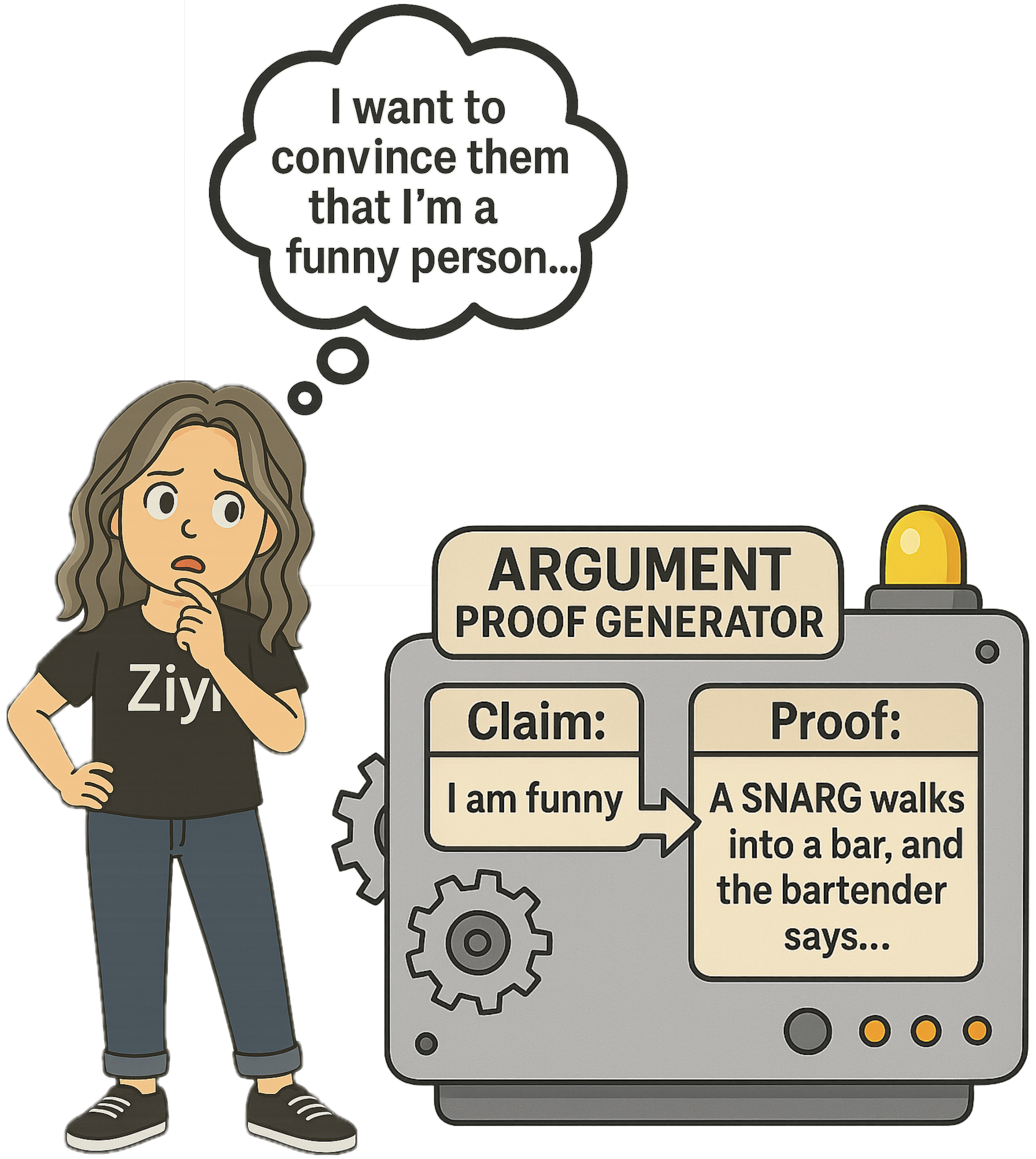
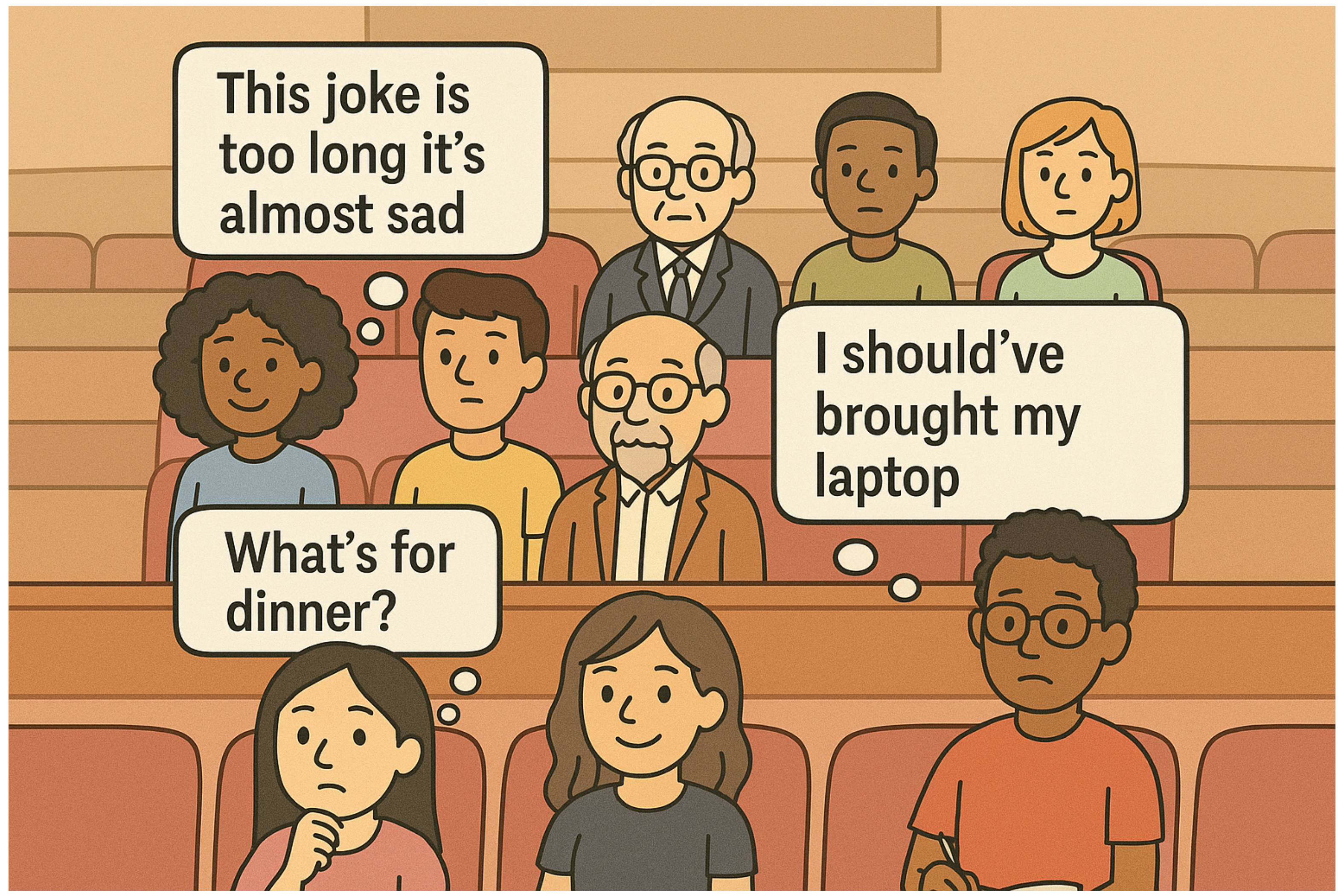
On the Security of Succinct Arguments from Probabilistic Proofs

Ziyi Guan

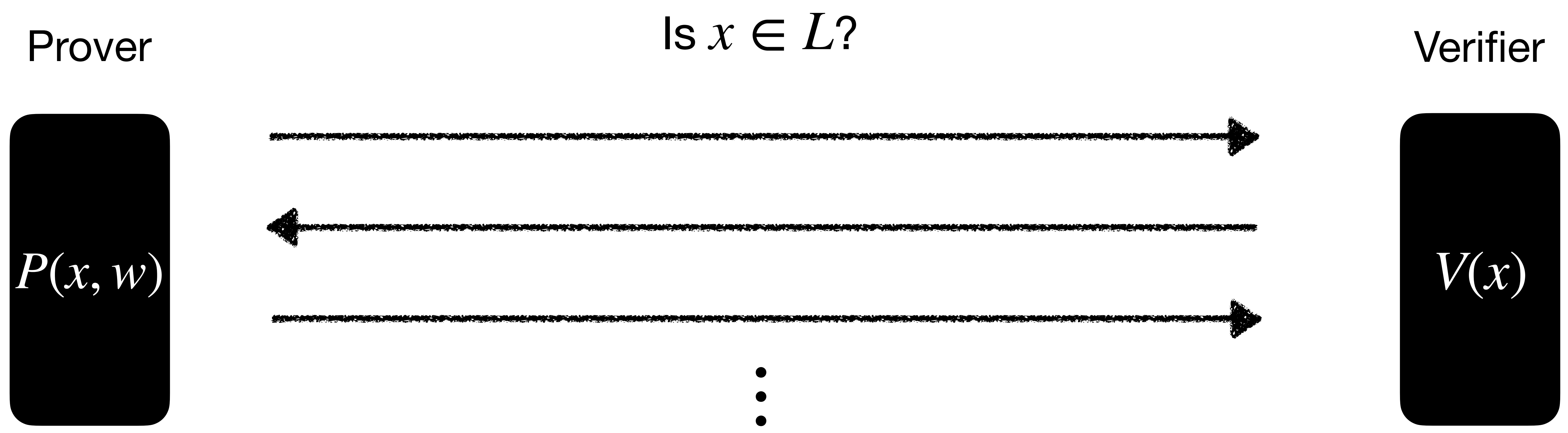




EPFL

What are succinct arguments?

Interactive proofs



Completeness: $\forall x \in L, \Pr\left[\langle P(x,w), V(x)\rangle = 1\right] = 1$

Soundness: $\forall x \notin L$ and adversary $\tilde{P}$, $\Pr\left[\langle \tilde{P}, V(x)\rangle = 1\right] \leq \epsilon$

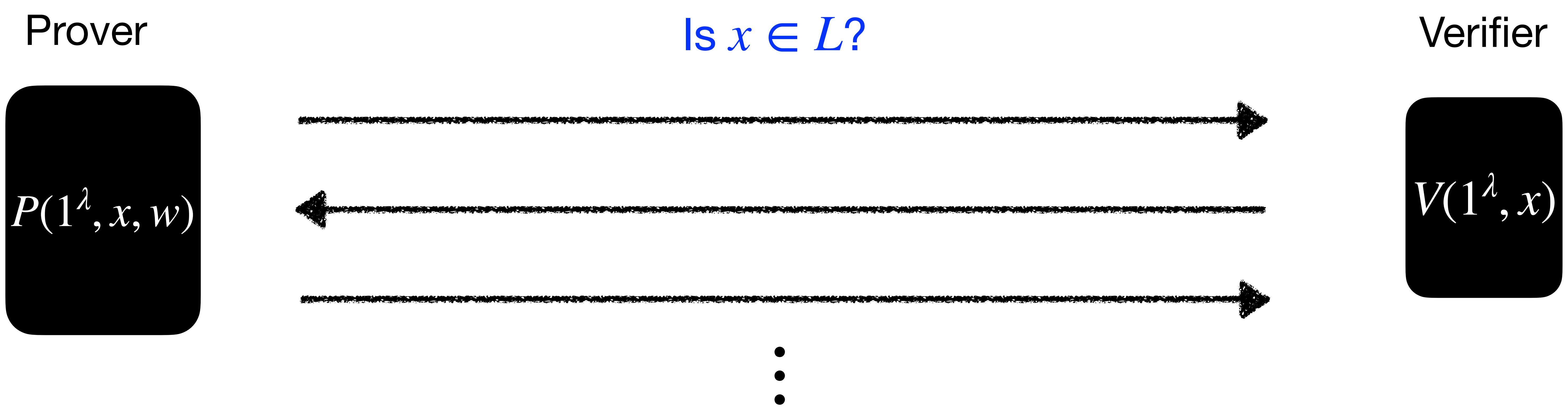
Target metric: **COMMUNICATION COMPLEXITY**

Limitation: NP-complete languages do not have IPs with **CC** $\ll |w|$

[GH97]: IP[CC] $\subseteq$ BPTIME[2^{CC}]

Interactive arguments

Interactive proofs with computational soundness



Computational soundness: $\forall\, x \notin L$ and t_{ARG}-time adversary $\tilde{P}$, $\Pr\left[\langle \tilde{P}, V(x) \rangle = 1\right] \leq \epsilon_{\text{ARG}}(t_{\text{ARG}})$

AMAZING: $\exists$ interactive arguments for NP with **CC** $\ll |w|$ (given basic cryptography)

Today's protagonist:
Succinct Interactive Arguments

Why study succinct interactive arguments?

CC $\ll |w|$

time$(V) \ll |w|$

They exist based on simple crypto assumptions...

... so they play a role in numerous cryptotheory results.

zero-knowledge with non-black-box simulation

malicious MPC

...

They are a stepping stone for SNARGs, which have numerous real-world applications.

Succinct, RISC ZERO, Aztec, VALIDA, Irreducible

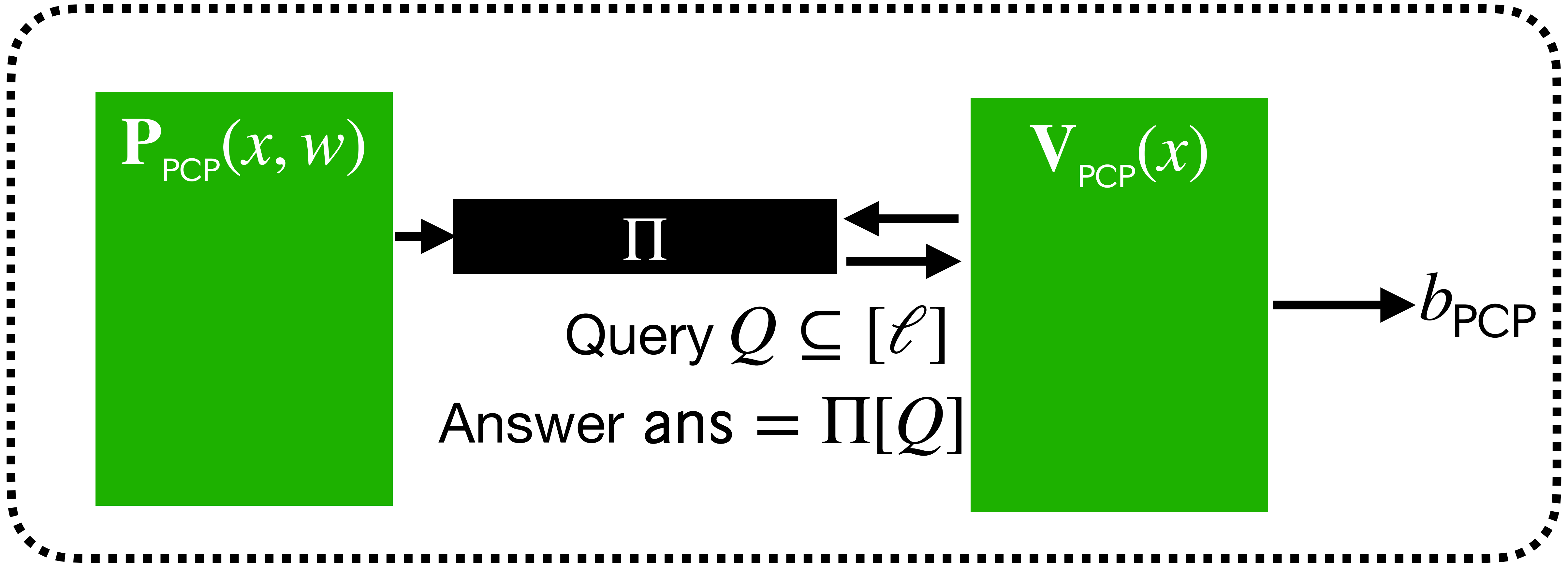
STARKWARE, polygon, NEXUS, Ligero, MatterLabs ...

