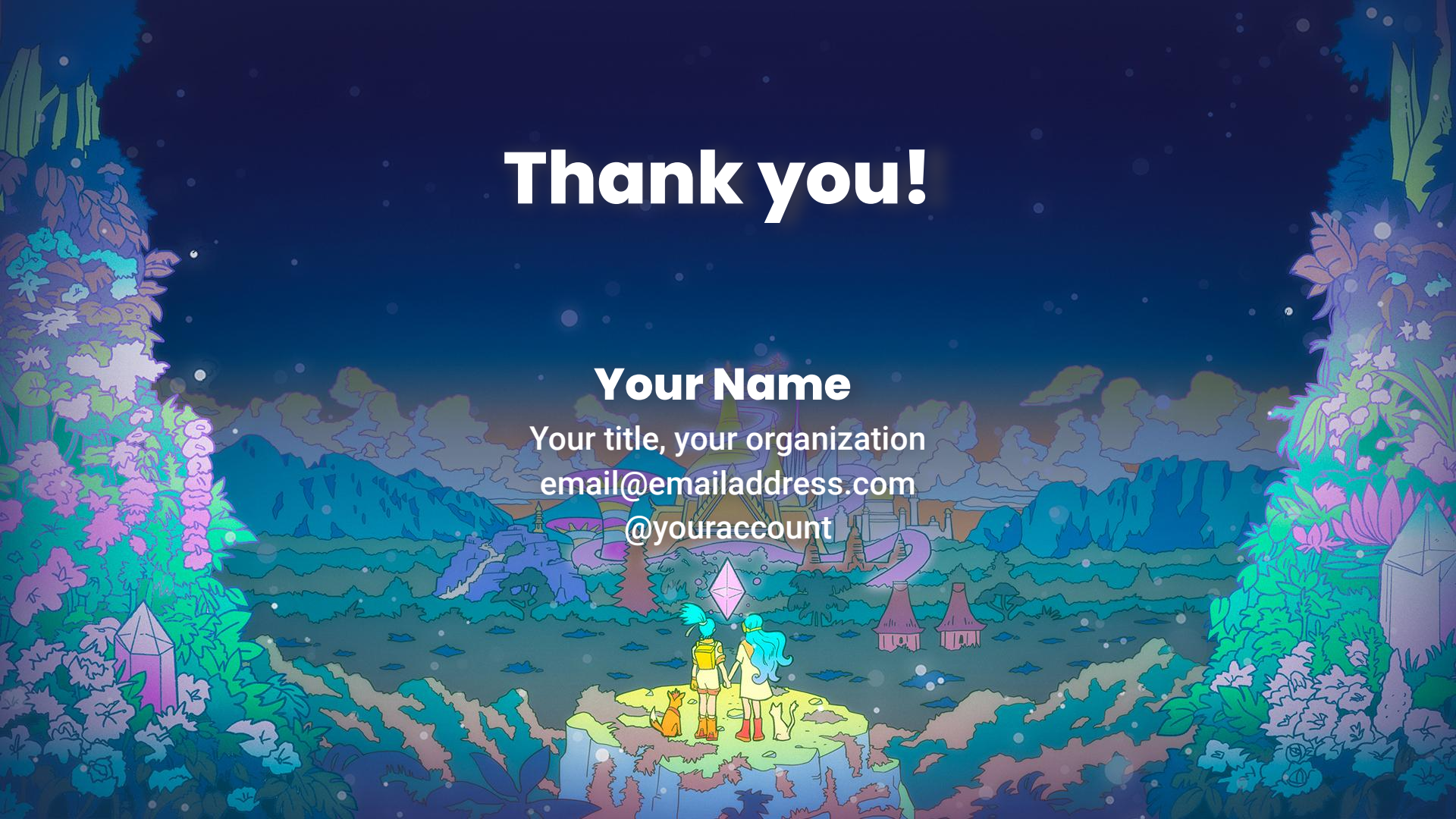

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Event 1

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Event 2

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“Number rules the universe.”

— Pythagoras

Thank you!

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Your Name

Your title, your organization

Section 1

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Section 3

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Section 4

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Event 1

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