Weakly Randomized Encryption

And the Strength of Weak Randomization

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“Executive” Summary

Weakly Randomized Encryption

- A safer upgrade to deterministic encryption
- Secure against most common “snapshot” attacks
- Easy to deploy
- ACID properties*
- Low overhead

Research Questions

1. What security can we achieve if **easy deployability** is a **hard constraint**?

2. Are there PPE-like constructions that provide **any meaningful security** against inference???

RELATED WORK

Property-Preserving Encryption (PPE)

- Deterministic and Efficiently Searchable Encryption [BBO07,ABO07]
- CryptDB [PRZB11]
- Microsoft SQL Server "Always Encrypted"

Parallel Invention

- [LP18] Lacharité and Paterson. Frequency Smoothing Encryption: Preventing snapshot attacks on deterministically encrypted data.
  - https://eprint.iacr.org/2017/1068
  - Most similar to our *Proportional Salt Allocation*

Inference Attacks

1. Offline inference (the “snapshot” model)
   – IKK12, NKW15
   – CGPR15, GSBNR17

2. Online inference
   – KKNO16, LMP18
   – GLMP18, GLMP19

3. Inference from database/OS artifacts
   – GRS17

Defense Against Inference Attacks

1. Offline inference:
   – IKK12, NKW15
   – CGPR15, GSBNR17

Focus of this work
- Defend against the **most common attacks** (i.e. snapshots / SQL injection)
- Maximize backwards compatibility
- What security & performance can we get?

2. Online inference
   – KKNO16, LMP18
   – GLMP18, GLMP19

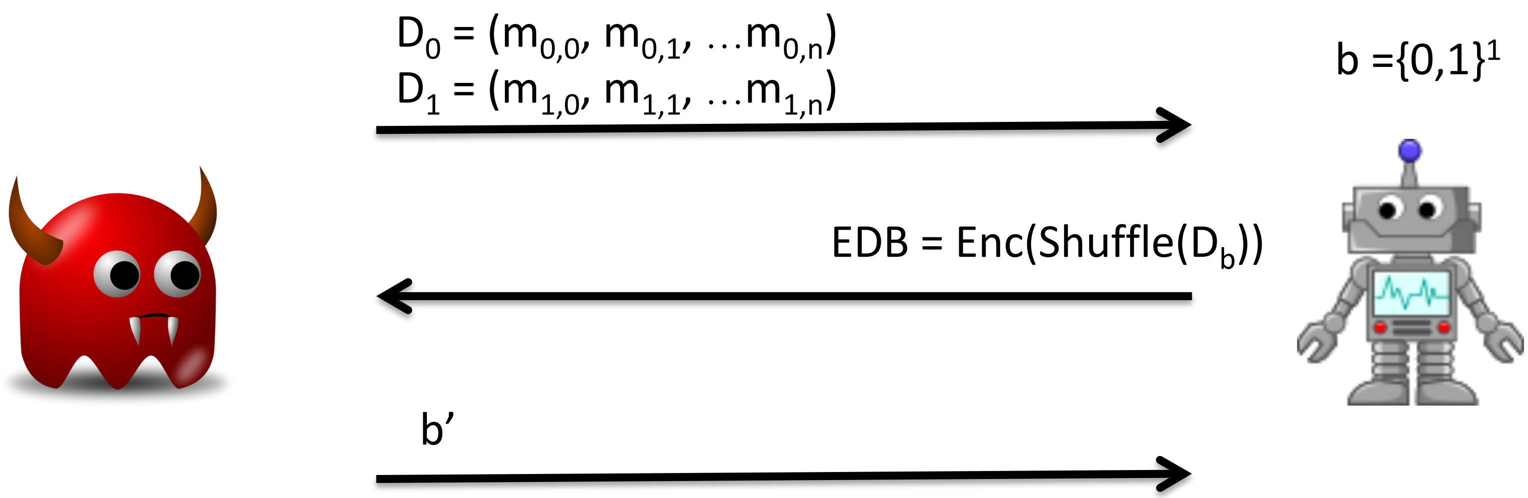
Harder problem / Future work
- Attacks apply to stronger constructions too

3. Inference from database/OS artifacts
   – GRS17

Mostly engineering??
- Not worth trying to fix this if you can't also defend #1

SECURITY GOALS

Security Game



Adversary wins iff b’ == b

Statistical Distance and Security

Definition 3 (Statistical Distance). *The* statistical distance Δ *between two random variables* X, Y *over a common domain* ω *is defined as:*

$$\Delta(X,Y) = \frac{1}{2} \sum_{\alpha \in \omega} \left| Pr(X = \alpha) - Pr(Y = \alpha) \right|$$

Definition 4 (Distinguishing Two Distributions). *Let* P_0 *and* P_1 *be probability distributions on a finite set R. Then for every adversary* $\mathcal{A}$*, we have the distinguishing advantage of* $\mathcal{A}$ *between* P_0 *and* P_1*,*

$$Pr[\mathsf{Dist}_{\mathcal{A}}(P_0, P_1)] \leq \Delta(P_0, P_1)$$

CONSTRUCTIONS

Efficiently Searchable Encryption [BBO07, ABO07]

Plain Table

Row ID	Animal
1	Dog
2	Horse
3	Cat
4	Cat
5	Dog
6	Horse
7	Dog
8	Dog
9	Cat

Efficiently Searchable Encryption [BBO07, ABO07]

Plain Table

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Encrypted Table

Row ID	Tag	Cipher
1	F(Dog)	E(Dog)
2	F(Horse)	E(Horse)
3	F(Cat)	E(Cat)
4	F(Cat)	E(Cat)
5	F(Dog)	E(Dog)
6	F(Horse)	E(Horse)
7	F(Dog)	E(Dog)
8	F(Dog)	E(Dog)
9	F(Cat)	E(Cat)

Efficiently Searchable Encryption [BBO07, ABO07]