Kilian's protocol:
The first and simplest succinct argument

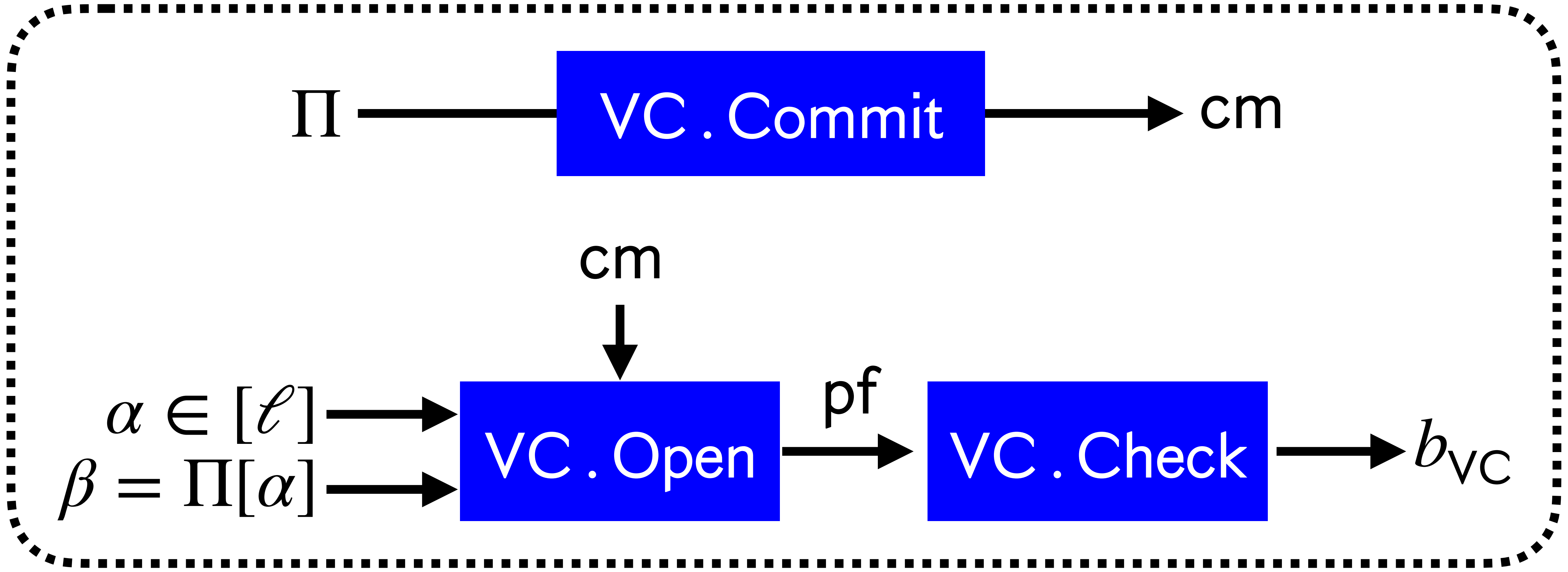
[Kilian92]

How to construct succinct arguments?

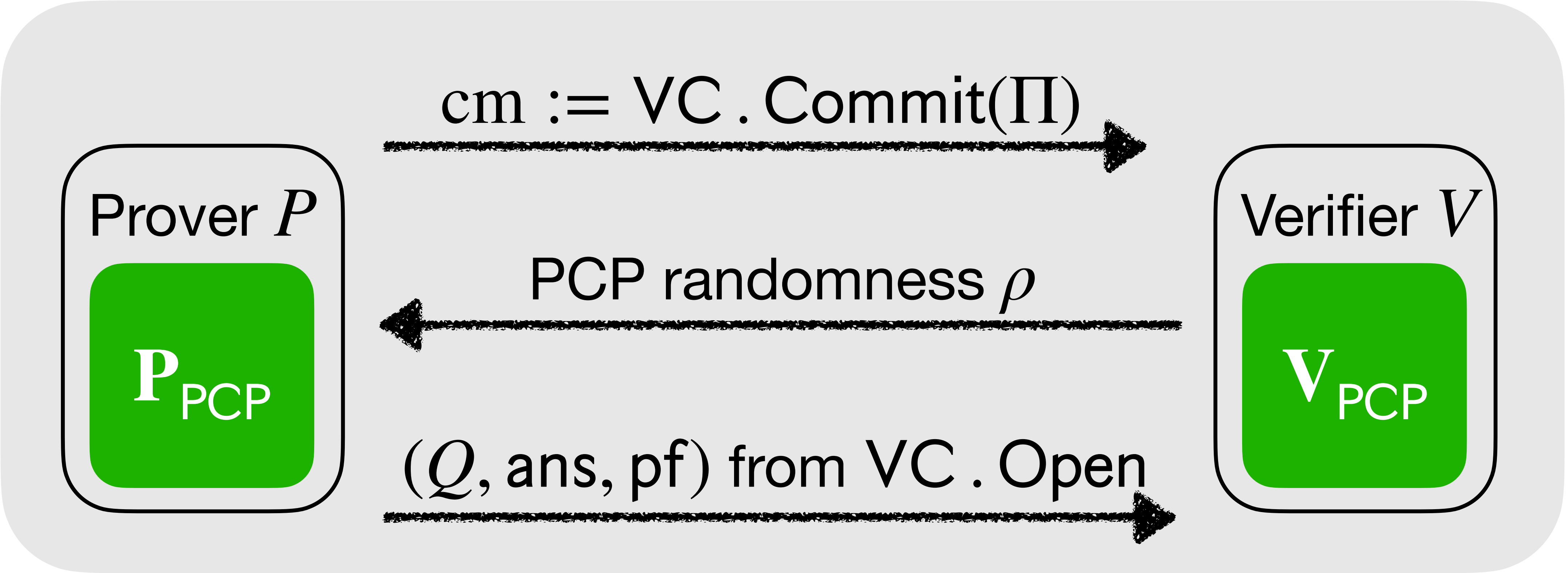
Building block #1: probabilistically checkable proof (PCP)



Building block #2: vector commitment scheme (VC)



Kilian's protocol

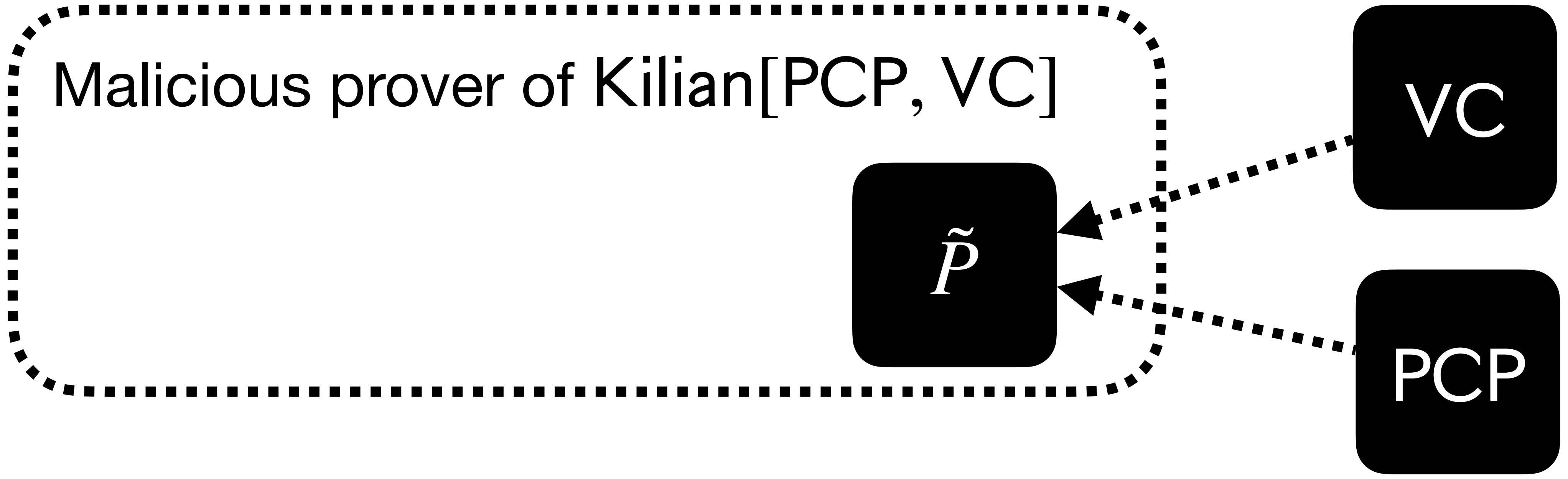


T-step computation:
- Prover time: poly(T)
- Verifier time: polylog(T)

(**CC**: polylog(T))

Simple (and only known) security analysis

Goal: relate the soundness error of Kilian[PCP, VC]
to the soundness error of PCP and the position binding error of VC.

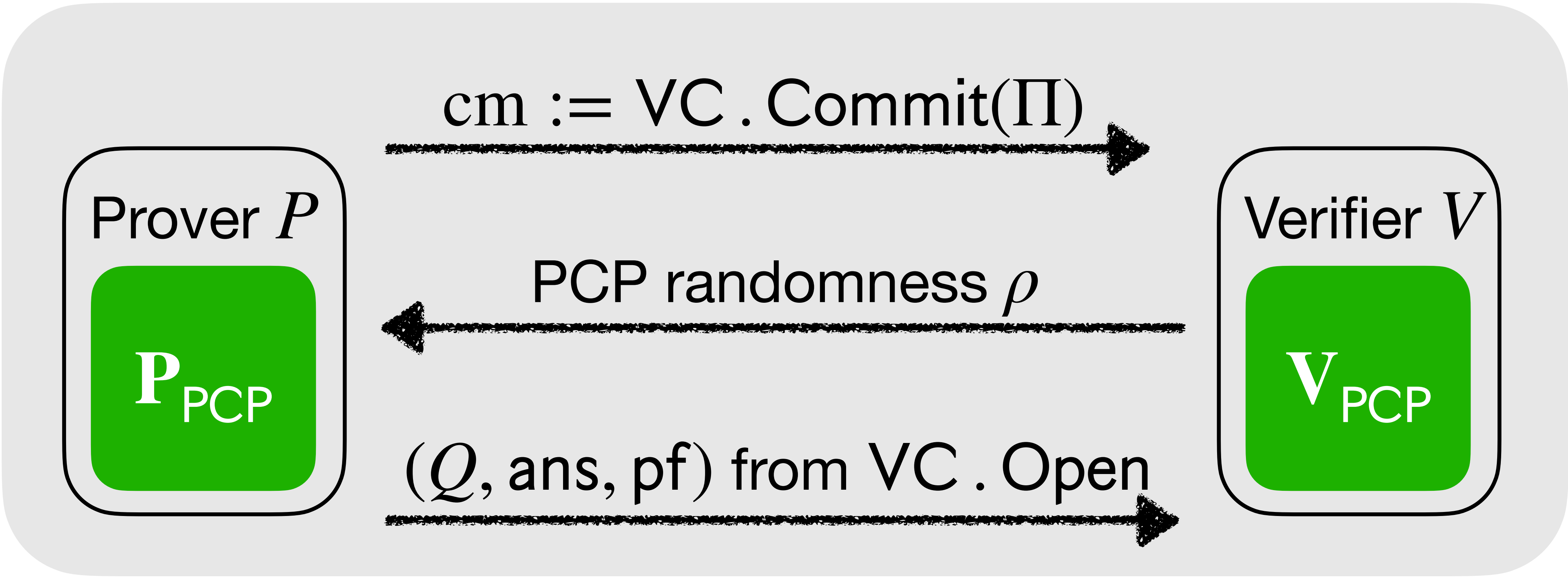


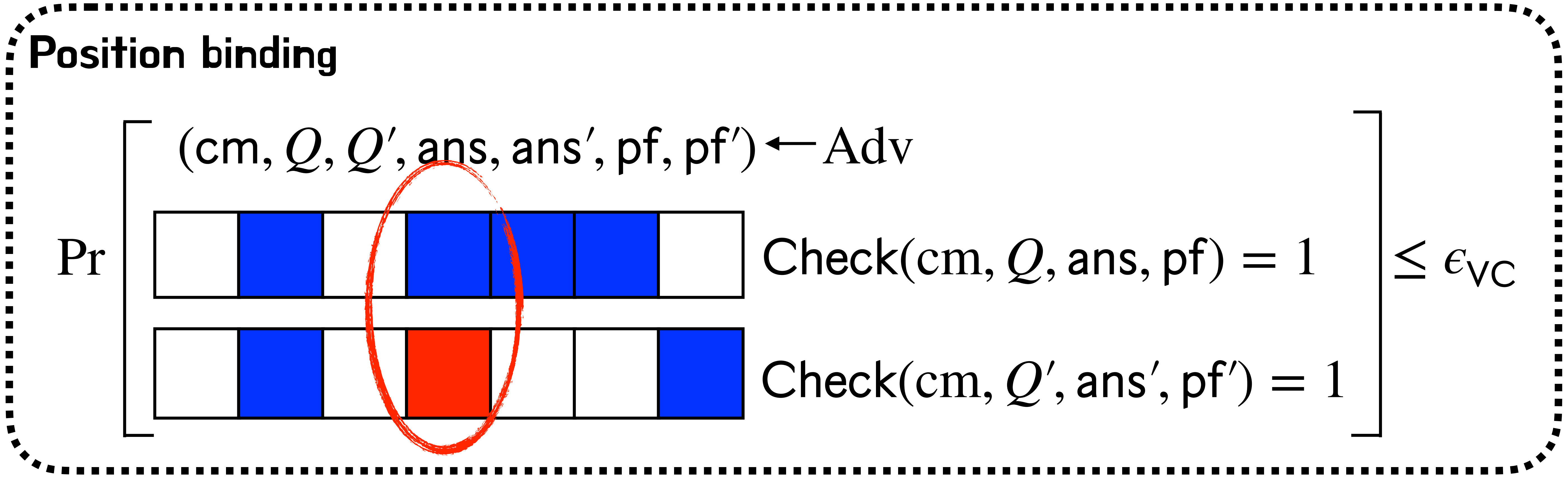
Rewind $\tilde{P}$ to get a malicious PCP string $\tilde{\Pi}$

$\Longrightarrow$ (PCP soundness) upper bound the success probability of $\tilde{\Pi}$

$\Longrightarrow$ (Position binding) $\tilde{\Pi}$ cannot be too different from $\tilde{P}$

