Inverting Sampled Traffic

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Inverting Sampled Traffic

- Motivation
- Sampling Techniques
  - **Packet** Sampling
  - **Flow** Sampling
- Comparison of sampling techniques
  - **Distribution** of the number of packets per flows
  - **Spectral density** of packet arrival process
- Application to traffic modelling

Introduction

Motivation

- Traffic statistics collected by routers don't scale well with link speed: exact traffic logging is **impossible** for backbone links
- Need to **sample** the traffic, export **partial** statistics
- Aim: **infer** statistics of **original** traffic from partial measurements

Introduction

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- Aim: **infer** statistics of **original** traffic from partial measurements

Short history

- 1993: Claffy et al. advocate sampling techniques at the **packet level** to reduce the load on measuring infrastructure.
- 2002-2003: Duffield et al. give estimates of **first order** quantities from **packet level** sampled traffic: average rate, mean number of packets per flows.

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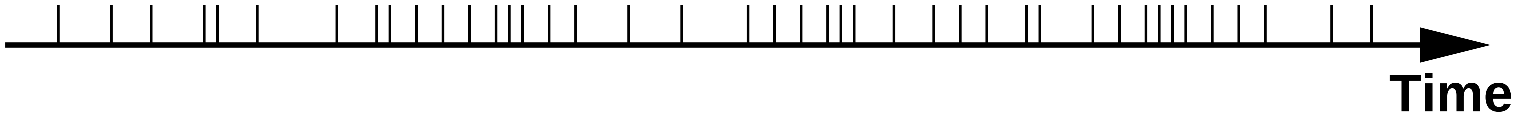
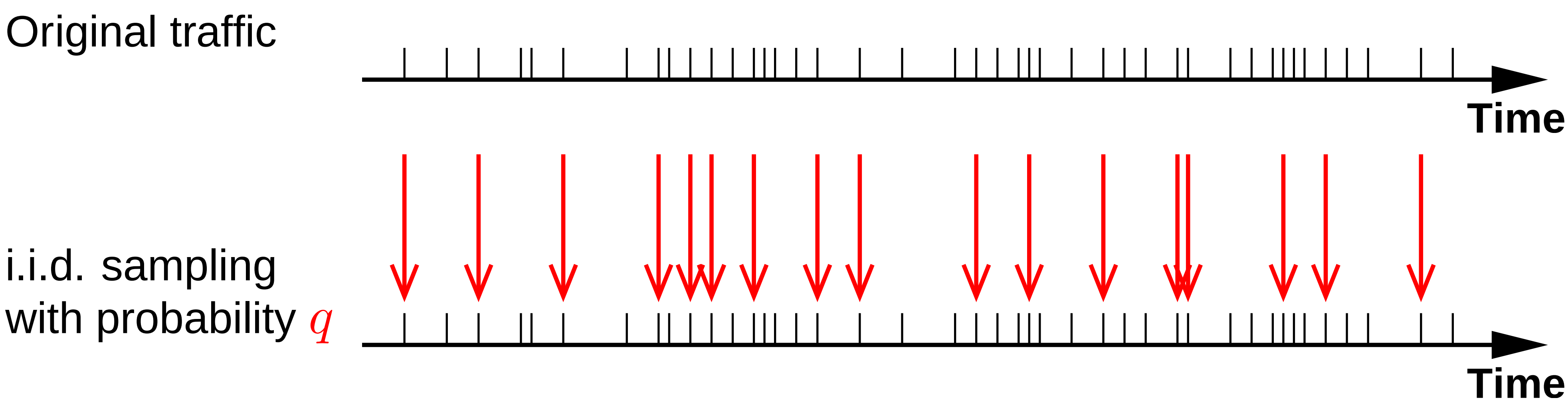
Packet Sampling