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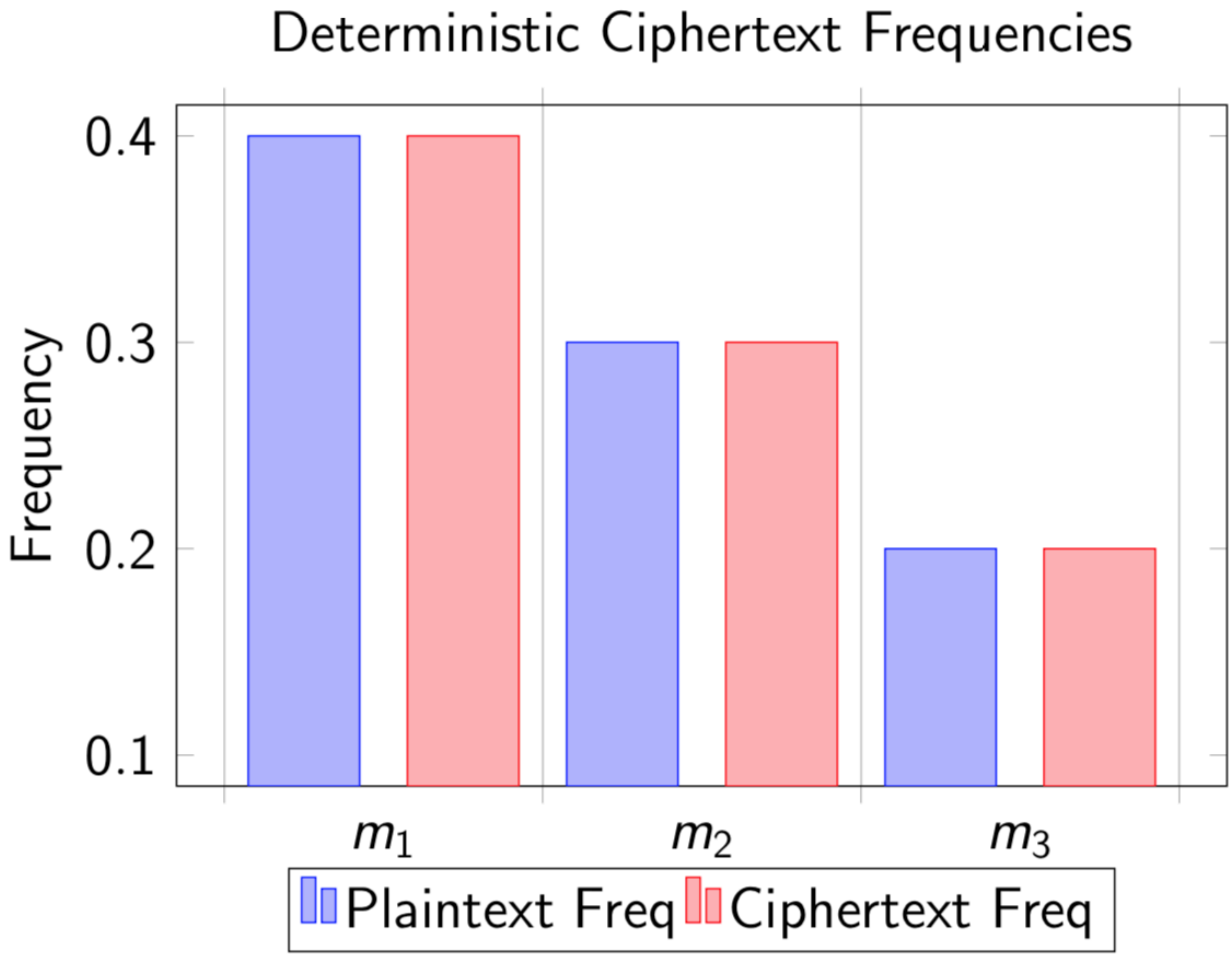
Encrypted Table

Row ID	Tag	Cipher
1	eb3f	653c
2	137a	bb21
3	6f20	e0f3
4	6f20	9201
5	eb3f	bbcf
6	137a	d830
7	eb3f	c971
8	eb3f	ee26
9	6f20	7a0b



Deterministic Ciphertext Frequencies
Frequency
0.4
0.3
0.2
0.1
m_1
m_2
m_3
Plaintext Freq
Ciphertext Freq