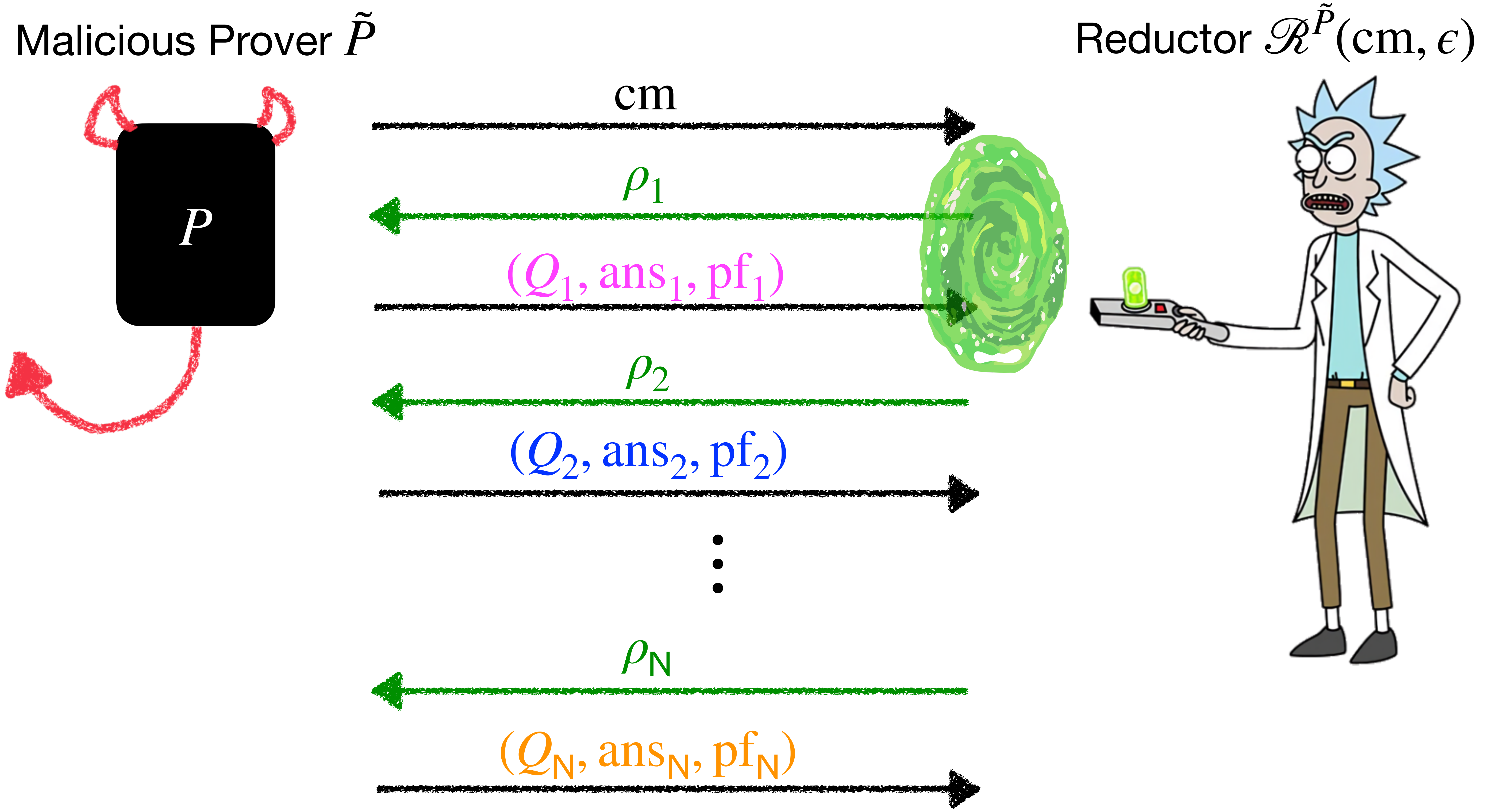
Kilian's protocol





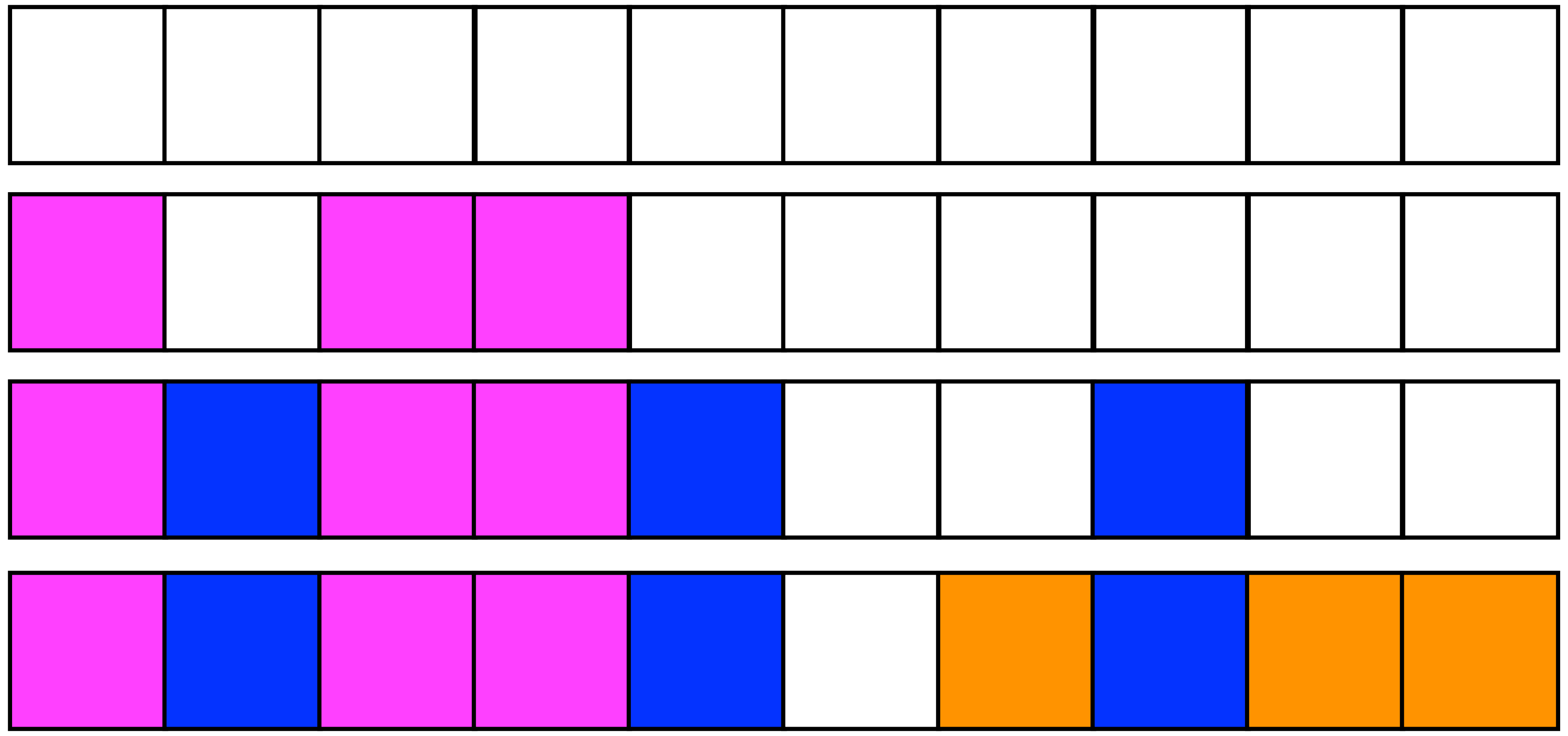
Security from rewinding

How to rewind?

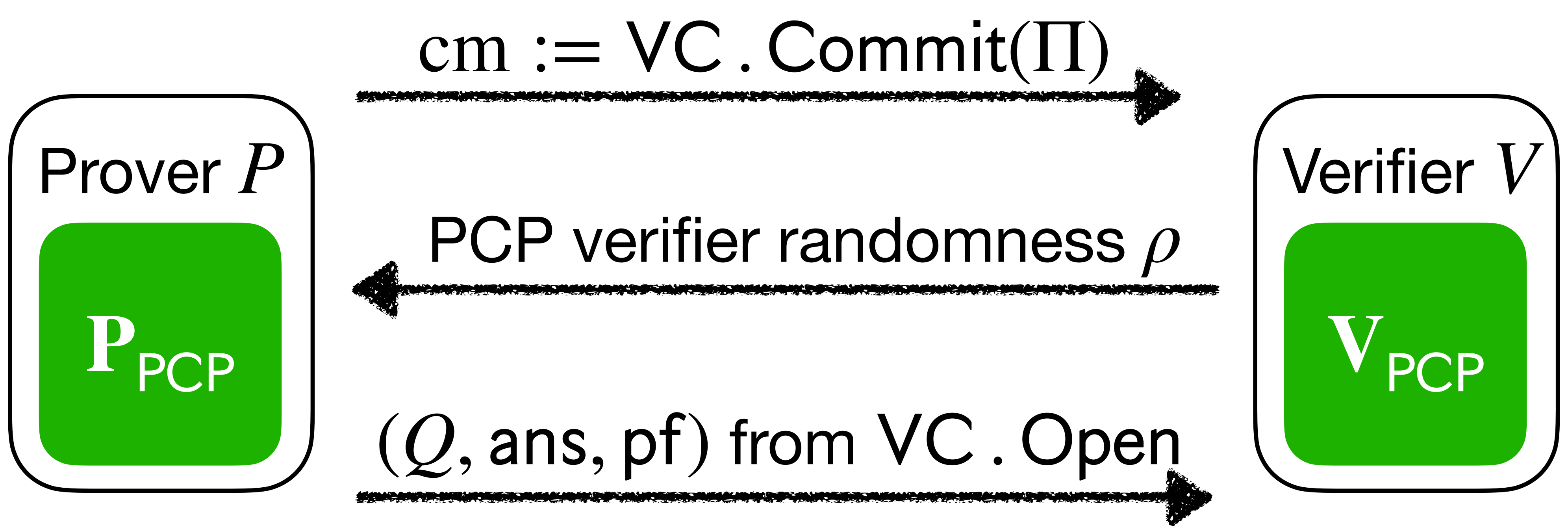


Subtle design choices:
- Strict time vs. expected time
- Sample with/without replacement
- Stopping conditions
- …

Recover $\tilde{\Pi}$



What is the security of Kilian's protocol?

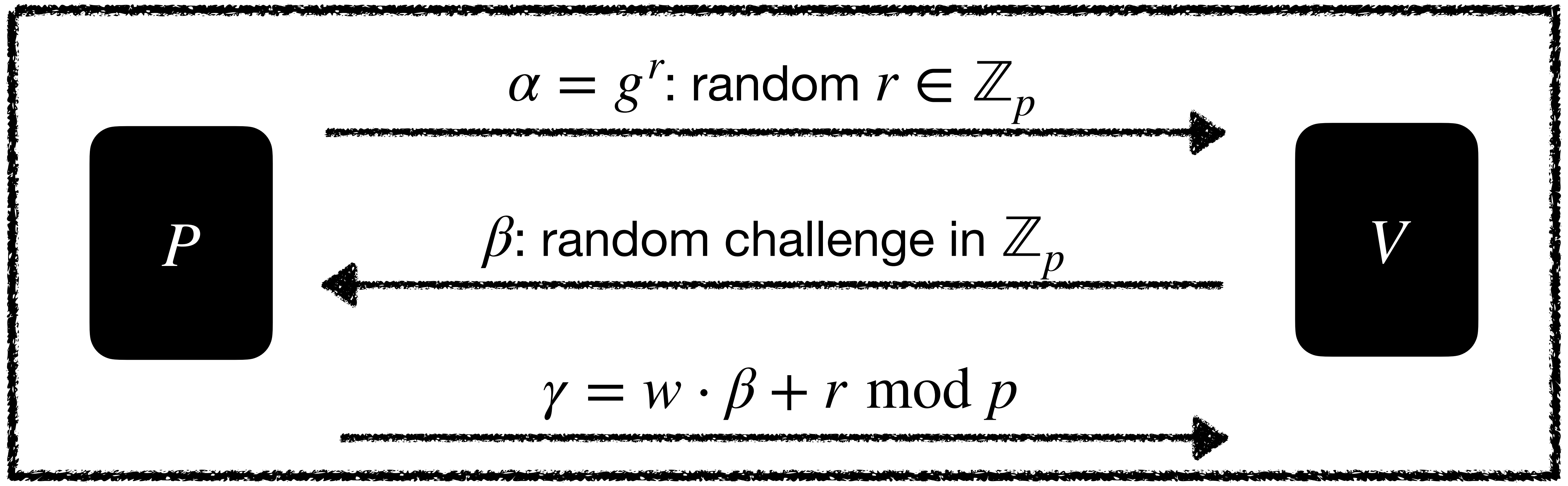


Previously:

- [Kilian92] gives an informal analysis
- [BG08] $\epsilon_{\mathsf{ARG}} \leq 8 \cdot \epsilon_{\mathsf{PCP}} + \sqrt[3]{\epsilon_{\mathsf{VC}}}$ and **assuming** PCP is non-adaptive & reverse-samplable (non-trivial restrictions)
- [CMSZ21] Kilian is secure when ϵ_{PCP} negligible (in a paper about post-quantum security)

We expect that $\epsilon_{\mathsf{ARG}} \leq \epsilon_{\mathsf{PCP}} + \epsilon_{\mathsf{VC}}$ ... right?

Surprise! A limitation: $\epsilon_{\text{ARG}} \leq \epsilon_{\text{PCP}} + \epsilon_{\text{VC}} \implies$ breakthrough on Schnorr



Lots of work on Schnorr security
[Sho97,PS00,BP02,FPS20,BD20,RS21,SSY23] ...
and yet there are still open questions on its optimal security!

Theorem. $\exists$ PCP and VC s.t.