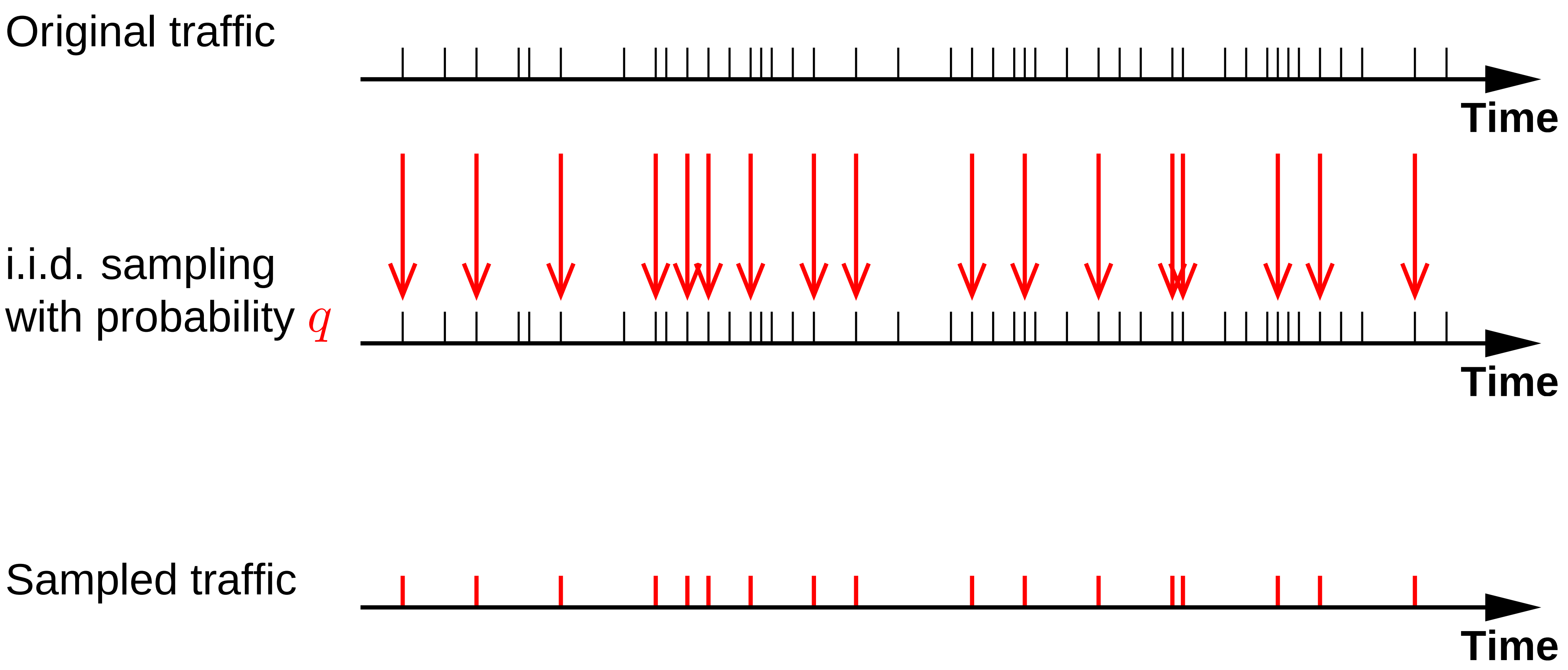
Original traffic



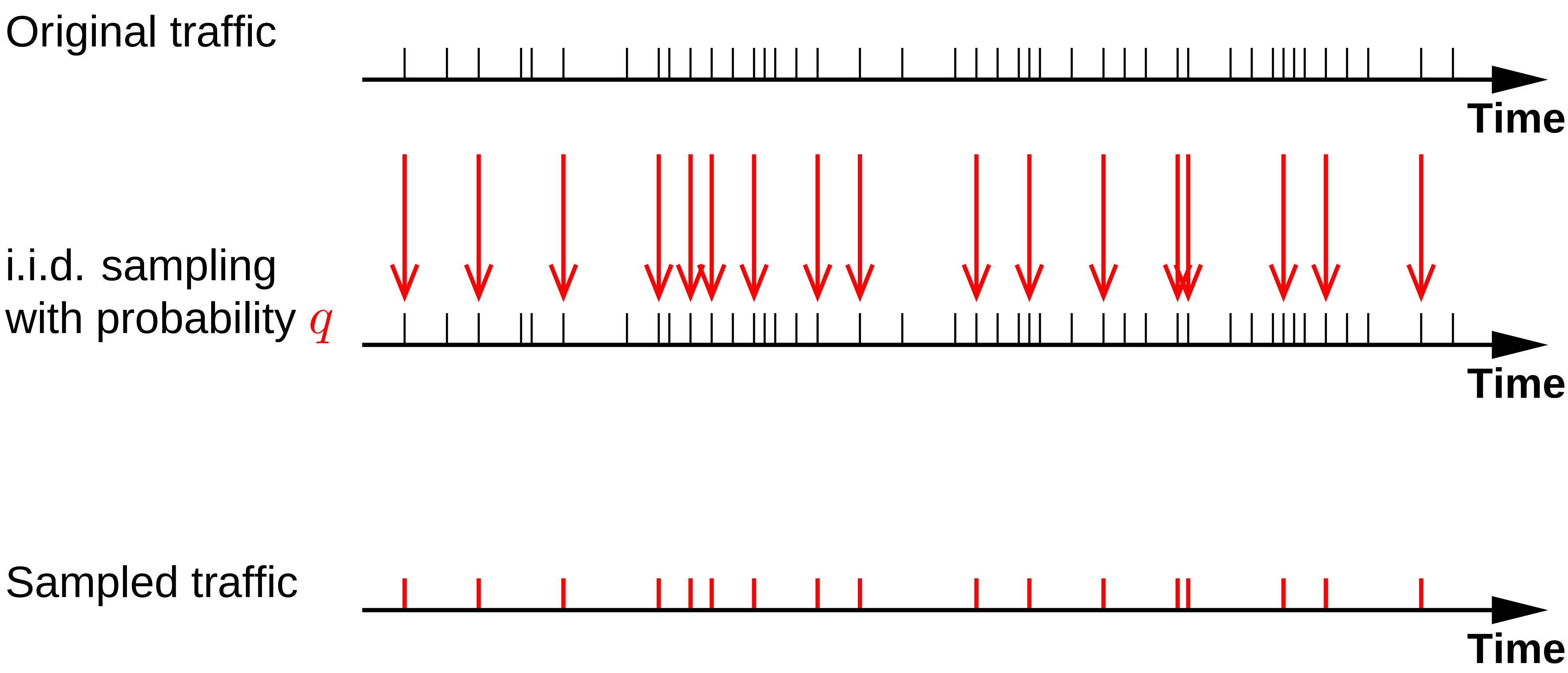
Packet Sampling



Packet Sampling



Packet Sampling



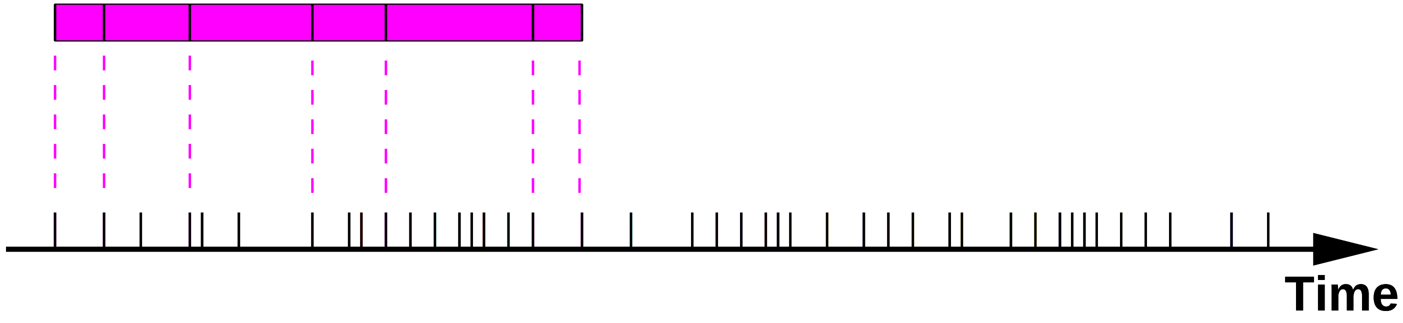
Simple example: recover original packet rate

- Sample packets with probability q,
- Measure rate of sampled traffic $\lambda^{(q)}$,
- Infer rate of original traffic $\lambda^{(q)}/q$.