Randomizing Deterministic Encryption

- Too random → Not useful ☹

- Too predictable → Not secure ☹

- Just enough randomness → ☺

To Encrypt

1. Choose random, **low entropy** salt s
2. Tag $t = F_{k1}(s \mid\mid m)$
3. (Randomized) ciphertext $c = E_{k2}(m)$

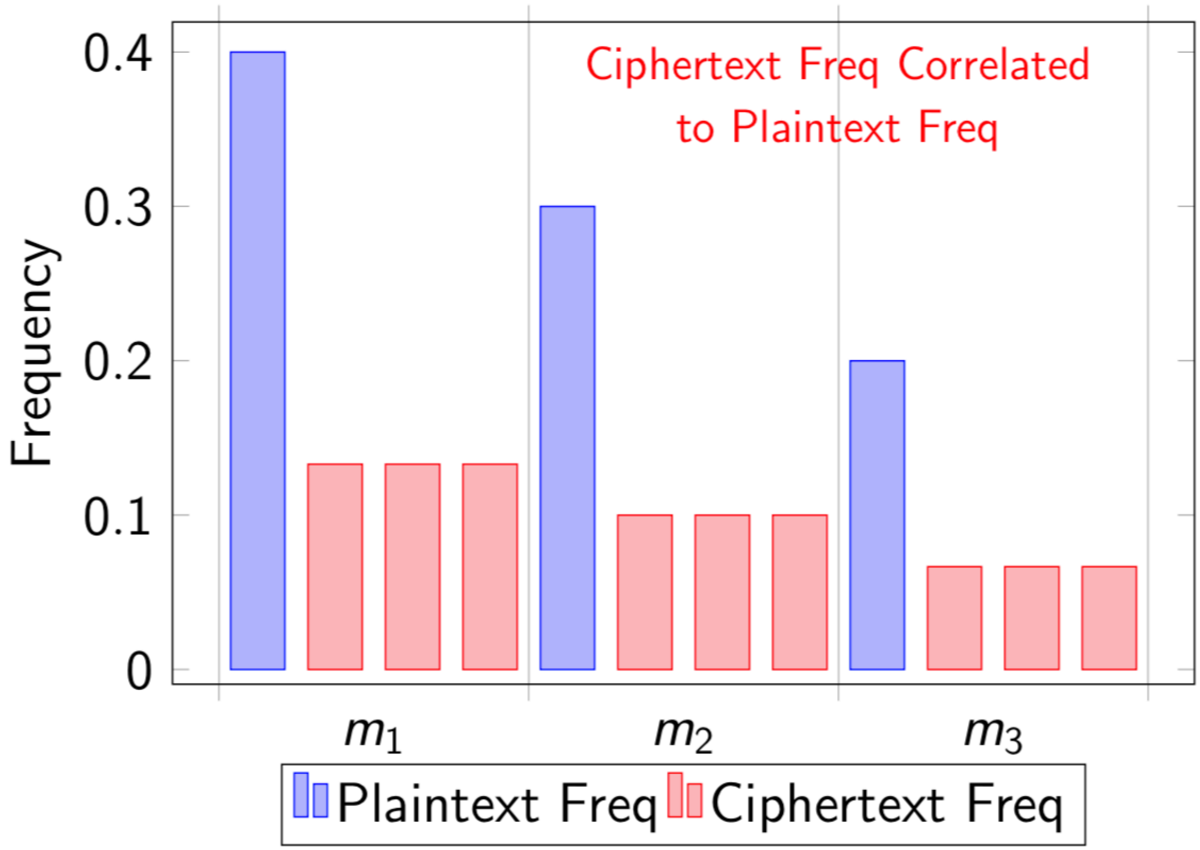
To Search

1. Generate all possible tags for msg m
   – For each salt s_i:
     Let $t_i = F_{k1}(s_i \mid\mid m)$

2. Encrypt query
   – SELECT …
     FROM enc_table
     WHERE tag in (t_1, t_2, …, t_n);

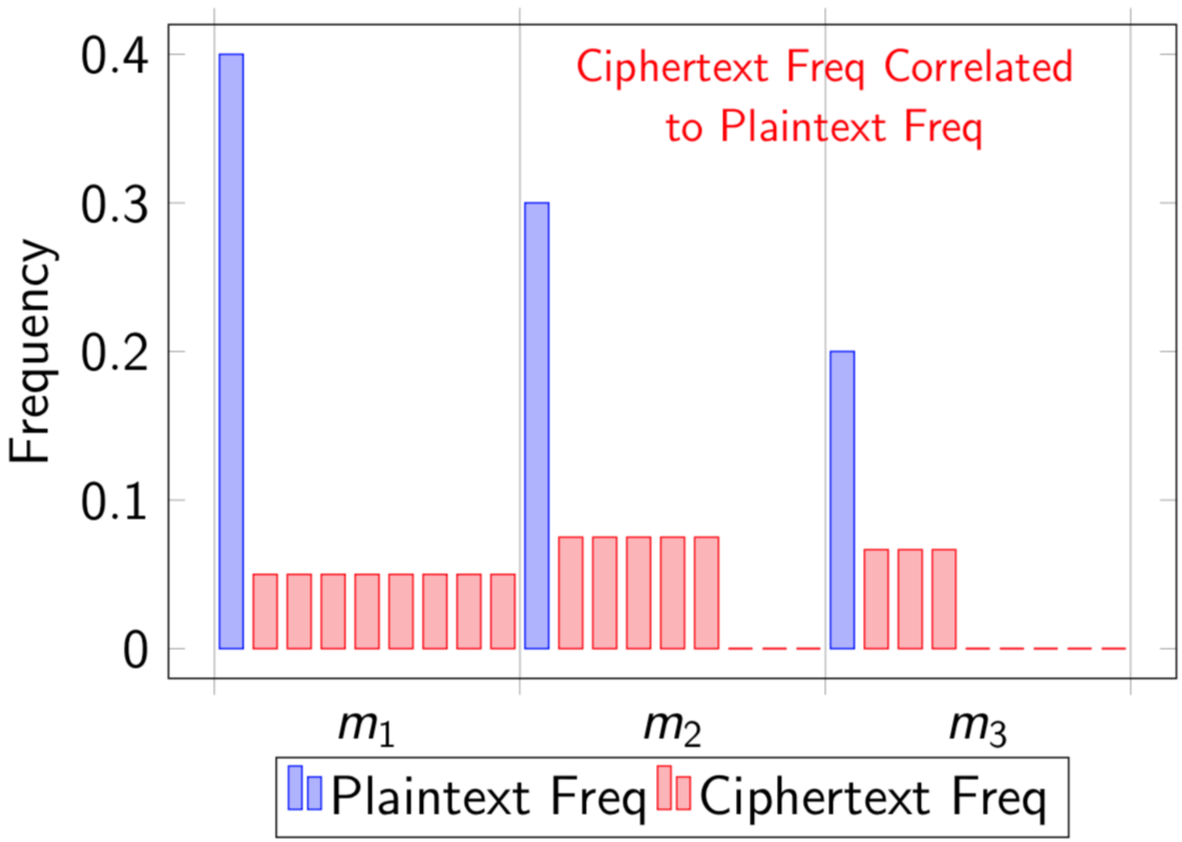
Strawman Construction: Fixed Salts

- Choose salt uniformly from [1..N]
  - e.g. N = 3



Proportional Salt Allocation

- Allocate salts in proportion to frequency



Frequencies are closer to Uniform

Some *aliasing* effects

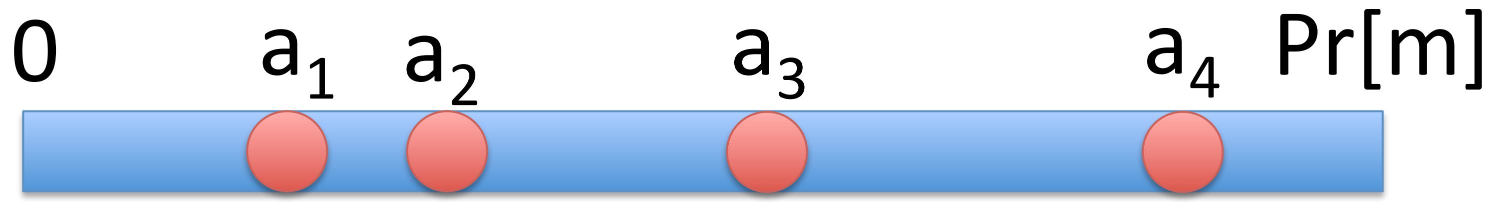
Poisson Salt Allocation

Question:
How to allocate message *m*'s probability mass to the ciphertexts?