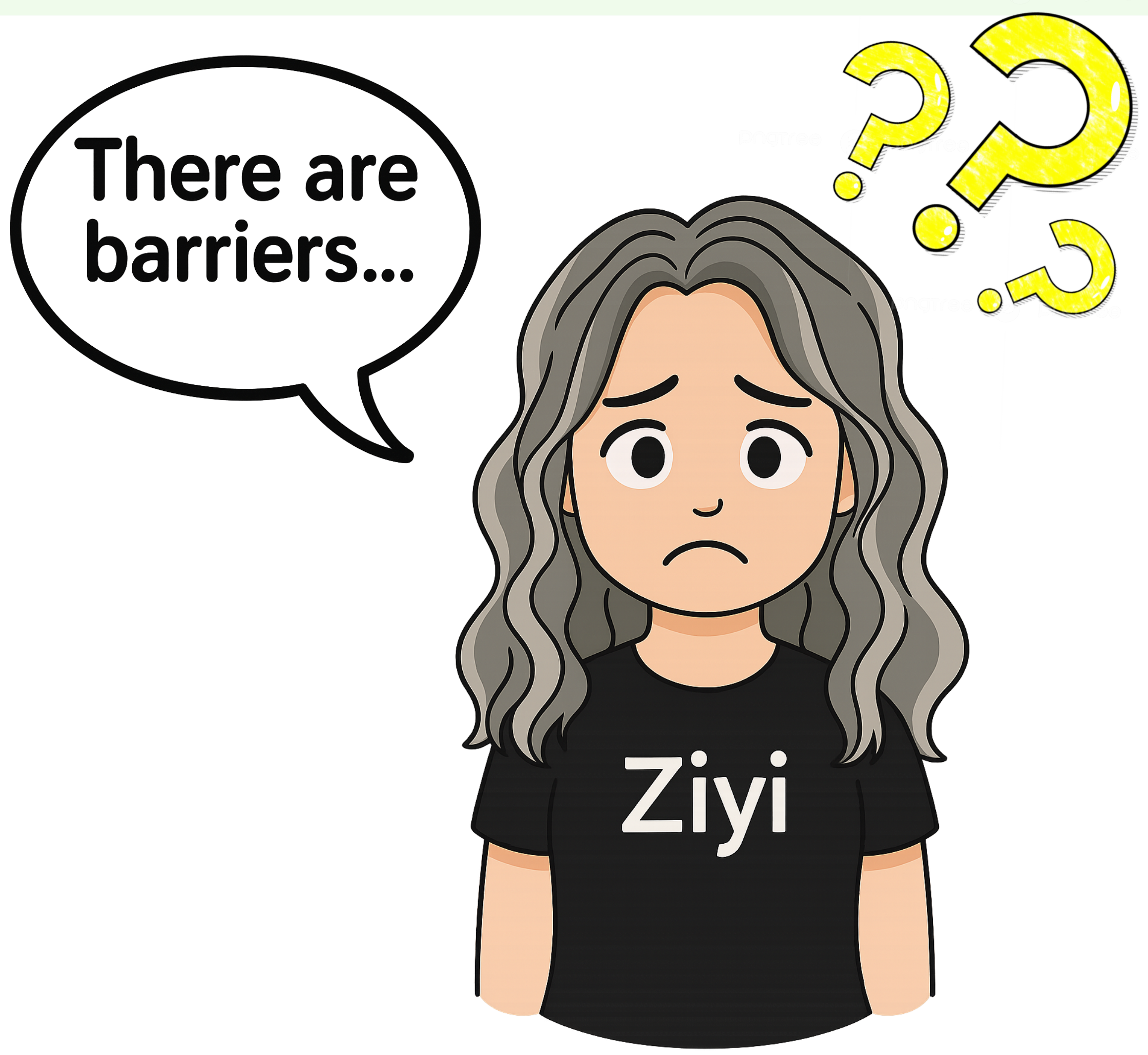
$$\epsilon_{\text{Schnorr}}(t) \leq \epsilon_{\text{ARG}}(t).$$

Similar bound holds for expected-time adversary

Suppose $\epsilon_{\text{ARG}} \leq \epsilon_{\text{PCP}} + \epsilon_{\text{VC}}$ $\implies$ $\epsilon_{\text{Schnorr}}(t_{\text{Schnorr}}) \leq \epsilon_{\text{DLOG}}(O(t_{\text{Schnorr}}))$

Best analysis of Schnorr [PS00]: $\epsilon_{\text{Schnorr}}(t_{\text{Schnorr}}) \leq \sqrt{\epsilon_{\text{DLOG}}(O(t_{\text{Schnorr}}))}$

... so the folklore is beyond current rewinding techniques



Improved security for Kilian

PCP for language L with
- proof length l
- query complexity q
- soundness error ϵ_{PCP}

→ ARG := Kilian[PCP, VC] ←

Vector commitment scheme with position binding error ϵ_{VC}

Theorem. $\forall\, \epsilon > 0$,

$$\epsilon_{\mathsf{ARG}}(t_{\mathsf{ARG}}) \leq \epsilon_{\mathsf{PCP}} + \epsilon_{\mathsf{VC}}(t_{\mathsf{VC}}) + \epsilon, \text{ where } t_{\mathsf{VC}} = O\left(t_{\mathsf{ARG}} \cdot l \cdot 1/\epsilon\right).$$

λ: security parameter

Why $l \cdot 1/\epsilon$ overhead?
- l locations in Π

$\Longrightarrow$ Rewind at least l times (e.g. maybe all PCP queries but 1 are fixed)
- Some rewinds yield garbage:
  - The locations were already found
  - VC check fails

$\Longrightarrow$ Need $1/\epsilon$ times for each location as buffer

Suppose $\epsilon_{\mathsf{VC}}(t) \leq O(t^2/2^{\lambda})$ (e.g. an ideal Merkle tree)

By **Theorem**:

$$\epsilon_{\mathsf{ARG}}(t_{\mathsf{ARG}}) \leq \epsilon_{\mathsf{PCP}} + l^{2/3} \cdot O\left(\sqrt[3]{t_{\mathsf{ARG}}^2/2^{\lambda}}\right)$$

That is, $\epsilon_{\mathsf{ARG}} \leq \epsilon_{\mathsf{PCP}} + \sqrt[3]{\epsilon_{\mathsf{VC}}}$

Alternative route: expected-time regime

PCP for language L with
- proof length l
- query complexity q
- soundness error ϵ_{PCP}

→ **ARG := Kilian[PCP, VC]** ←

Vector commitment scheme with expected-time position binding error $\epsilon^{\star}_{\text{VC}}$

Theorem. $\forall\, \epsilon > 0$,

$$\epsilon^{\star}_{\text{ARG}}(t^{\star}_{\text{ARG}}) \leq \epsilon_{\text{PCP}} + \epsilon^{\star}_{\text{VC}}(t^{\star}_{\text{VC}}) + \epsilon, \text{ where } t^{\star}_{\text{VC}} = O\left(t^{\star}_{\text{ARG}} \cdot \log(\mathsf{q}/\epsilon)\right).$$

λ: security parameter

Set $\epsilon^{\star}_{\text{VC}}(t^{\star}) \leq O\left(\sqrt{(t^{\star})^2/2^{\lambda}}\right)$ (e.g. an ideal Merkle tree)

Theorem $\Longrightarrow$

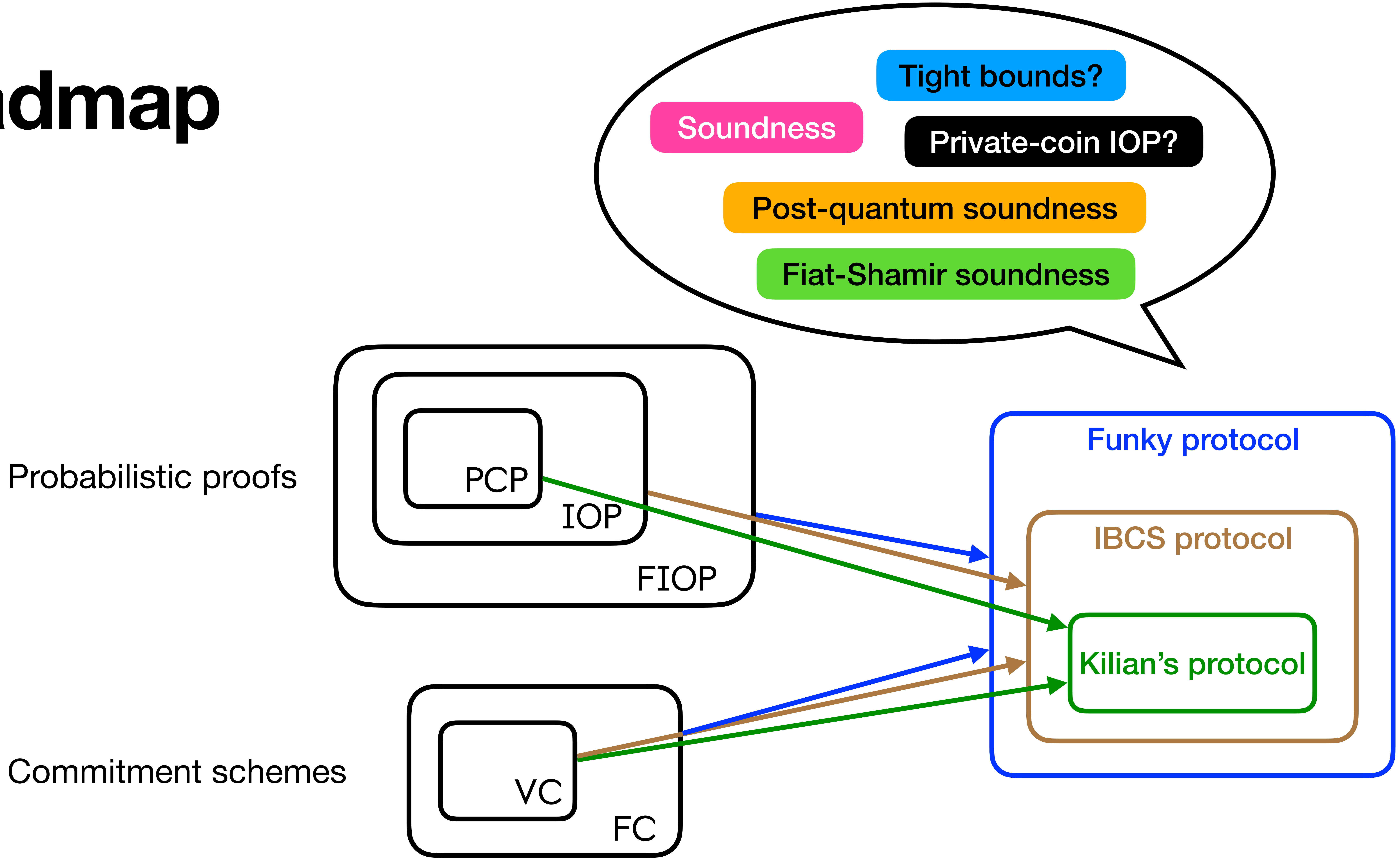
$$\epsilon^{\star}_{\text{ARG}}(t^{\star}_{\text{ARG}}) \leq \epsilon_{\text{PCP}} + \epsilon^{\star}_{\text{VC}}(t^{\star}_{\text{ARG}} \cdot \log(\mathsf{q}/\epsilon)) + \epsilon$$

$$\leq \epsilon_{\text{PCP}} + \text{polylog}\left(\mathsf{q} \cdot \sqrt{(t^{\star}_{\text{ARG}})^2/2^{\lambda}}\right) \cdot O\left(\sqrt[2]{(t^{\star}_{\text{ARG}})^2/2^{\lambda}}\right)$$

small factor

We achieved $\epsilon^{\star}_{\text{ARG}} \leq \epsilon_{\text{PCP}} + \epsilon^{\star}_{\text{VC}}$!

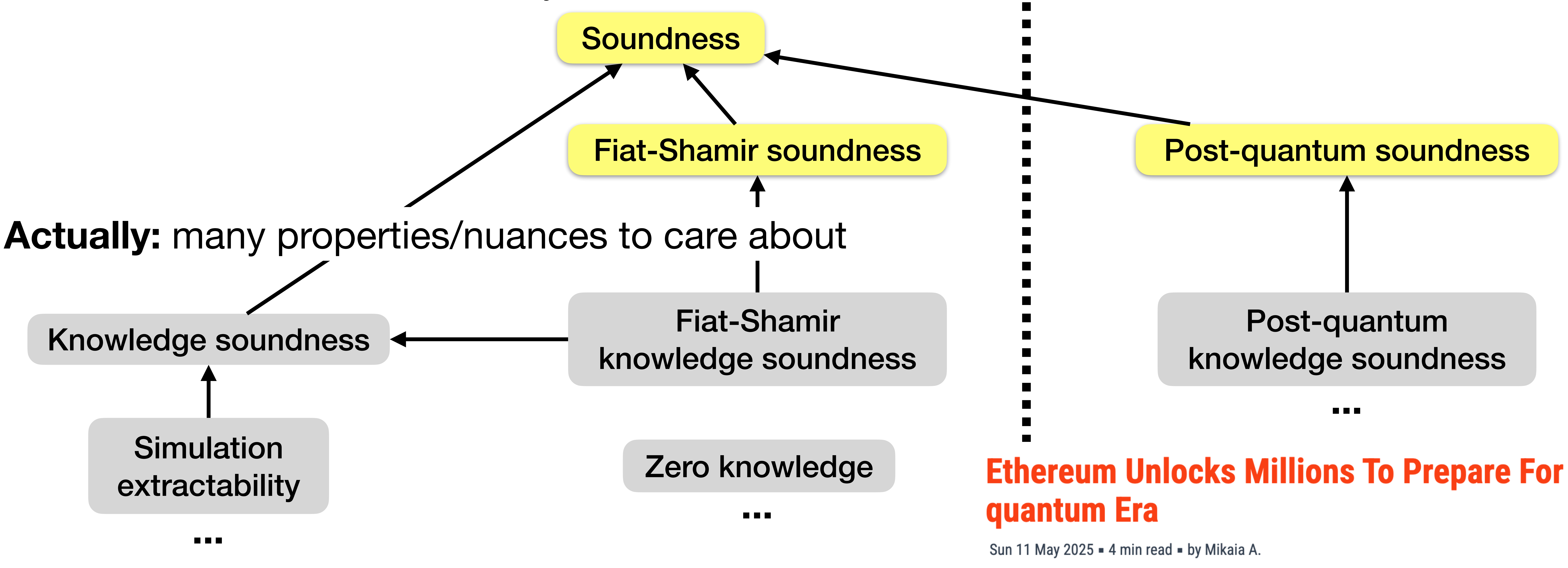
Roadmap


Tight bounds?
Soundness
Private-coin IOP?
Post-quantum soundness
Fiat-Shamir soundness
Probabilistic proofs
PCP
IOP
FIOP
Commitment schemes
VC
FC
Funky protocol
IBCS protocol
Kilian's protocol

On security notions of arguments

Today: focus on soundness only

Classical | Post-quantum



Actually: many properties/nuances to care about

Strict-time adversary vs. Expected-time adversary

e.g., [BL02] zero-knowledge protocols do not have strict poly-time (black-box) extractor