Terminology

IP flow: set of packets with same **5-tuple**

IP protocol	Source Address	Destination Address	Source Port	Destination Port



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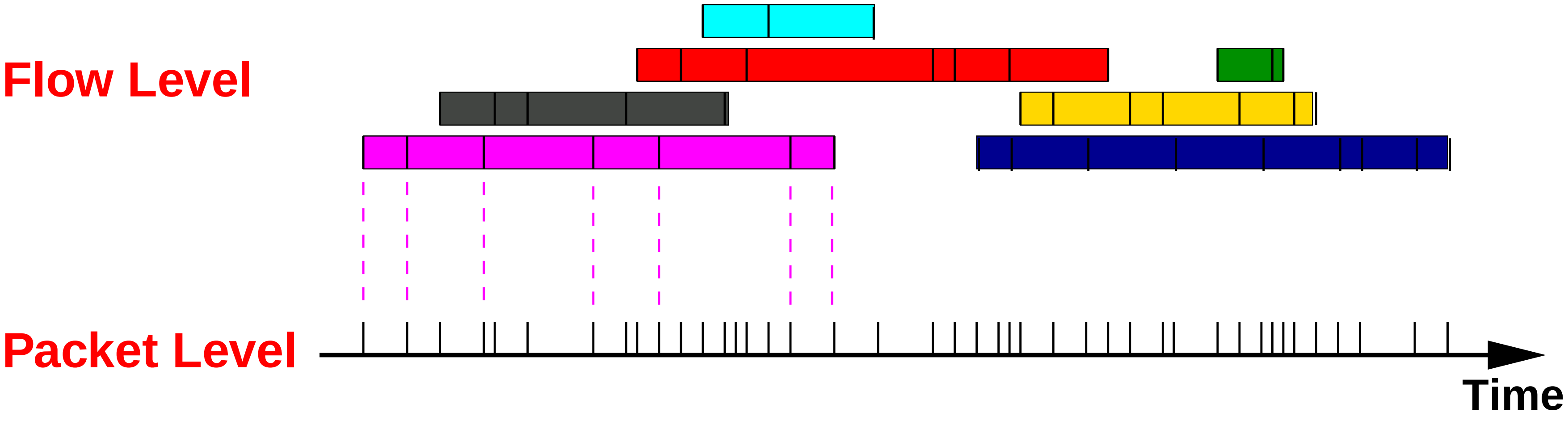
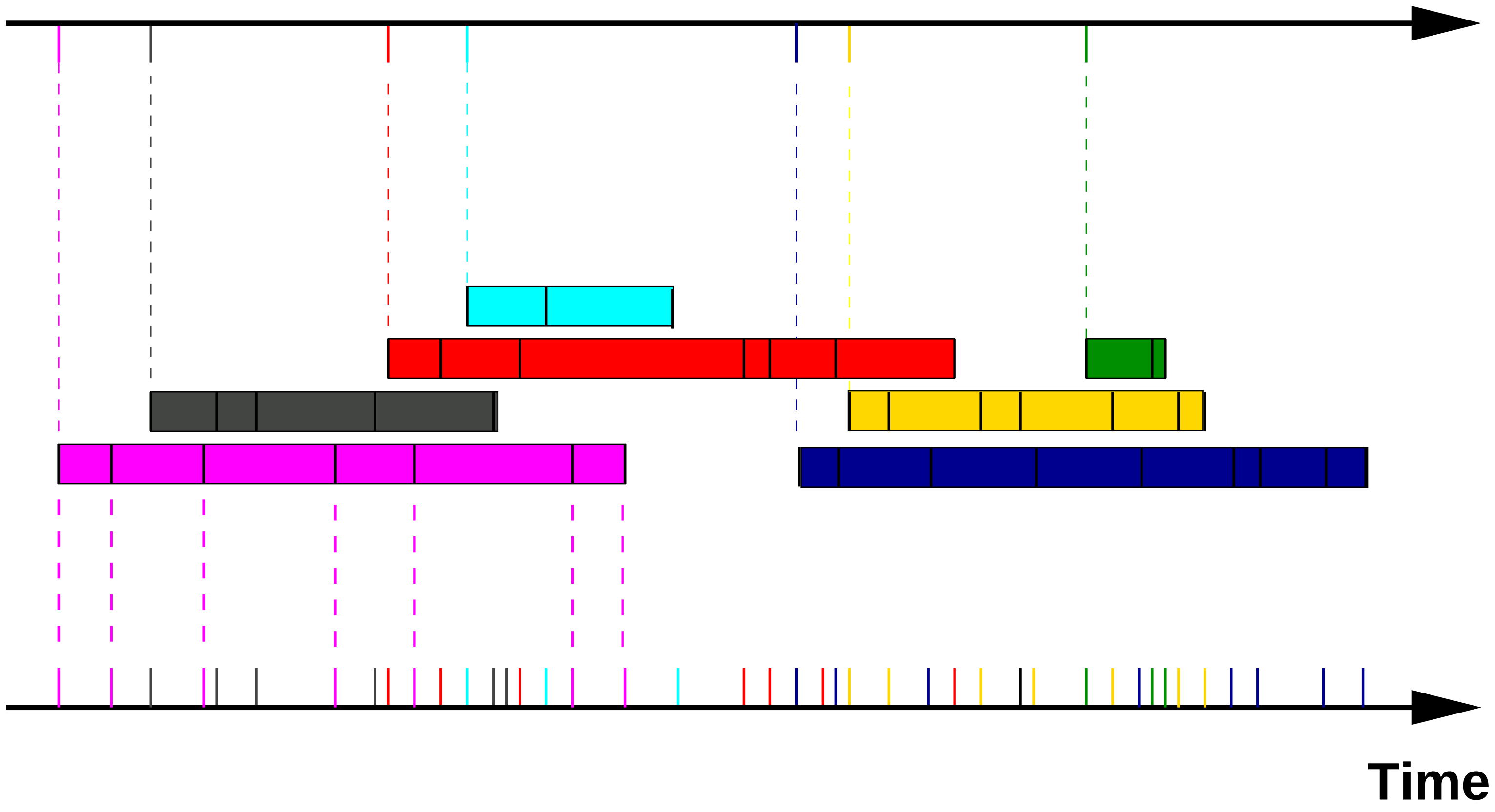
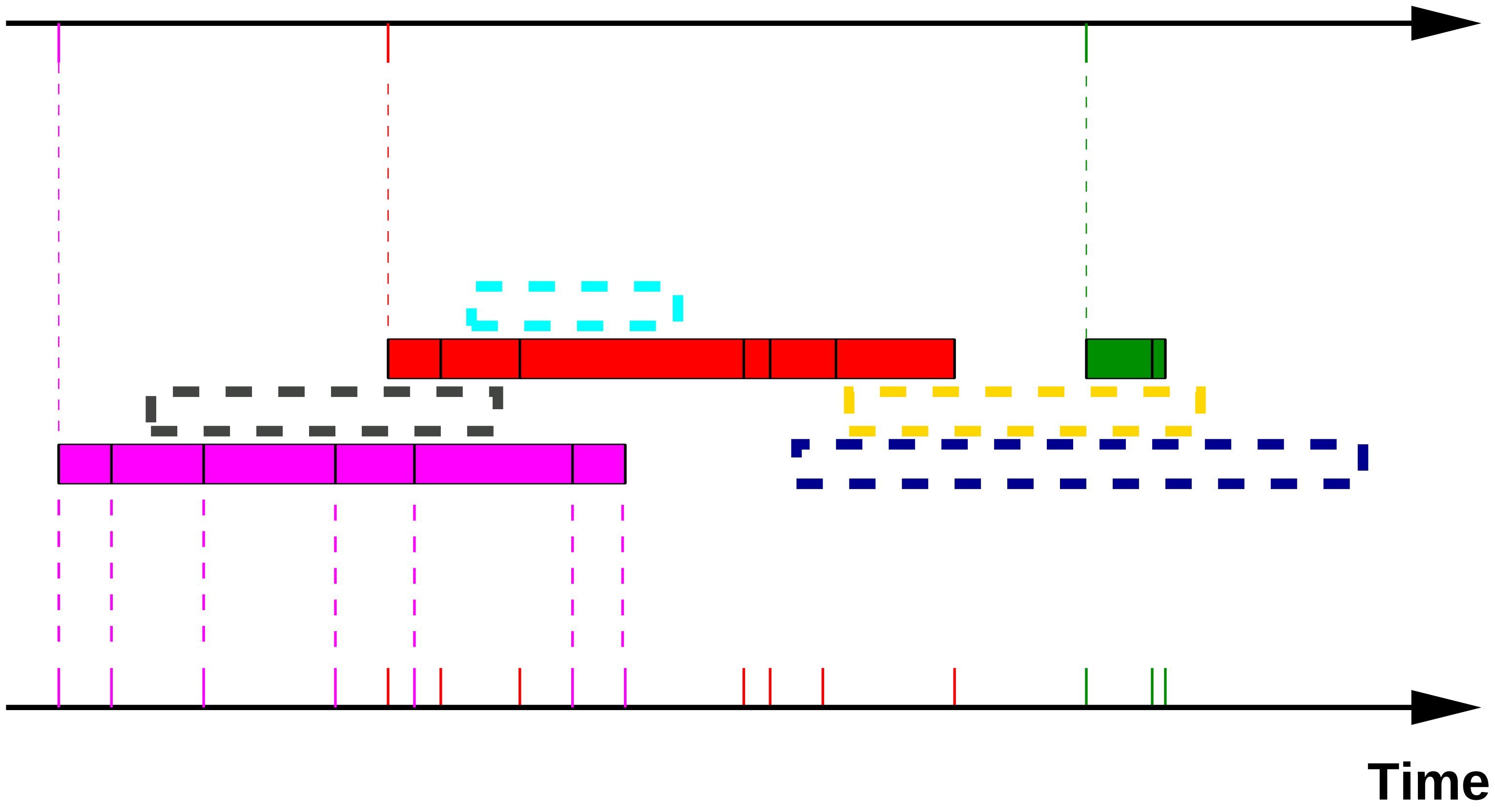