Poisson Salt Allocation

Idea:

Sample points from a Poisson process w rate param λ

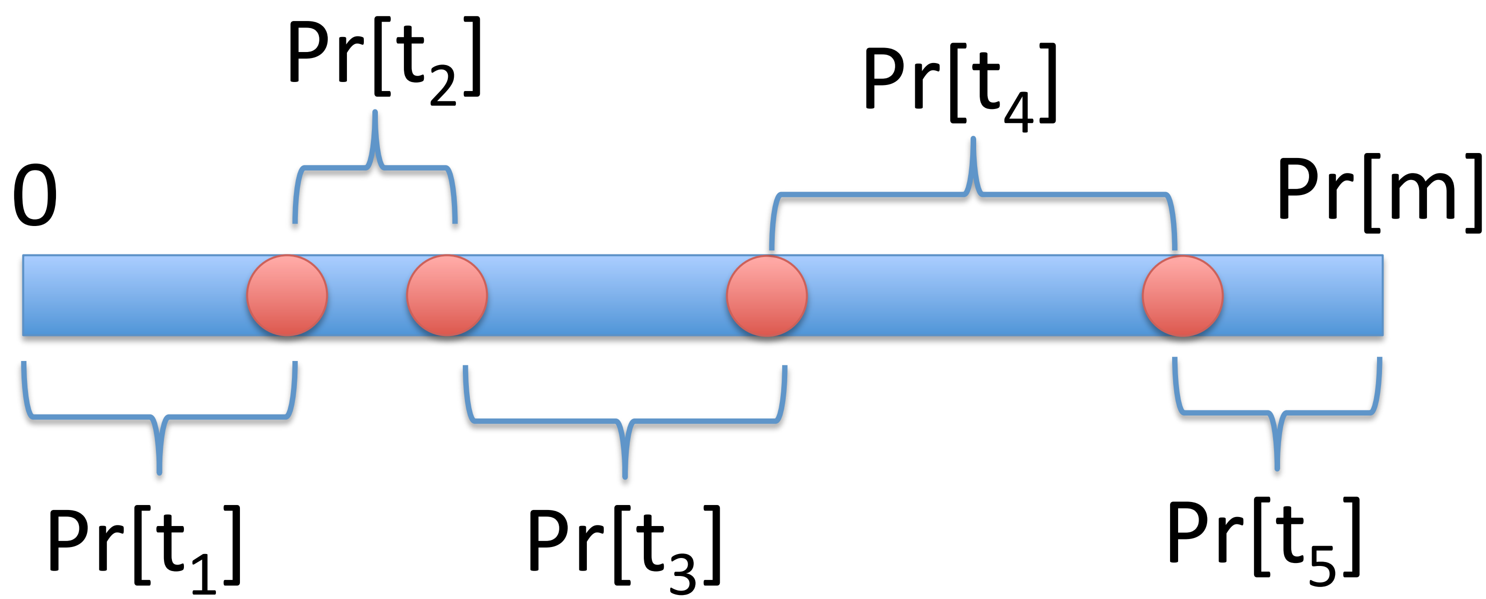


Poisson Salt Allocation

Idea:

Sample points from a Poisson process w rate param λ

Distances between points (“inter-arrivals”) give tag frequencies



Poisson Security

- Ciphertext freqs are identically distributed!
  - $\Pr[t_j] \sim \text{Exponential}(\lambda)$ for all j

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- Identical distribution → No statistical distance

- No statistical distance → No guessing advantage

Poisson Security

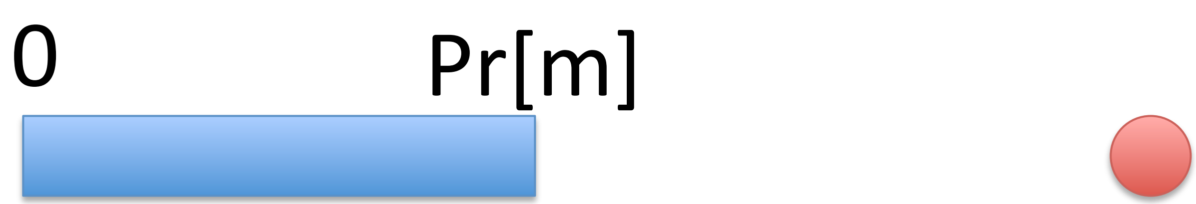
- Ciphertext freqs are identically distributed!
  - Pr[t_j] ~ Exponential(λ) for all j

> **Whoops… Not quite true..**
>
> **They are *almost identically* distributed. :-**

- Identical distributi … e
- No statistical distance → No guessing advantage

Something Fishy About Poisson

Problem:
What if there are no arrivals in the interval [0, Pr[m]] ???

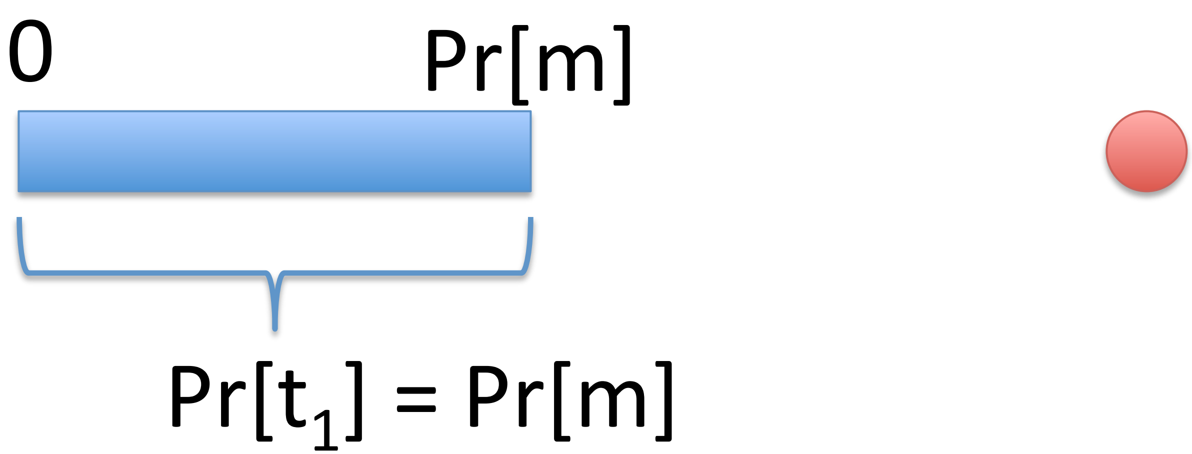


Something Fishy About Poisson

Problem:

What if there are no arrivals in the interval [0, Pr[m]] ???