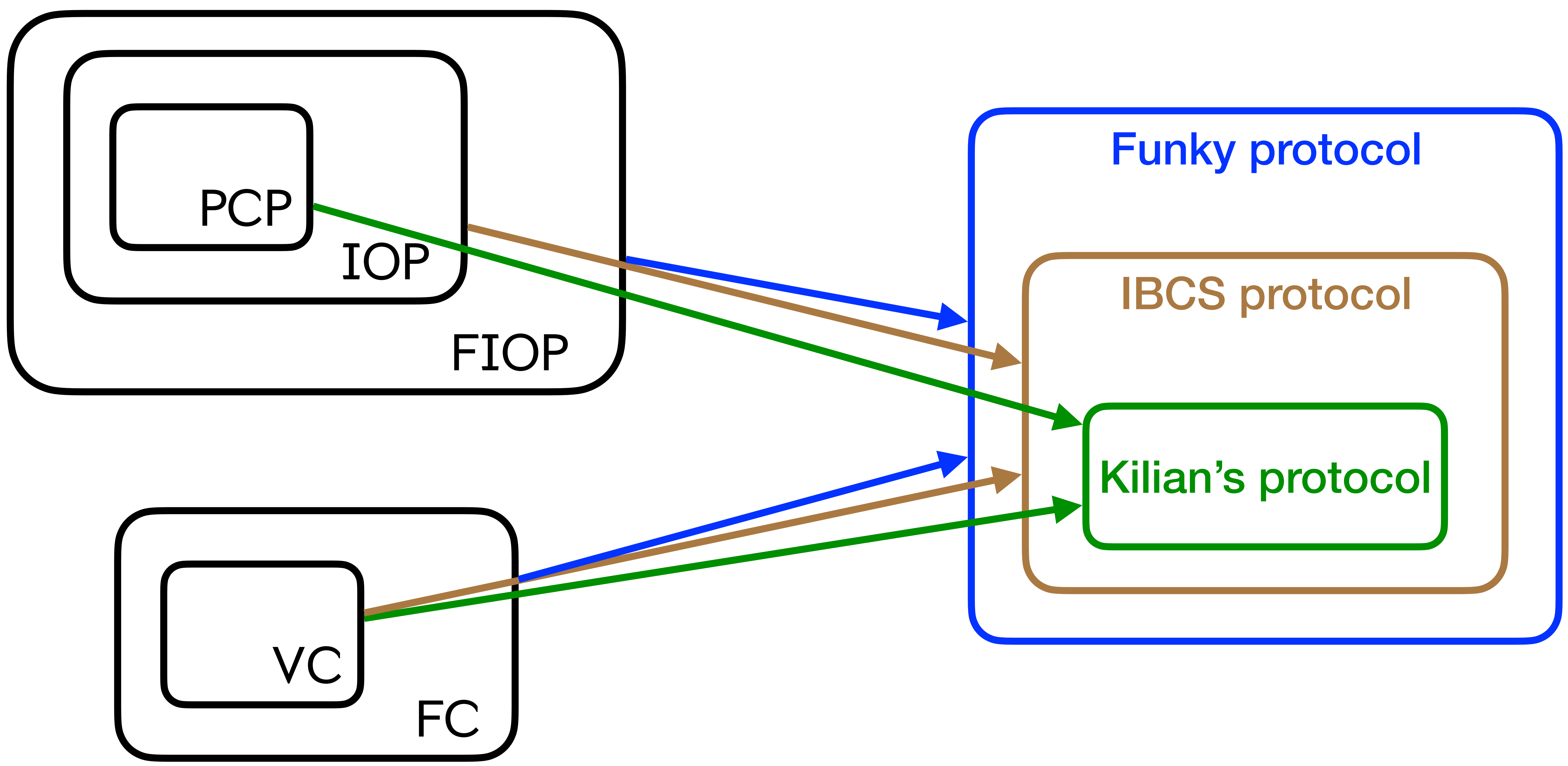
Ethereum Unlocks Millions To Prepare For The Post-quantum Era

Sun 11 May 2025 ▪ 4 min read ▪ by Mikaia A.

zkEVM Formal Verification Project

A project by the Ethereum Foundation to accelerate the application of formal verification methods to zkEVMs

IBCS protocol: Using IOPs instead of PCPs

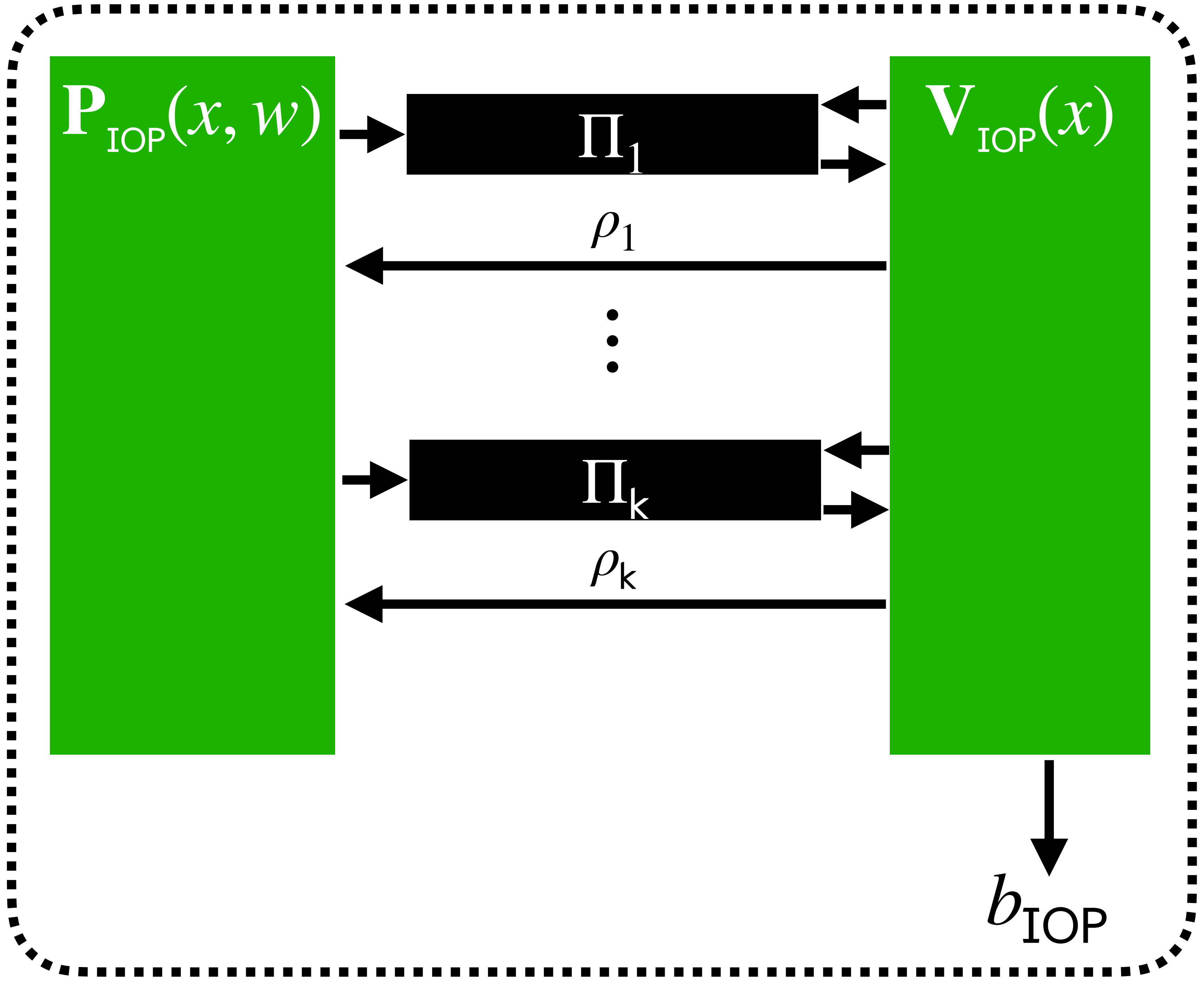


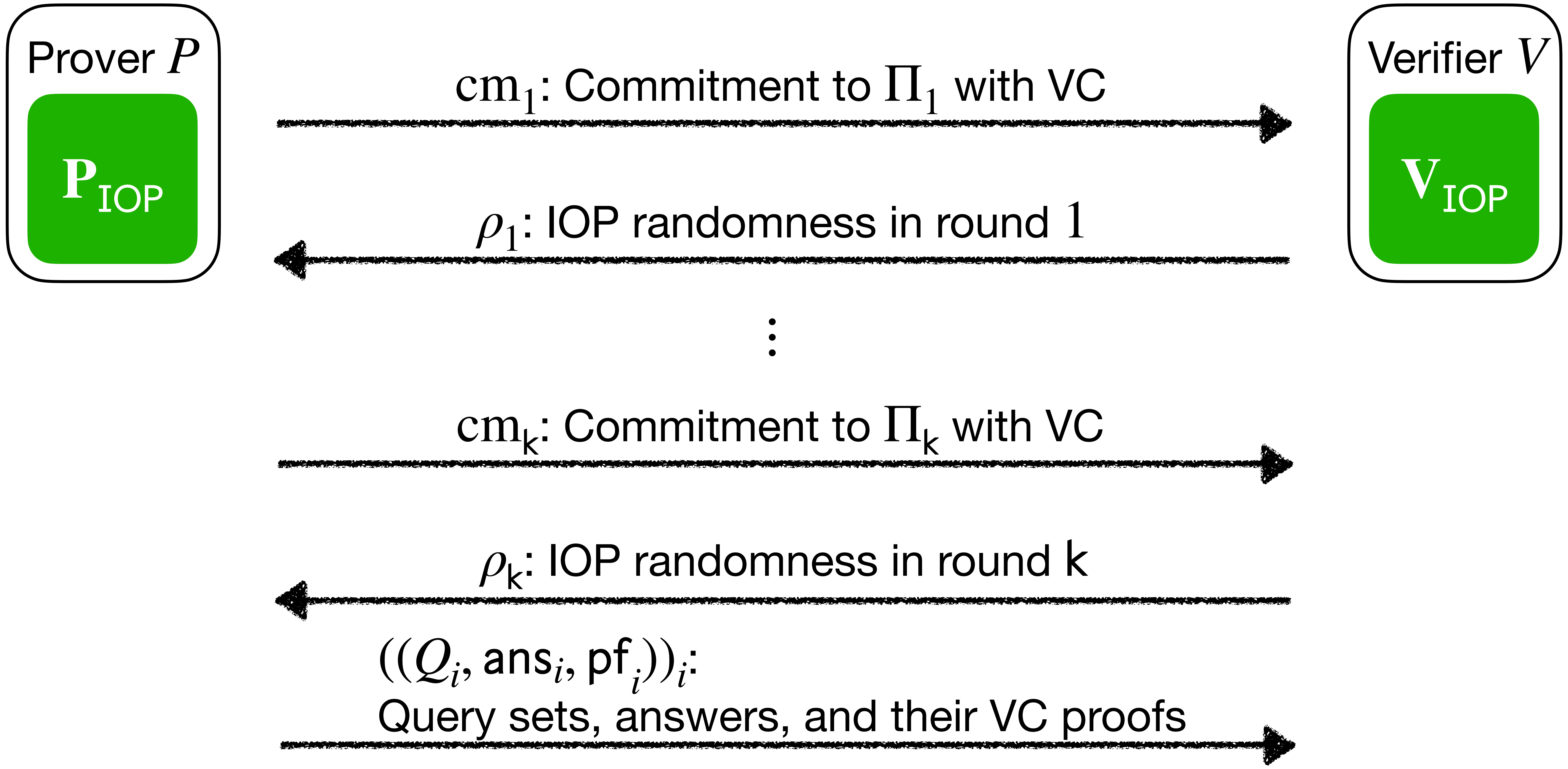
IBCS protocol

Existing PCPs are not concretely efficient: prover time too big

People use IOPs

Public-coin interactive oracle proof (IOP)





Security of IBCS protocol

Public-coin IOP for language L with
- proof length l
- query complexity q
- round complexity k
- soundness error ϵ_{IOP}

→ **ARG := IBCS[IOP, VC]** ←

Vector commitment scheme with position binding error ϵ_{VC}

The ideal bound ~~$\epsilon_{\text{ARG}} \leq \epsilon_{\text{IOP}} + \epsilon_{\text{VC}}$~~ is not possible… What can we get?

Theorem. $\forall\, \epsilon > 0$,

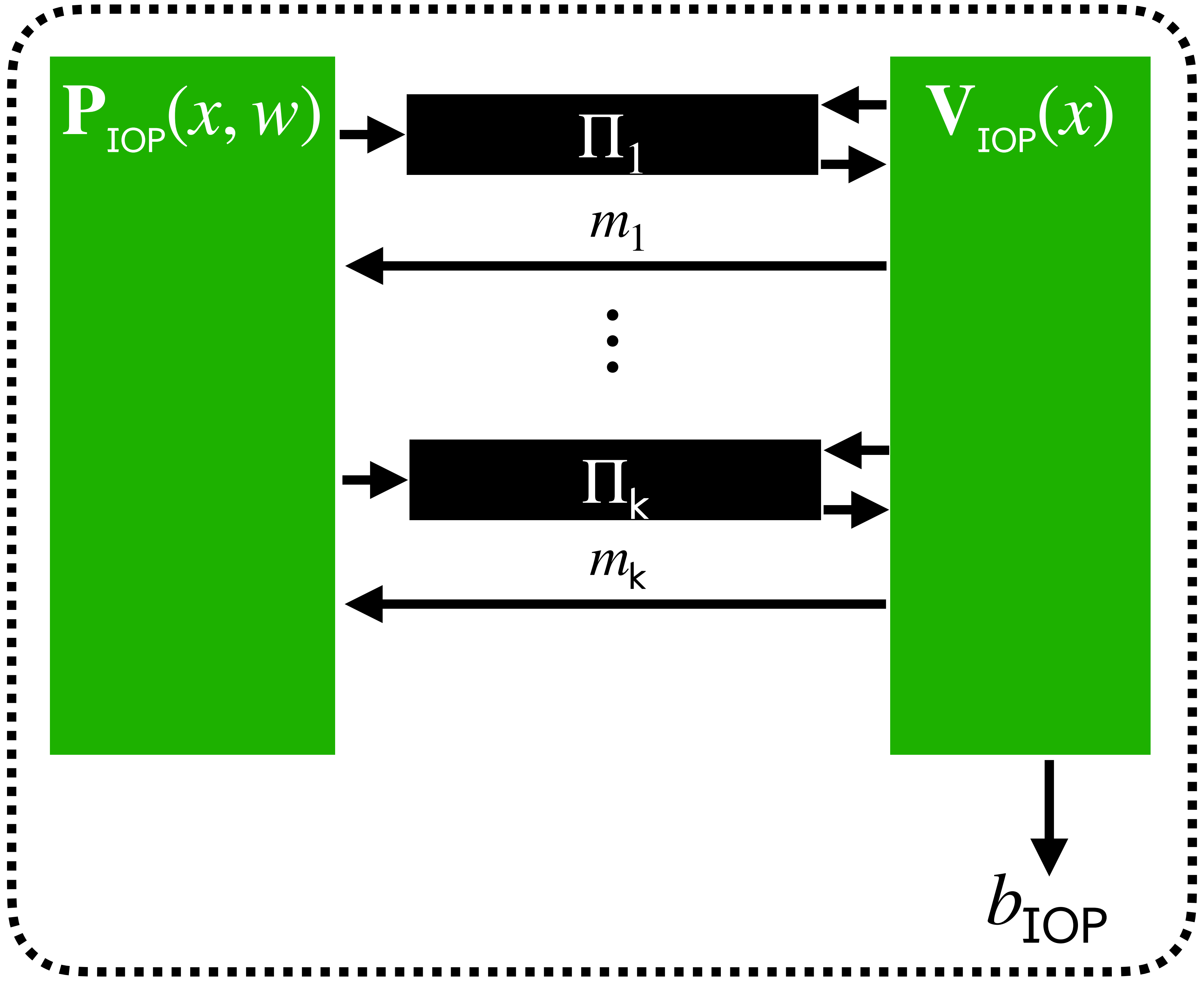
$$\epsilon_{\text{ARG}}(t_{\text{ARG}}) \leq \epsilon_{\text{IOP}} + \text{k} \cdot \epsilon_{\text{VC}}(t_{\text{VC}}) + \epsilon, \text{ where } t_{\text{VC}} = O\left(t_{\text{ARG}} \cdot l/\epsilon\right).$$