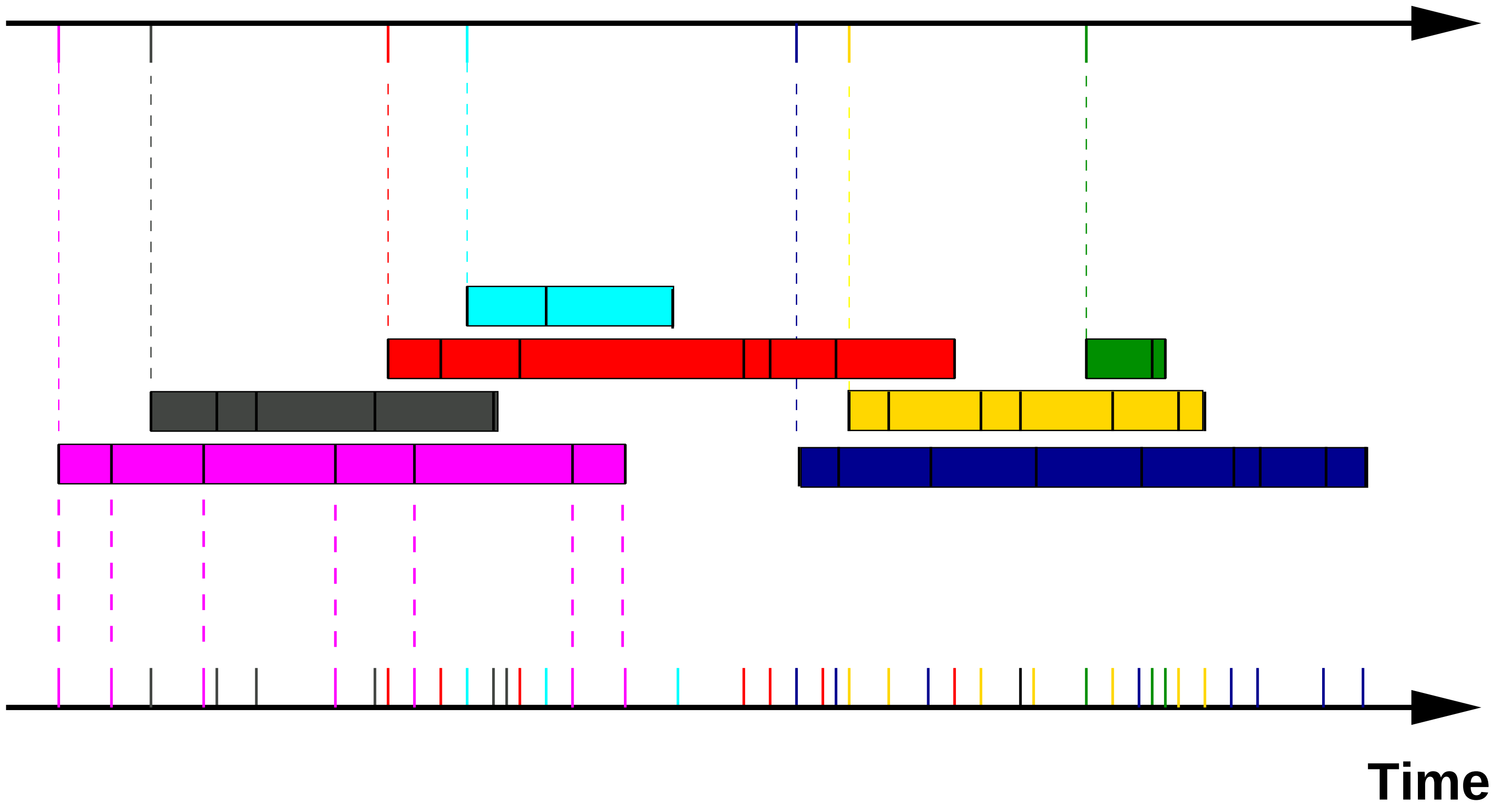
Original Traffic



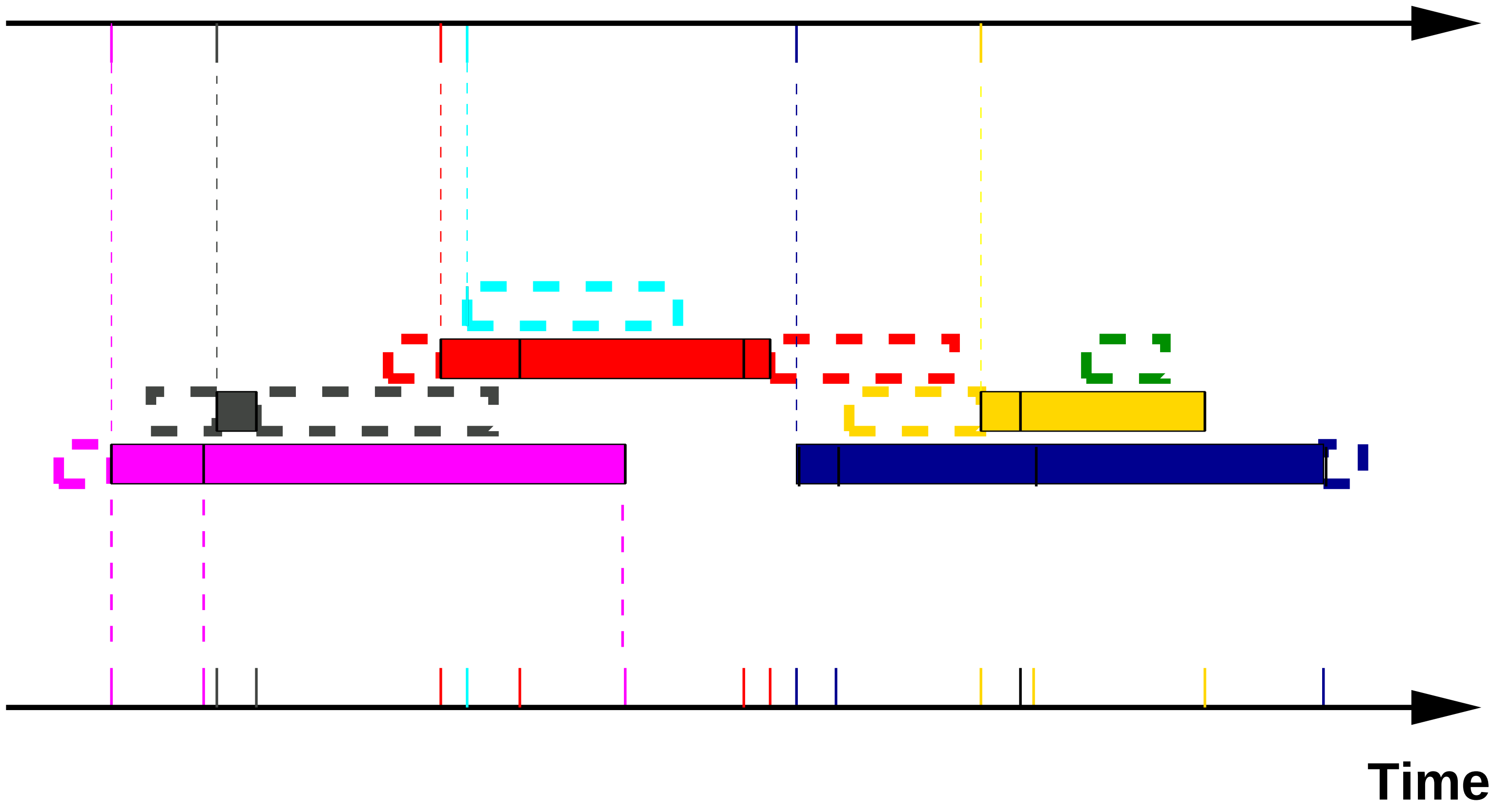
Flow Sampling



Original Traffic



Packet Sampling



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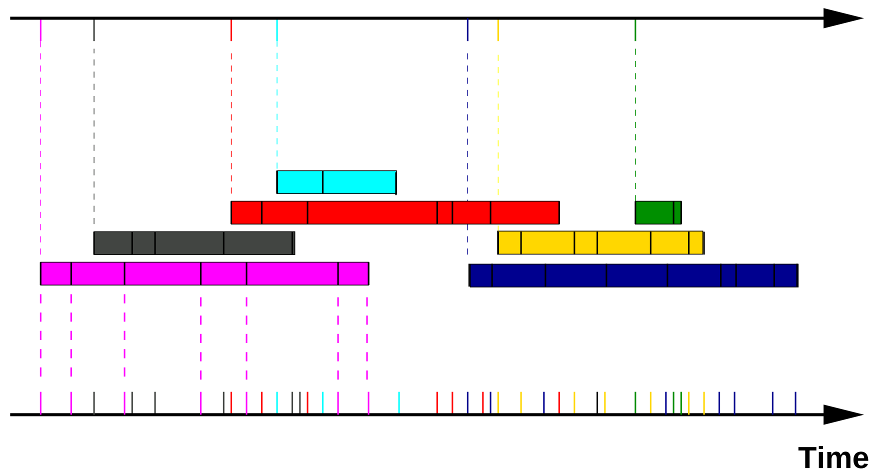
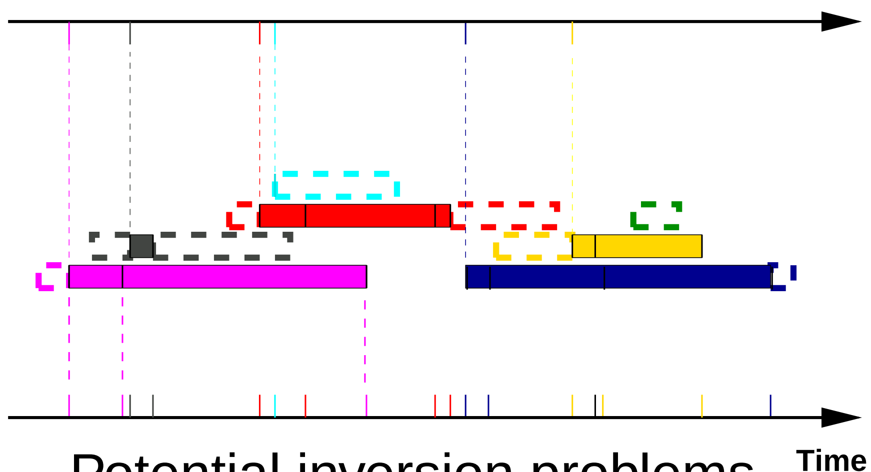
Distribution of number of packets per flow

Original traffic

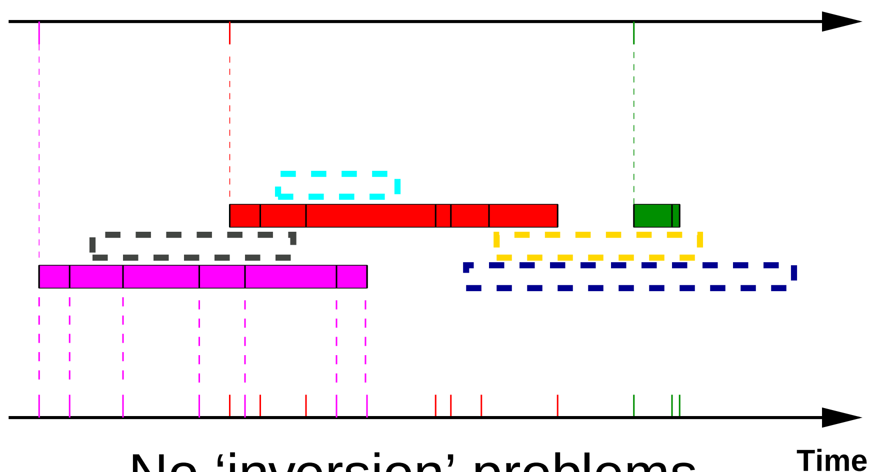


Packet sampling



Potential inversion problems

Flow Sampling



No ‘inversion’ problems

Distribution of number of packets per flow

Packet sampling

p_j: Probability that a flow had j packets **before** sampling.

$p_k^{(q)}$: Probability that a flow has k packets **after** sampling,

$$p_k^{(q)} = \sum_{j=k}^{\infty} \Pr\{\text{k packets after thinning} |\ \text{j packets before thinning}\} p_j$$

$$p_k^{(q)} = \sum_{j=k}^{\infty} \binom{j}{k} q^k (1-q)^{j-k} p_j \qquad (1)$$

- Aim: express p_j as a function of $p_k^{(q)}$ by inverting (1)

Inverting (1) with generating functions

- Definition: $$G_{\mathrm{P}}(z) = \sum_{j=0}^{\infty} p_j z^j, \; z \in \mathcal{D}(0,1).$$

  $\mathcal{D}(z,r)$: open disc centered at z with radius r

  Singularity at $z = 1$ if heavy tailed distribution.