No choice but to give all of *m*'s probability mass to a single t*ag*



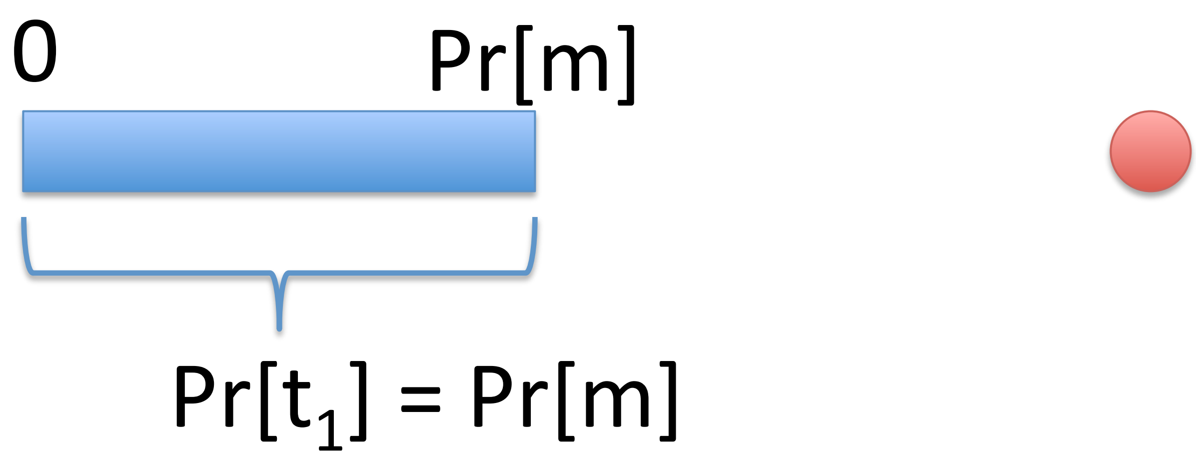
Something Fishy About Poisson

Problem:

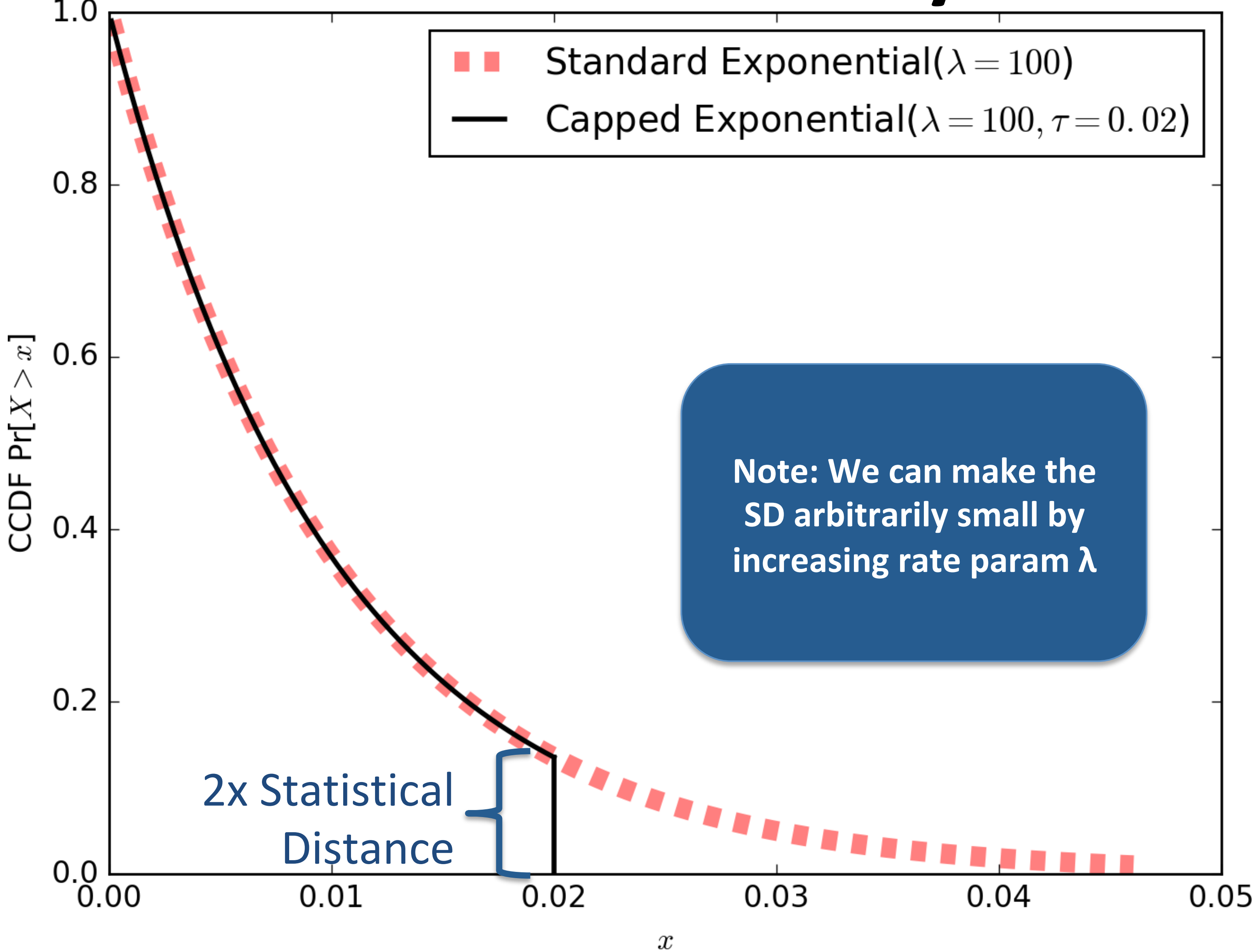
What if there are no arrivals in the interval [0, Pr[m]] ???