Recall, for Kilian's protocol: $\forall\, \epsilon > 0$,

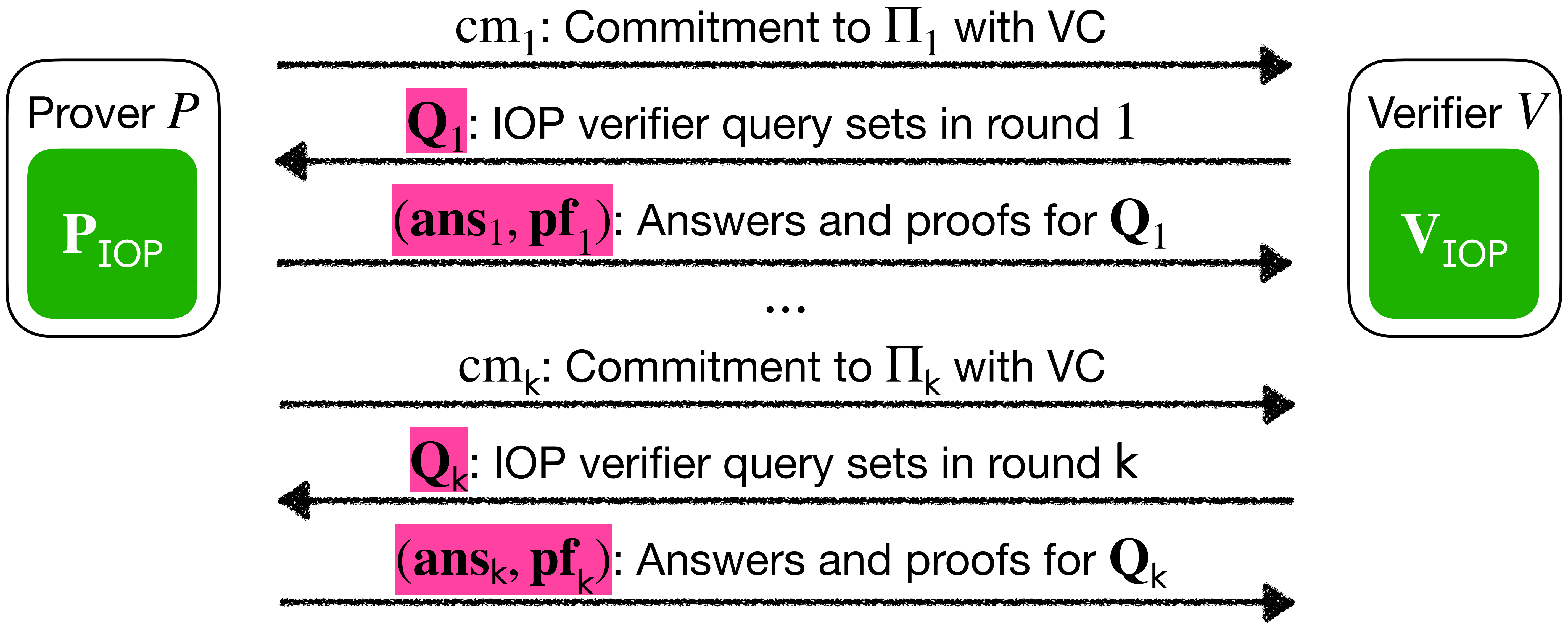
$$\epsilon_{\text{ARG}}(t_{\text{ARG}}) \leq \epsilon_{\text{PCP}} + 1 \cdot \epsilon_{\text{VC}}(t_{\text{VC}}) + \epsilon, \text{ where } t_{\text{VC}} = O\left(t_{\text{ARG}} \cdot l/\epsilon\right).$$

Why do we need public-coin IOPs?

Private-coin interactive oracle proof (IOP)



$\mathbf{Q}_i$ contains verifier's queries to $\Pi_1, \ldots, \Pi_i$



Not secure!
e.g. IOP verifier accepts if IOP prover guesses all its queries

How about public-query IOPs?

Queries can be learned by the prover (in "real-time")

Clearly, the IBCS protocol is secure whenever the underlying IOP is public-query... right?

Lemma: secure if IOP has an "efficient random continuation sampler"

Open question: can we prove security for ALL public-query IOPs?
(Or maybe there is a black-box barrier?)

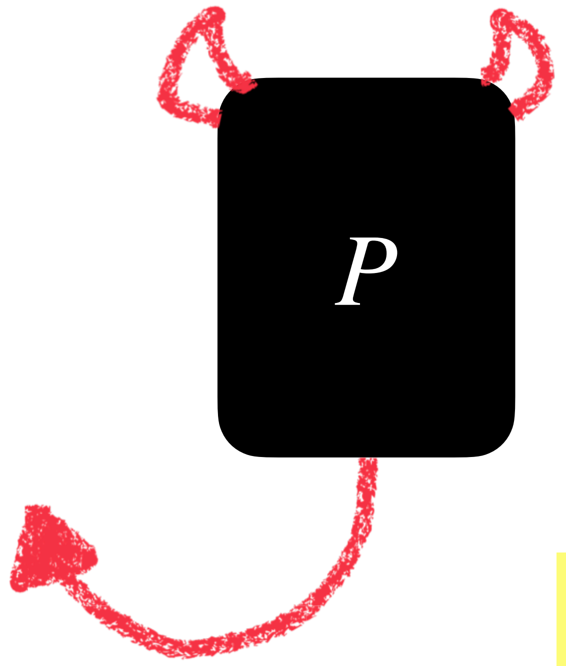
Interlude: post-quantum security

Post-quantum soundness: same as classical soundness but adversary is quantum

$$\forall\ t_{\mathsf{ARG}}\text{-time } \textbf{QUANTUM} \text{ adversary } \tilde{P}, \Pr\left[\langle \tilde{P}, V\rangle = 1\right] \leq \epsilon_{\mathsf{ARG}}(t_{\mathsf{ARG}})$$

On quantum rewinding

Malicious Prover $\tilde{P}$



Prover state $|\phi\rangle$

cm

ρ_1

Prover state $|\phi'\rangle$

$(Q_1, \mathrm{ans}_1, \mathrm{pf}_1)$

Measure!

ρ_2

How to go back to $|\phi\rangle$?

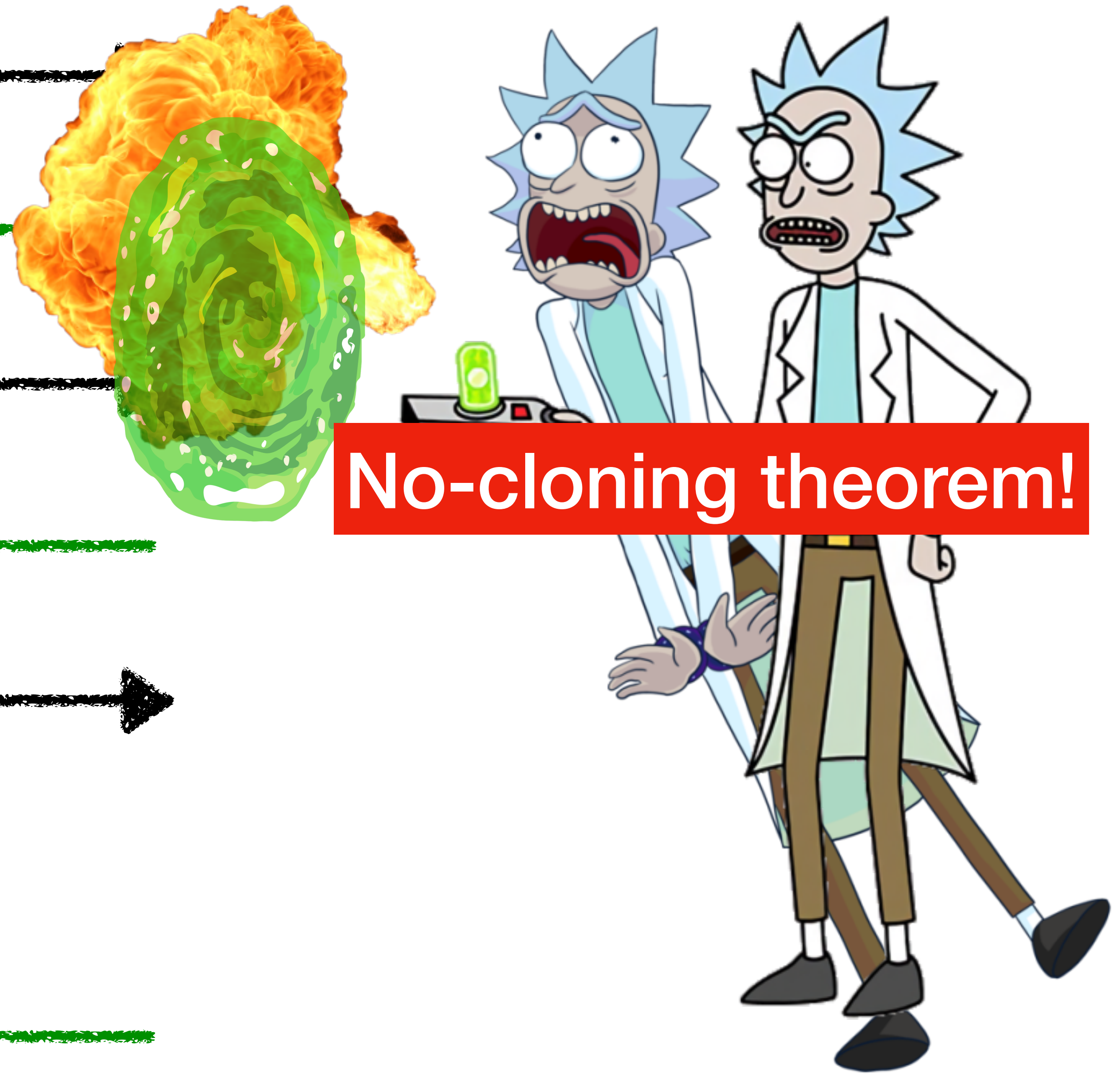
$(Q_2, \mathrm{ans}_2, \mathrm{pf}_2)$

⋮

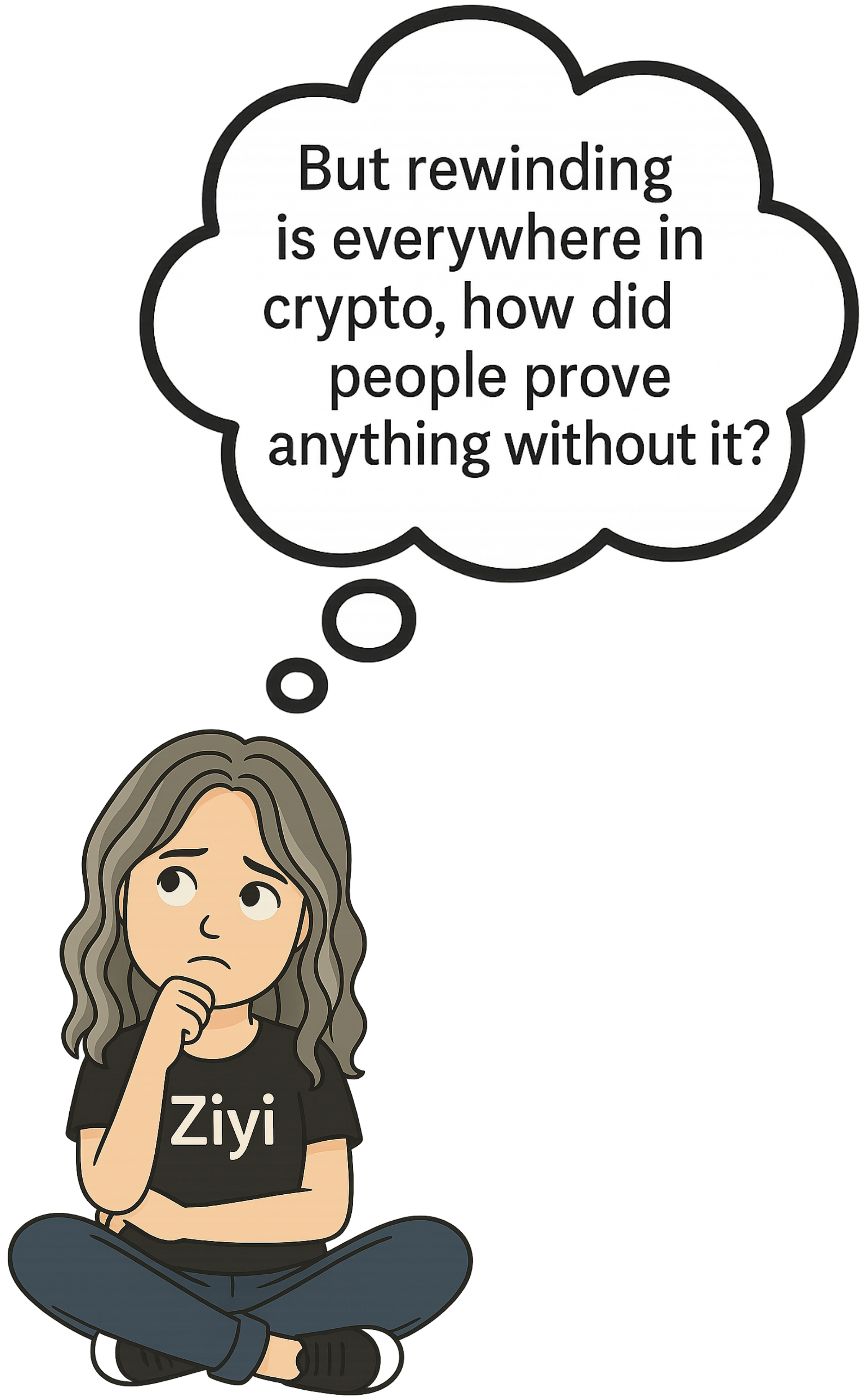
ρ_{N}

$(Q_{\mathrm{N}}, \mathrm{ans}_{\mathrm{N}}, \mathrm{pf}_{\mathrm{N}})$

Reductor $\mathscr{R}^{\tilde{P}}(\mathrm{cm}, \epsilon)$



No-cloning theorem!



For many years: can rewind O(1) times [Wat06,Unr12,Unr16b]

Problem: Kilian's protocol needs many rewindings

Recent new tools for quantum rewinding [CMSZ21]: "repair" the state instead of "rewind"
$\Longrightarrow$ post-quantum security of Kilian's protocol

- Quantum rewinding toolset is cumbersome
- Only other paper studying many-round interactive arguments [LMS22] had to white-box adapt the tools in [CMSZ21]… (work for log rounds)

Adapting for IBCS protocol runs into challenges

Post-quantum security of IBCS protocol

IOP is statistically sound
Post-quantum already

IOP for language L with
- proof length l
- query complexity q
- round complexity k
- soundness error ϵ_{IOP}

ARG := IBCS[IOP, VC]

Quantum analogue of position binding

Vector commitment scheme with collapsing error $\epsilon_{\text{VCCollapse}}$

Technical contribution: We build on [CMSZ21] and more…

Theorem. $\forall\, \epsilon > 0$,

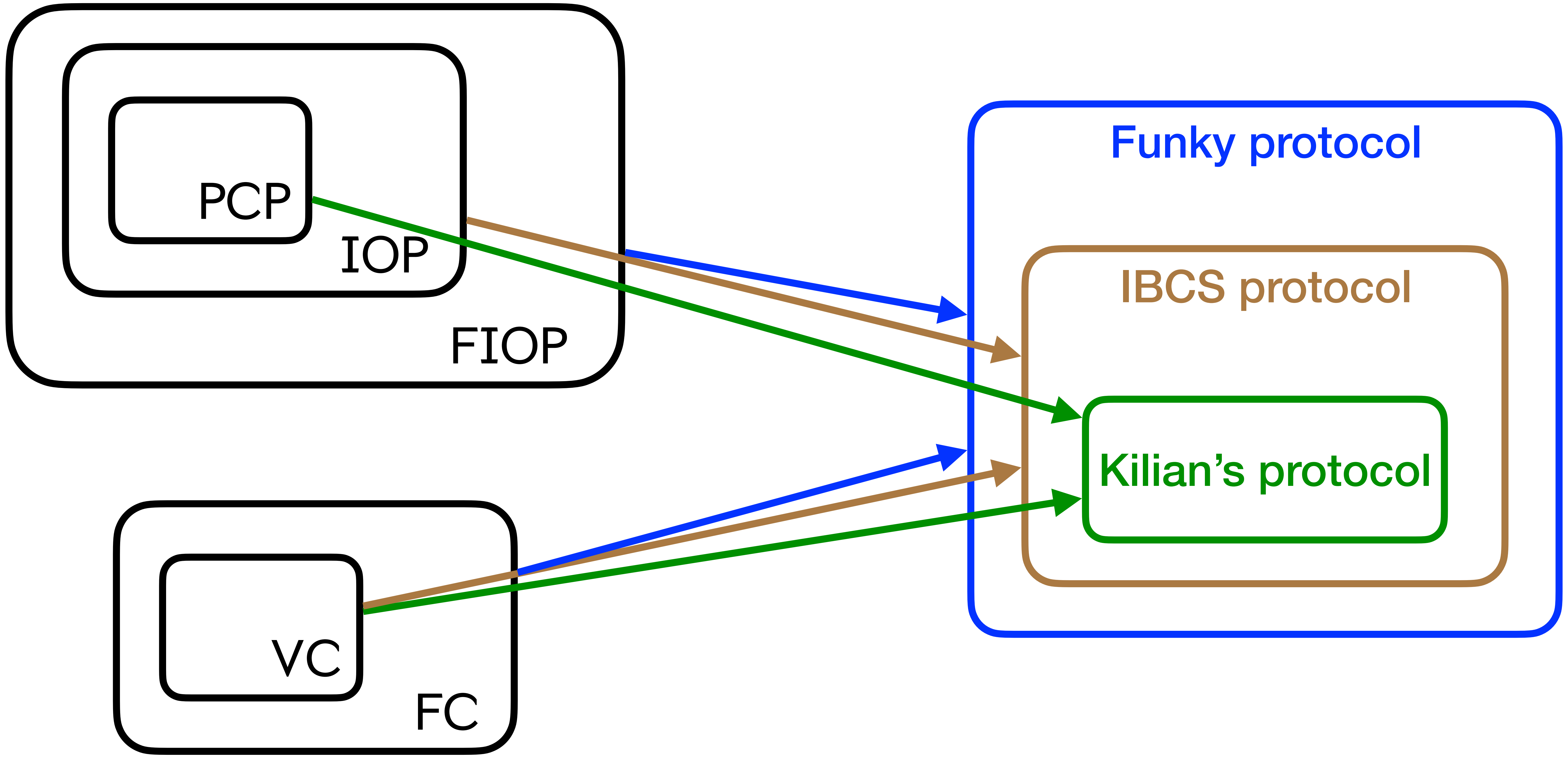
$$\epsilon^{\text{PQ}}_{\text{ARG}}(t_{\text{ARG}}) \leq \epsilon_{\text{IOP}} + \text{k} \cdot l \cdot \epsilon_{\text{VCCollapse}}(t_{\text{VC}}) + \epsilon, \text{ where } t_{\text{VC}} = \text{poly}\left(t_{\text{ARG}} \cdot l/\epsilon\right).$$

Extra l factor: cost of quantum rewinding

IBCS soundness: $\epsilon_{\text{ARG}}(t_{\text{ARG}}) \leq \epsilon_{\text{IOP}} + \text{k} \cdot \epsilon_{\text{VC}}(t_{\text{VC}}) + \epsilon$, where $t_{\text{VC}} = O\left(t_{\text{ARG}} \cdot l/\epsilon\right)$.

Corollary: post-quantum secure succinct arguments in the standard model (no oracles), with the best asymptotic complexity known.

Funky protocol:
Construction from all probabilistic proofs



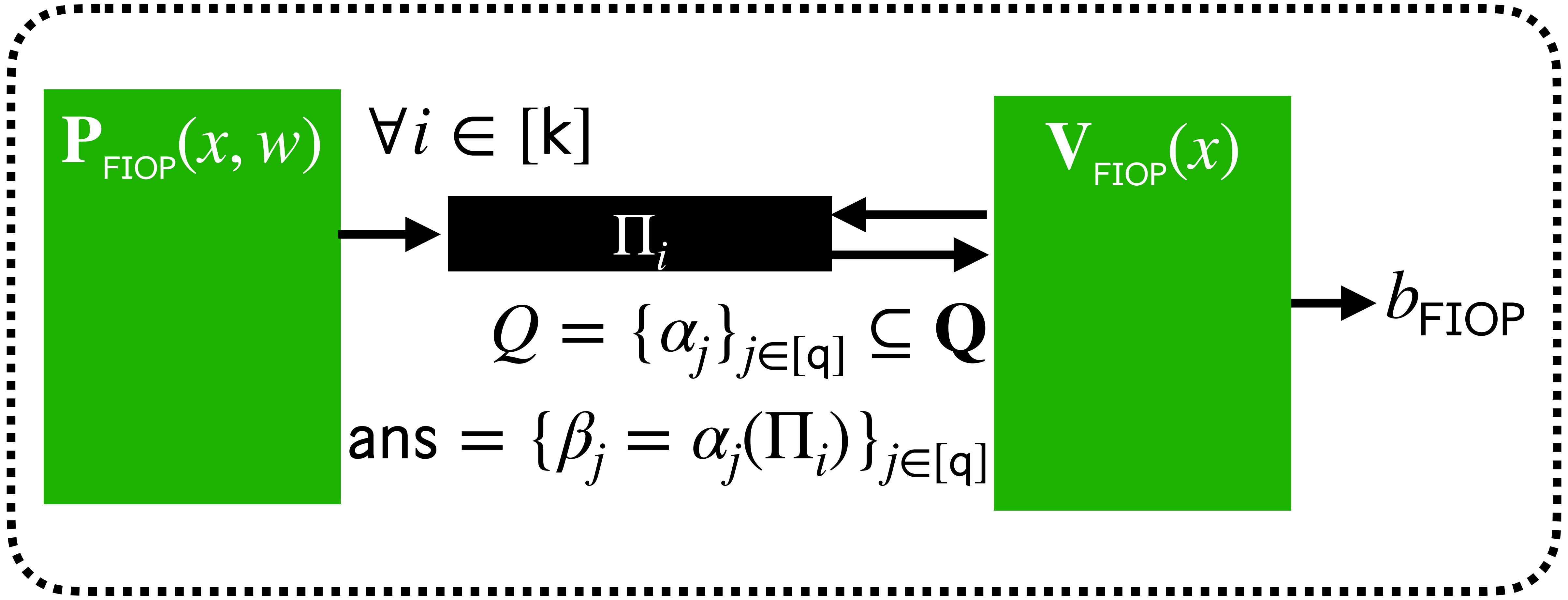
[CGKY25]

Building blocks

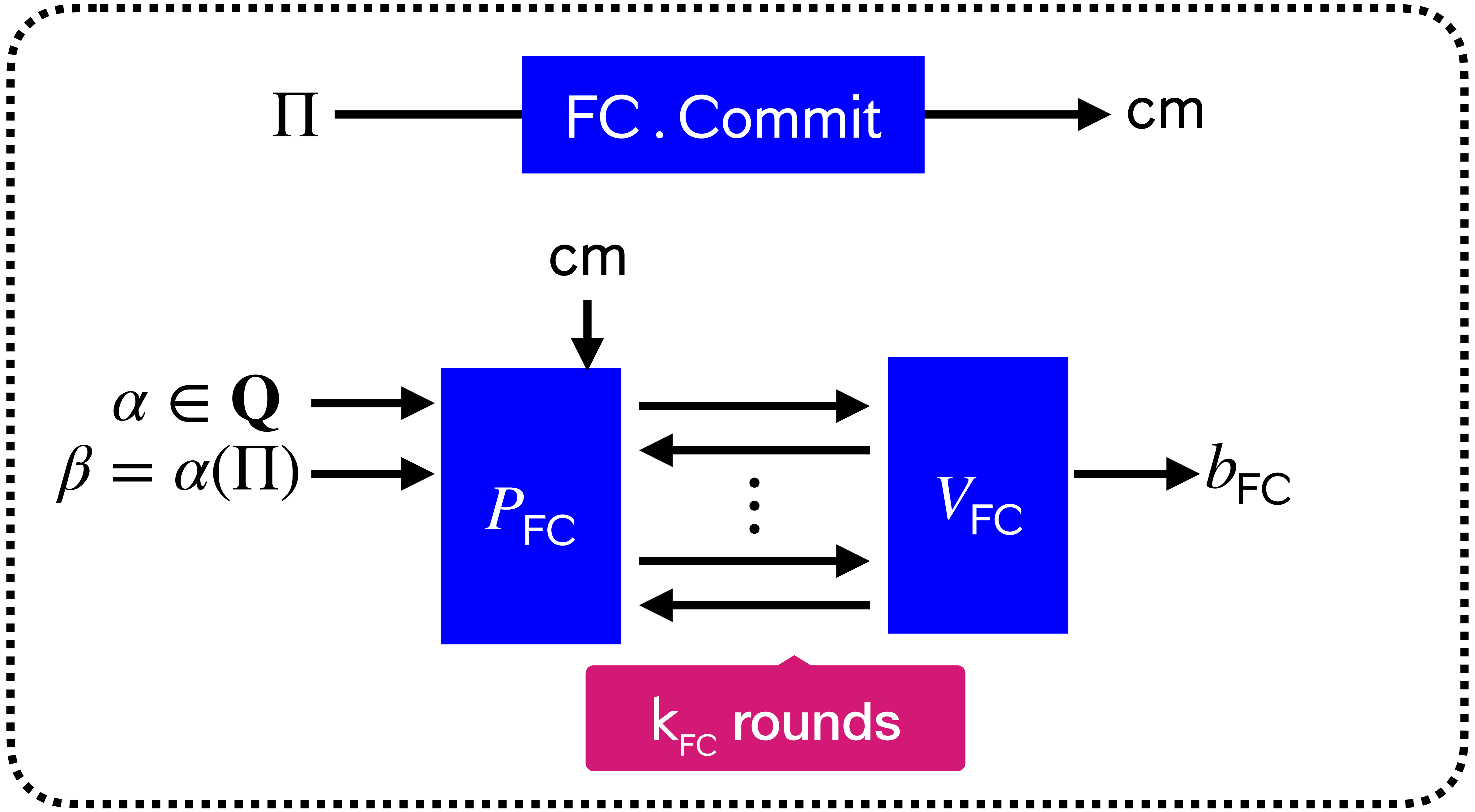
Building block #1: query class $\mathbf{Q}$

- $\mathbf{Q} \subseteq \{\alpha \colon \Sigma^{\ell} \to \mathbb{D}\}$

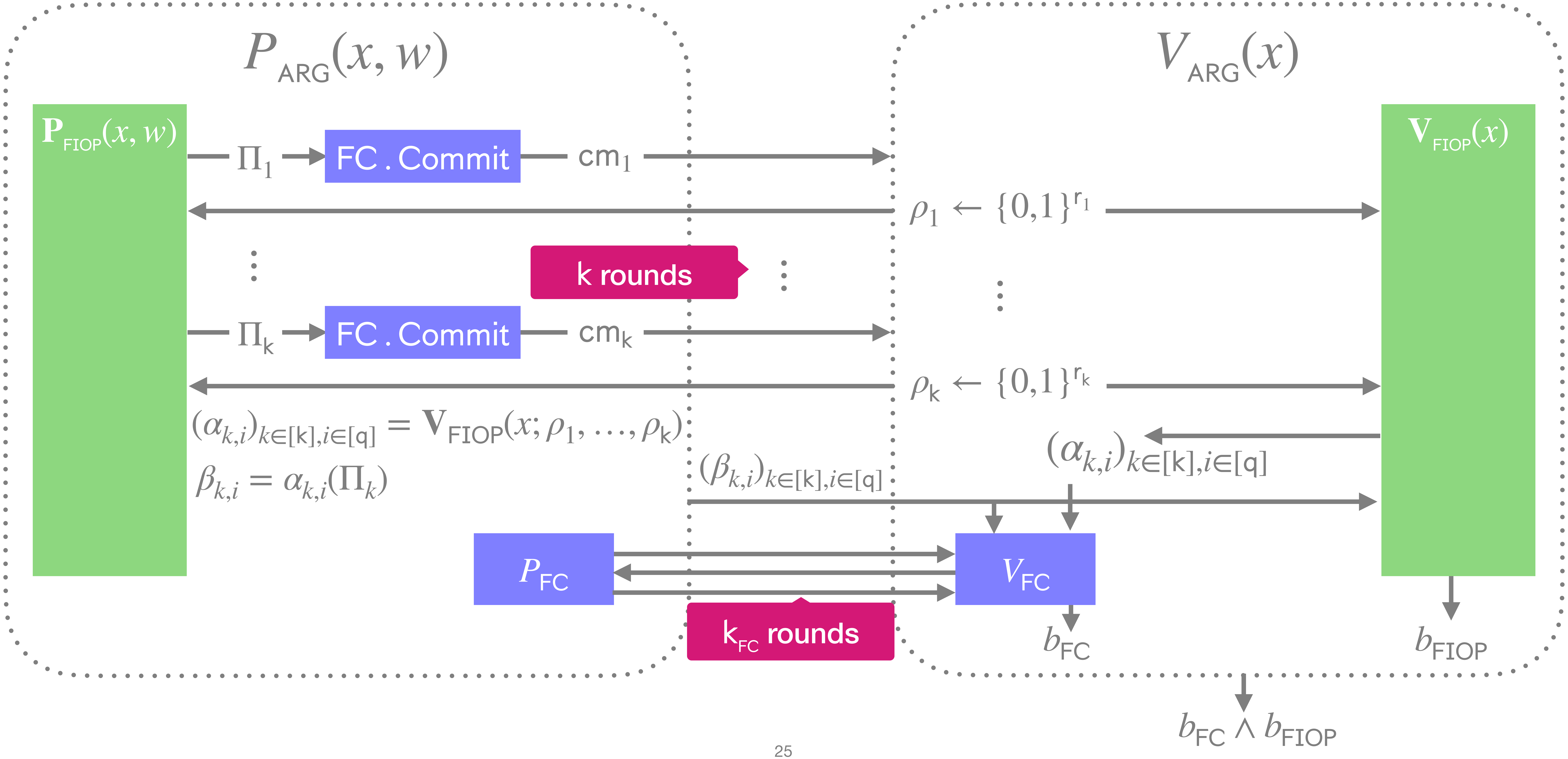
Building block #2: functional interactive oracle proof (FIOP)



Building block #3: functional commitment scheme (FC)



Funky protocol



Special cases of the Funky protocol

	Proof string	Query class	Answer
PCP+VC [Kilian92] **IOP+VC** [BCS16,CDGS23]	$\Pi \in \Sigma^{\ell}$	point queries $\mathbf{Q}_{\text{point}}$	$\beta = \Pi[\alpha]$ for $\alpha \in [\ell]$
LPCP+LC [LM19]	$\Pi \in \mathbb{F}^{\ell}$	linear queries $\mathbf{Q}_{\text{lin}}$	$\beta = \sum_{i \in [\ell]} \Pi[i] \cdot \alpha[i]$ for $\alpha \in \mathbb{F}^{\ell}$
PIOP+PC [CHM+20,BFS20]	$\Pi \in \mathbb{F}[X]^{\leq \text{D}}$	evaluation queries on polynomials $\mathbf{Q}_{\text{poly}}$	$\beta = \sum_{i \in [\ell]} \Pi[i] \cdot \alpha^{i-1}$ for $\alpha \in \mathbb{F}$
PIOP*+PC* [GWC19]	$\Pi \in (\mathbb{F}[X]^{\leq \text{D}})^{m+n}$ $= (f_1, \ldots, f_m, g_1, \ldots, g_n)$	evaluation queries on structured polys $\mathbf{Q}_{\text{poly}*}$	$\beta = \sum_{k \in [n]} h_k(f_1(\alpha), \cdots, f_m(\alpha)) \cdot g_k(\alpha)$

Beyond Funky: Bulletproofs (and other sumcheck-based arguments), linear-only encodings [BCIOP13, GGPR13, Groth16], …

Special cases of the Funky protocol

	Proof string	Query class	Answer
PCP+VC IOP+VC			
LPCP+L			
PIOP+P			
PIOP*+P			$_k(\alpha)$

Funky protocol is everywhere

Succinct · RISC ZERO · Ligero · VALIDA · STARKWARE · Aztec · MatterLabs · polygon · NEXUS · Irreducible · ...