No choice but to give all of *m*'s probability mass to a single tag

Not really a true Exponential. Can the Adv now distinguish?



Poisson: Security

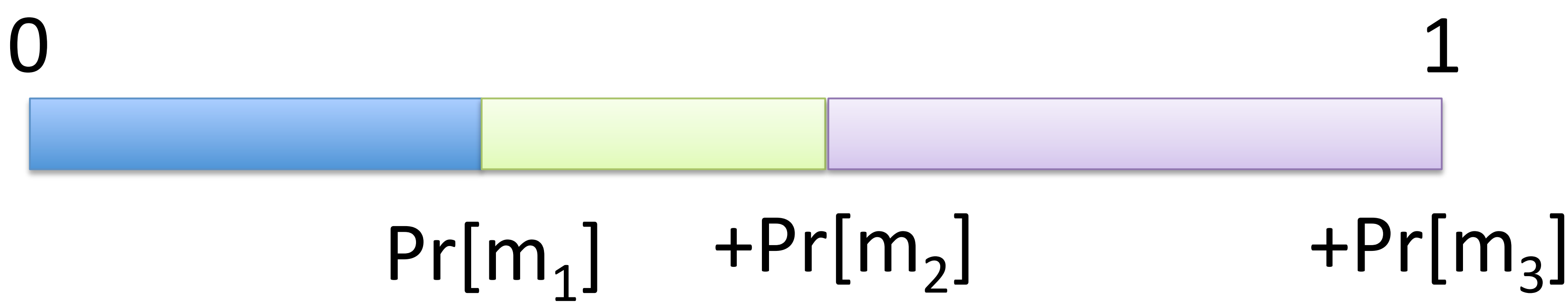


Poisson: One More Problem

- Lacharite-Paterson attack: What if Adv looks at more than one ciphertext?
  - Goal: Find a set of search tags $t_1, t_2, \ldots, t_n$ s.t.
    - $Pr[m] = \sum_j Pr[t_j]$
    - These records are *probably* (???) the encryptions of m
  - Difficulty: Bin packing problem :-\
    - On the bright side:
      - Might be a hard (NP) instance
      - Solution might (tend to) select the wrong records

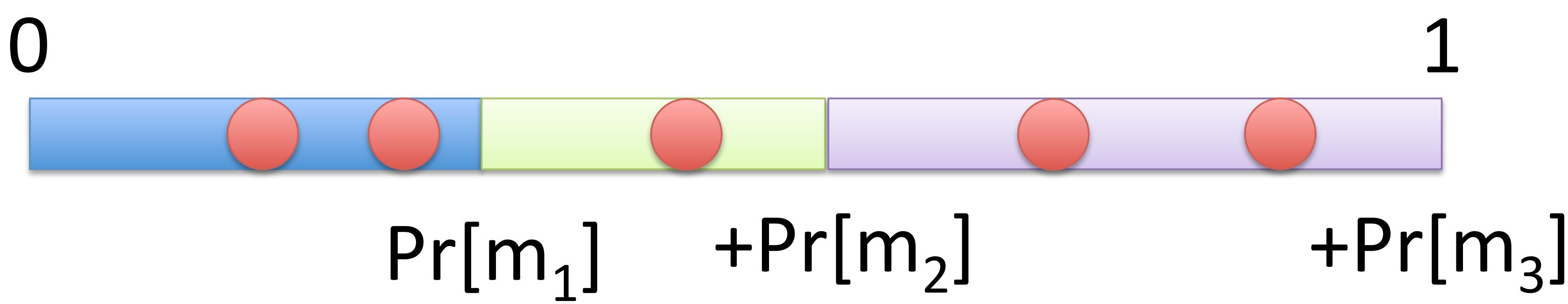
Bucketized Poisson

Lay out plaintext freqs on the number line [0..1]



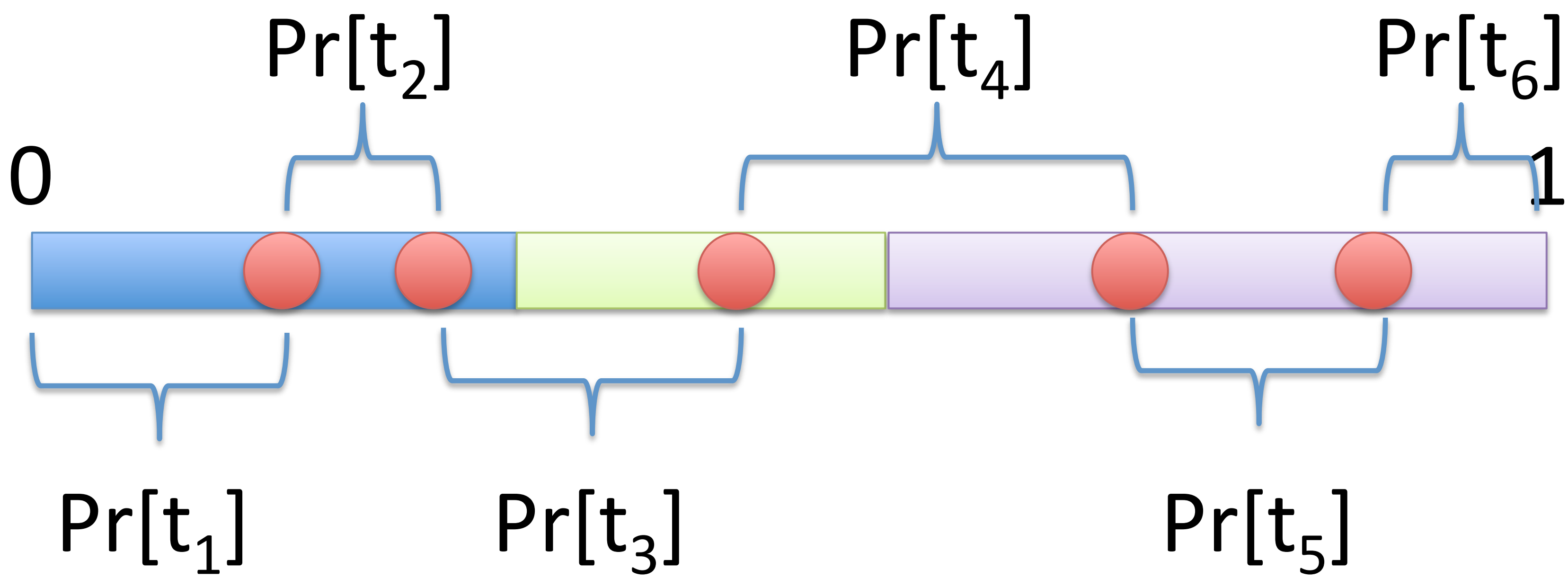
Bucketized Poisson

Lay out plaintext freqs on the number line [0..1]
Sample from the Poisson process