Beyond Funky: Bulletproofs (and other sumcheck-based arguments), linear-only encodings [BCIOP13, GGPR13, Groth16], …

Which security property for FC?

Earlier in this talk IOP+VC
$\epsilon_{\text{ARG}} \approx \epsilon_{\text{IOP}} + \epsilon^{\text{PB}}_{\text{VC}}$

Vector Commitments position binding: $\Pr\left[\begin{array}{l}\beta_1 \neq \beta_2 \\ \wedge\, \forall i: \mathsf{FC.Check}(\mathsf{pp}, \mathsf{cm}, \alpha_i, \beta_i, \mathsf{pf}_i) = 1\end{array} \,\middle|\, (\mathsf{cm}, \alpha, \beta_1, \mathsf{pf}_1, \beta_2, \mathsf{pf}_2) \leftarrow A(\mathsf{pp})\right] \leq \epsilon$

[LM19] LPCP+LC
$\epsilon_{\text{ARG}} \approx \epsilon_{\text{LPCP}} + \epsilon^{\text{FB}}_{\text{LC}}$

Linear Commitments function binding: $\Pr\left[\begin{array}{l}\nexists \Pi: \forall i: \langle \alpha_i, \Pi \rangle = \beta_i \\ \wedge\, \forall i: \mathsf{FC.Check}(\mathsf{pp}, \mathsf{cm}, \alpha_i, \beta_i, \mathsf{pf}_i) = 1\end{array} \,\middle|\, (\mathsf{cm}, (\alpha_i, \beta_i, \mathsf{pf}_i)_{i \in [n]}) \leftarrow A(\mathsf{pp})\right] \leq \epsilon$

[CHMMVW20, BFS20] PIOP+PC
$\epsilon_{\text{ARG}} \approx \epsilon_{\text{PIOP}} + \kappa_{\text{PC}}$

Polynomial Commitments binding? strong correctness? interpolation binding? extractability?
[KZG10] [AJMMS23] [CHM+20, BFS20]

Too strong

Functional Commitments function binding: $\Pr\left[\begin{array}{l}\nexists \Pi: \forall i: \alpha_i(\Pi) = \beta_i \\ \wedge\, \forall i: \mathsf{FC.Check}(\mathsf{pp}, \mathsf{cm}, \alpha_i, \beta_i, \mathsf{pf}_i) = 1\end{array} \,\middle|\, (\mathsf{cm}, (\alpha_i, \beta_i, \mathsf{pf}_i)_{i \in [n]}) \leftarrow A(\mathsf{pp})\right] \leq \epsilon$

Security of Funky protocol

Internal property of $\mathbf{Q}$
Independent of FIOP/FC

FIOP for language L with
- proof length l
- query complexity q
- round complexity k
- soundness error ϵ_{FIOP}

ARG := Funky[FIOP, FC]

Query class $\mathbf{Q}$ with tail error $\epsilon_{\mathbf{Q}}$

Functional commitment scheme with function binding error ϵ_{FC}

Theorem. $\forall\, \mathsf{N} \in \mathbb{N}$,

$$\epsilon_{\mathsf{ARG}}(t_{\mathsf{ARG}}) \leq \epsilon_{\mathsf{FIOP}} + \mathsf{k} \cdot \epsilon_{\mathsf{FC}}(t_{\mathsf{FC}}) + \mathsf{k} \cdot \epsilon_{\mathbf{Q}}(l, \mathsf{N}), \text{ where } t_{\mathsf{FC}} = O\left(t_{\mathsf{ARG}} \cdot \mathsf{N}\right).$$

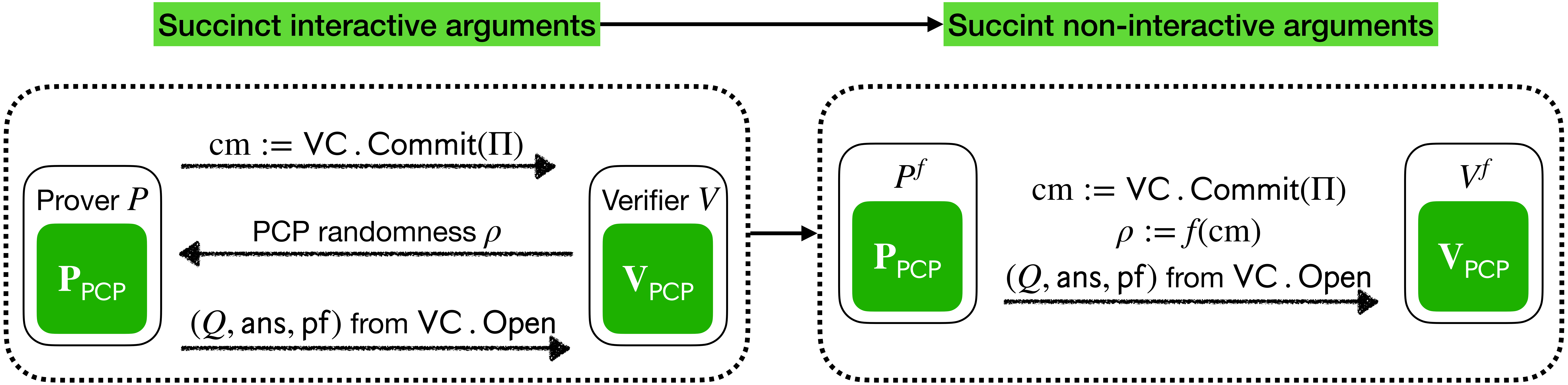
TLDR:
- **A “tight” security notion for FC schemes**
- **Concrete and tight bounds using tail errors**

$\epsilon_{\mathbf{Q}_{\mathsf{point}}}(l, \mathsf{N}) = l/\mathsf{N} \implies$ **recovers the bounds for Kilian’s protocol and IBCS protocol**

Fiat-Shamir security:
From succinct arguments to SNARGs

Fiat-Shamir transformation

Random oracle: $\mathcal{O} = \{\mathcal{O}_\lambda\}_{\lambda \in \mathbb{N}}$
$\mathcal{O}_\lambda$: uniform distribution over $\{f\colon \{0,1\}^* \to \{0,1\}^\lambda\}$



Central question: Is security preserved after the Fiat-Shamir transformation?

In generical no [CY24]: $\epsilon_{\mathsf{NARG}}(x, t, m) \leq (m+1)^{\mathsf{k}} \cdot \epsilon_{\mathsf{ARG}}(x, t)$

RO queries

k might be superconstant!

Fiat-Shamir security

FIOP for language L with
- proof length l
- query complexity q
- round complexity k
- Fiat-Shamir soundness error $\epsilon^{\mathsf{FS}}_{\mathsf{FIOP}}$

→ ARG := Funky[FIOP, FC] ←

Query classes $\mathbf{Q}$ with tail error $\epsilon_{\mathbf{Q}}$

Functional commitment scheme with
Fiat-Shamir function binding error $\epsilon^{\mathsf{FSFB}}_{\mathsf{FC}}$

Theorem. $\forall$ N $\in \mathbb{N}$,

$$\epsilon_{\mathsf{NARG}}(t_{\mathsf{ARG}}, m_{\mathsf{ARG}}) \leq \epsilon^{\mathsf{FS}}_{\mathsf{FIOP}}(O(m_{\mathsf{ARG}})) + \mathsf{k} \cdot \epsilon^{\mathsf{FSFB}}_{\mathsf{FC}}(t_{\mathsf{FC}}, m_{\mathsf{FC}}) + \mathsf{k} \cdot \epsilon_{\mathbf{Q}}(l, \mathsf{N}), \text{ where } \begin{cases} t_{\mathsf{FC}} = O\left(t_{\mathsf{ARG}} \cdot \mathsf{N}\right) \\ m_{\mathsf{FC}} = O\left(m_{\mathsf{ARG}} \cdot \mathsf{k} \cdot \mathsf{N}\right) \end{cases}.$$

A theorem that generalizes everything we saw (except post-quantum)

Corollary: security analysis of Plonk [GWC19] from falsifiable assumption

Aztec polygon ZKsync ...

Open problems

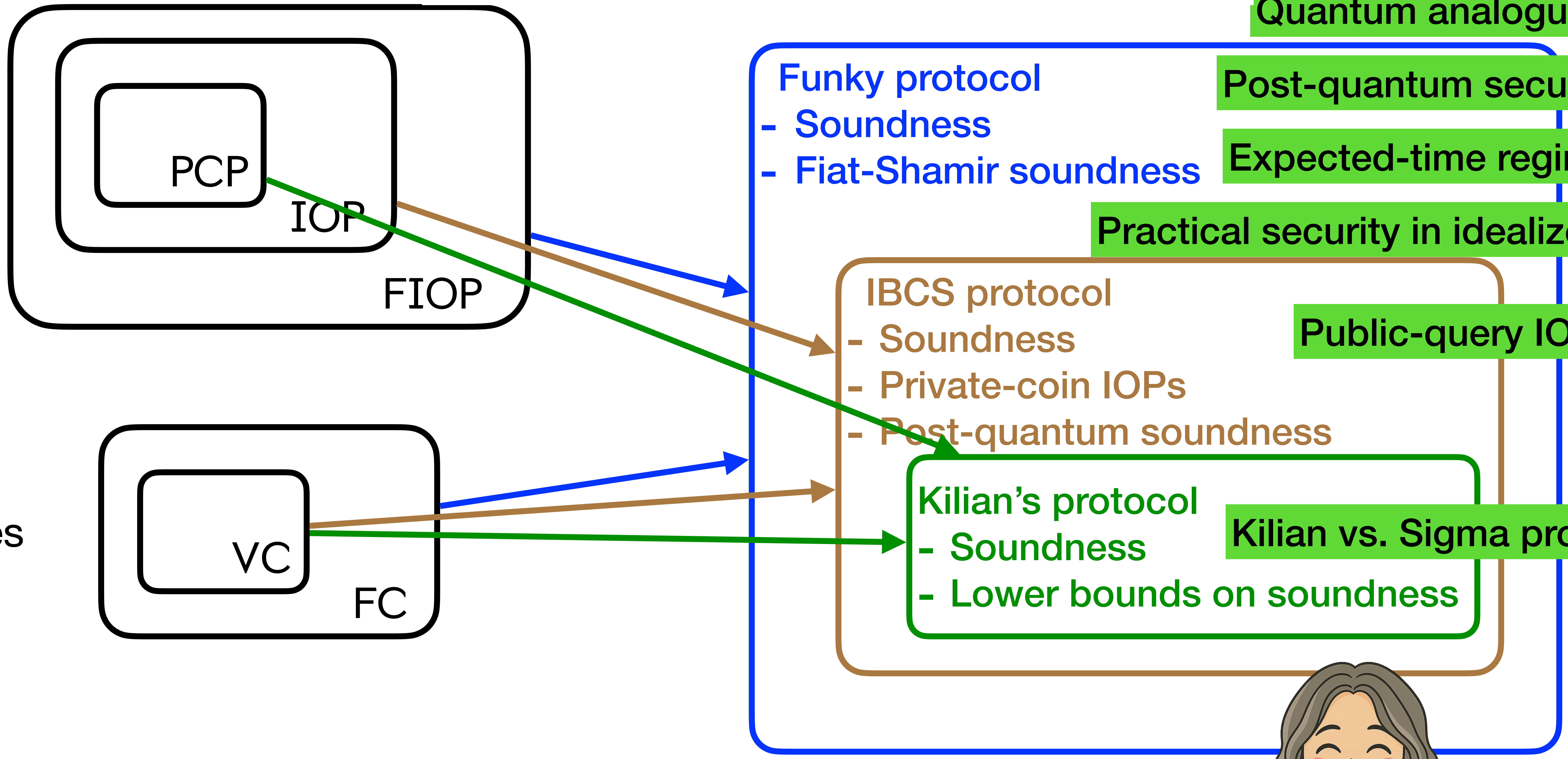
SNARGs for NP via Fiat–Shamir in the Plain Model

Ziyi Guan
ziyi.guan@epfl.ch
EPFL

Eylon Yogev
eylon.yogev@biu.ac.il
Bar-Ilan University

Probabilistic proofs

Commitment schemes



Standard model Fiat-Shamir wo/ iO?

Quantum analogue?

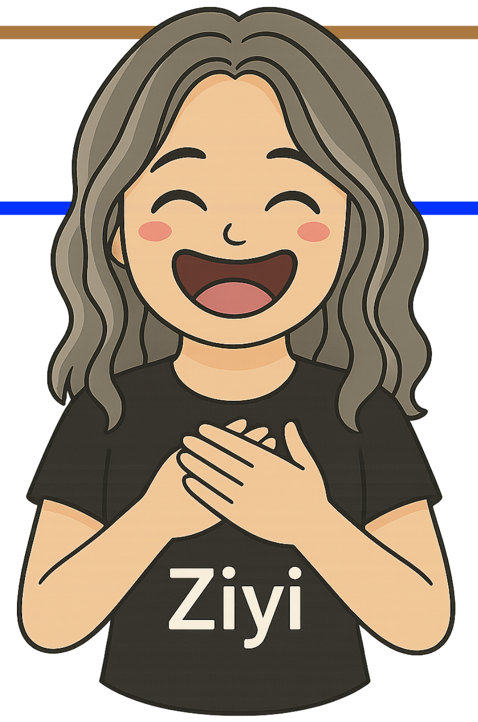
Post-quantum security?

Expected-time regime?

Practical security in idealized models?

Public-query IOPs?

Kilian vs. Sigma protocols?



Thank you!

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