Bucketized Poisson

Lay out plaintext freqs on the number line [0..1]
Sample from the Poisson process
Use inter-arrivals to fix a set of search tags for **all** plaintexts to share



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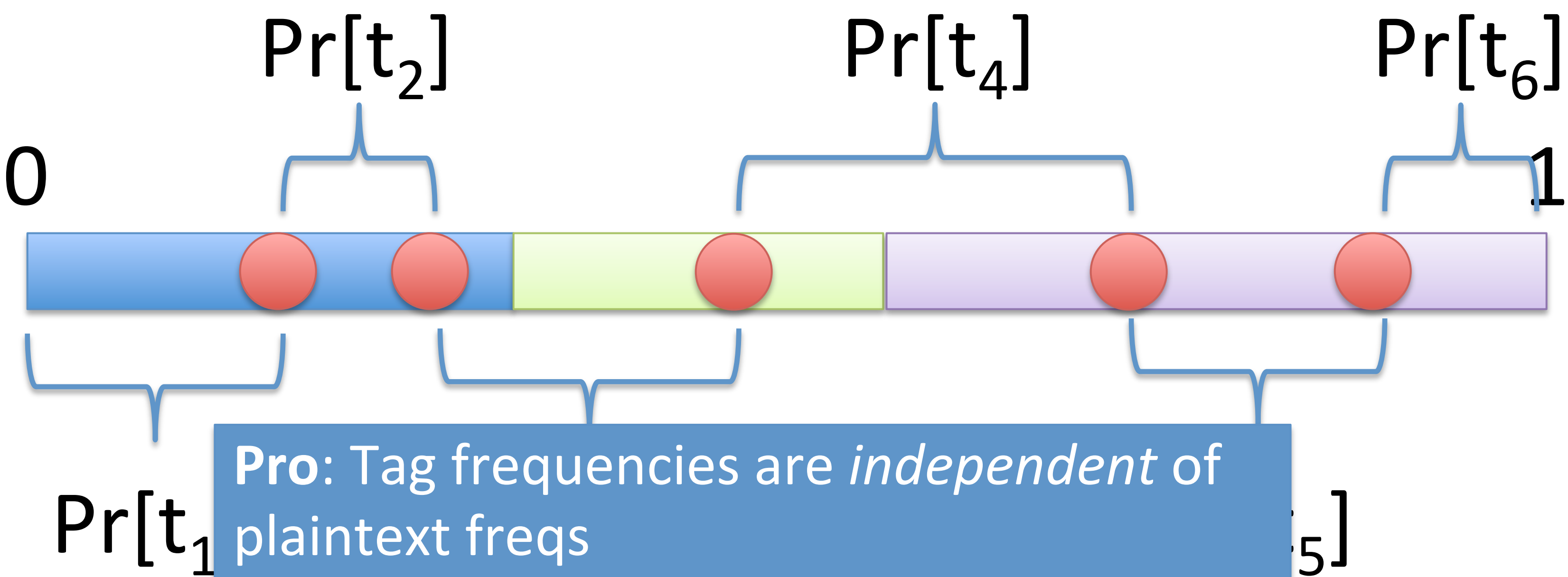


Pro: Tag frequencies are *independent* of plaintext freqs

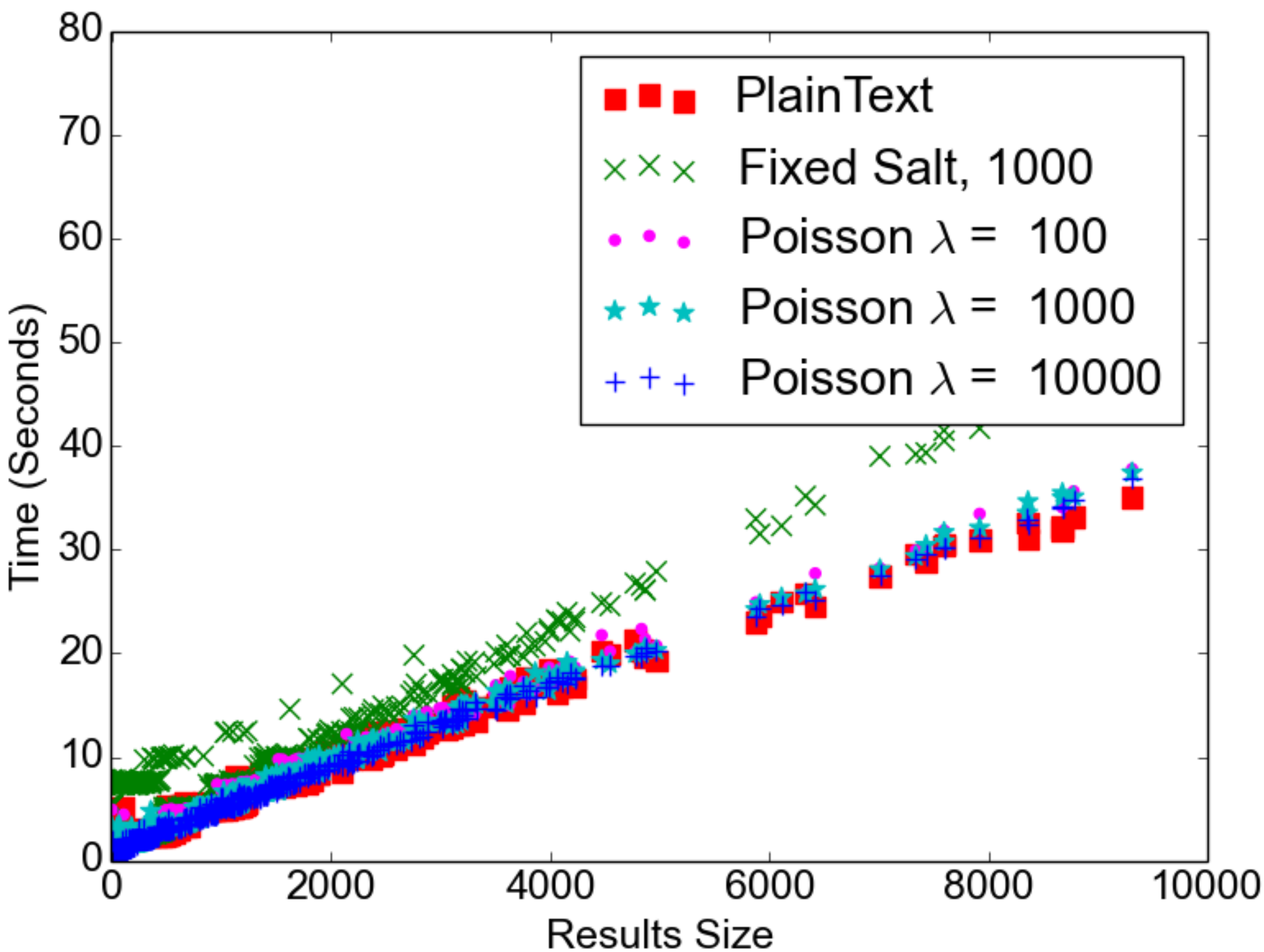
Con: Tags are now *buckets* representing multiple plaintexts

EMPIRICAL EVALUATION

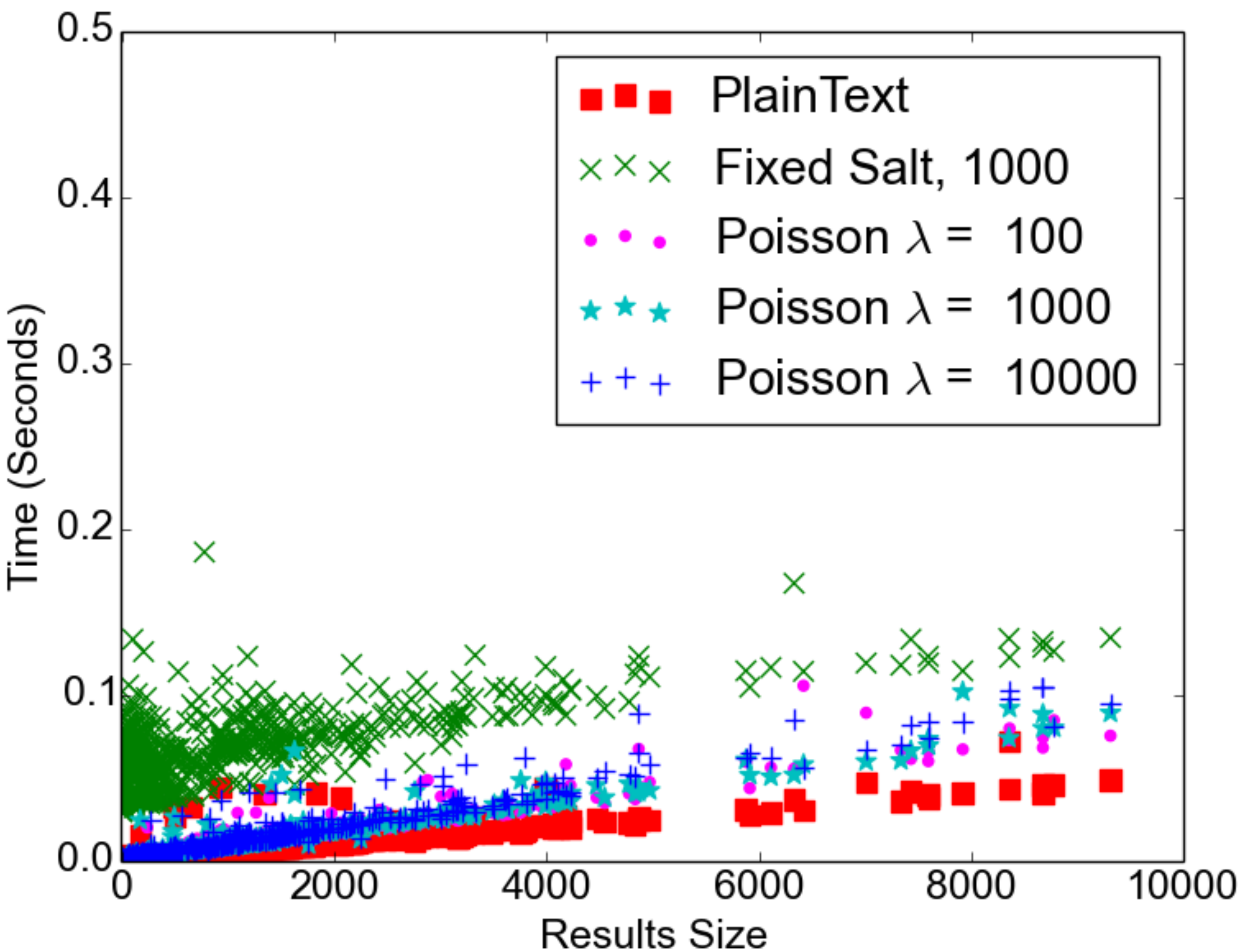
Experimental Procedure

- Used SPARTA testing framework from MIT-LL
  - Generated synthetic databases
    - 1M, 10M records
  - Generated synthetic queries
    - SELECT … FROM table WHERE column = value;
    - Return up to 10k matching records
- Ran queries on real SQL databases
  - Google Compute Engine
  - Local Postgres server

Performance: Cold Cache



Performance: Warm Cache



Conclusion

- WRE Contributions
  - Easy to deploy
  - Secure against most common threats
  - Performance close to plaintext

- Future Work / Open Problems
  - Security for queries? For access pattern?
  - Security for multiple (correlated) columns?
  - Range queries?