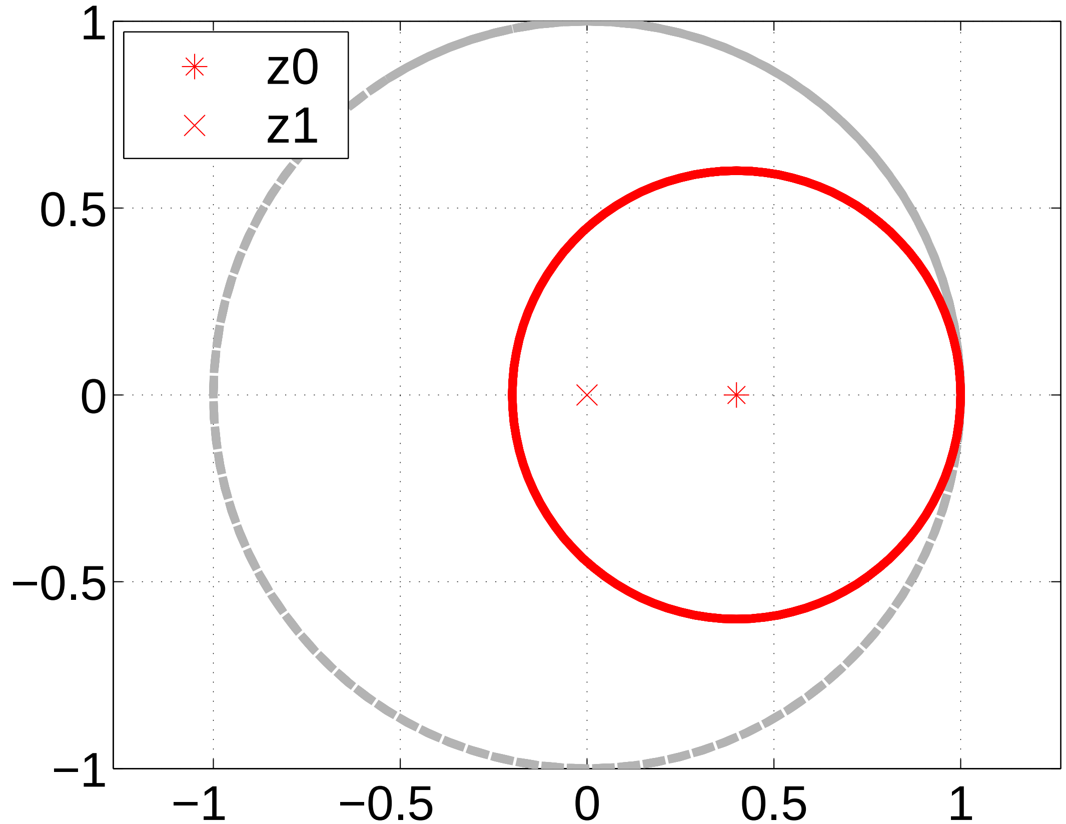
- From (1): $$\begin{aligned} G_{\mathrm{P}}^{(q)}(z) &= \sum_k p_k^{(q)} z^k = G_{\mathrm{P}}(1-q+qz), \; z \in \mathcal{D}(0,1) \\ G_{\mathrm{P}}(z) &= G_{\mathrm{P}}^{(q)}\left(\frac{z-(1-q)}{q}\right), \; z \in \mathcal{D}(1-q,q) \end{aligned}$$

- Aim: Find power series expansion of G_{P} at $z = 0$

- Methods:
  - Analytic Continuation
  - Cauchy Integral

Scheme 1: Analytic Continuation

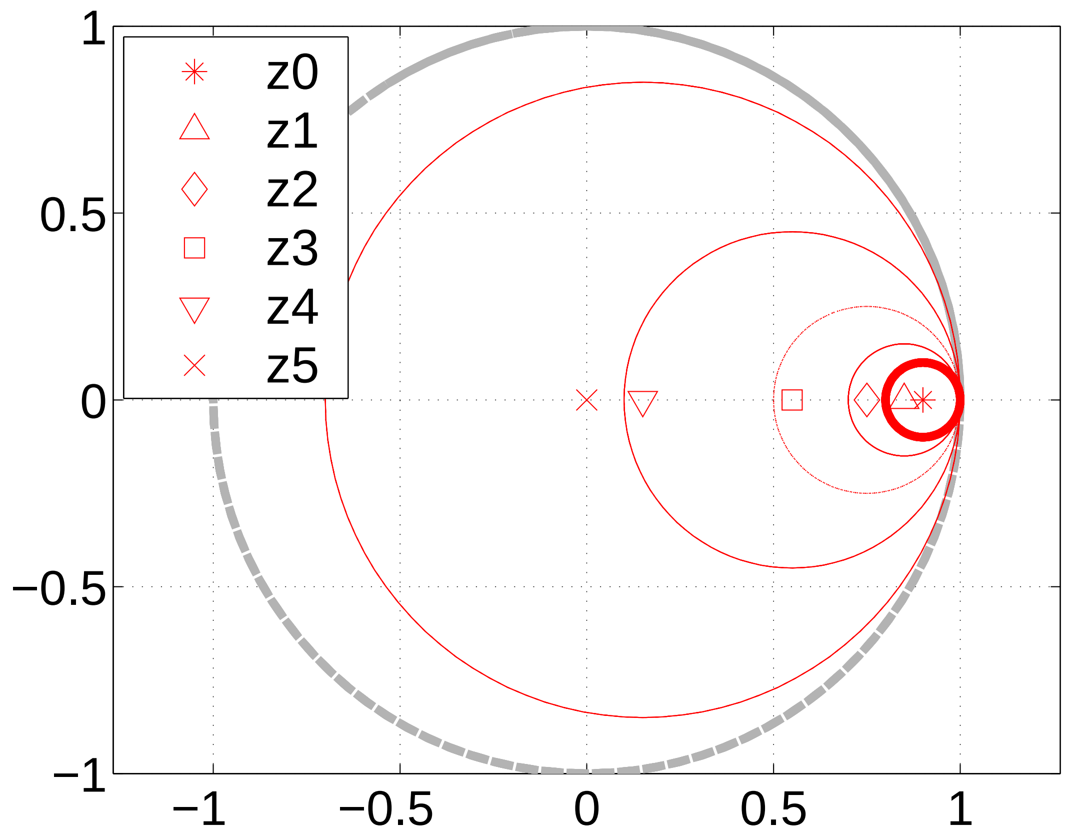
$q = 0.6$



$$p_j = \sum_{n=j}^{\infty} \binom{n}{j} \frac{(-1)^{n-j}}{q^n} (1-q)^{n-j} p_n^{(q)} \tag{2}$$

Scheme 1: Analytic Continuation

$q = 0.1$



$$p_j = \ldots$$

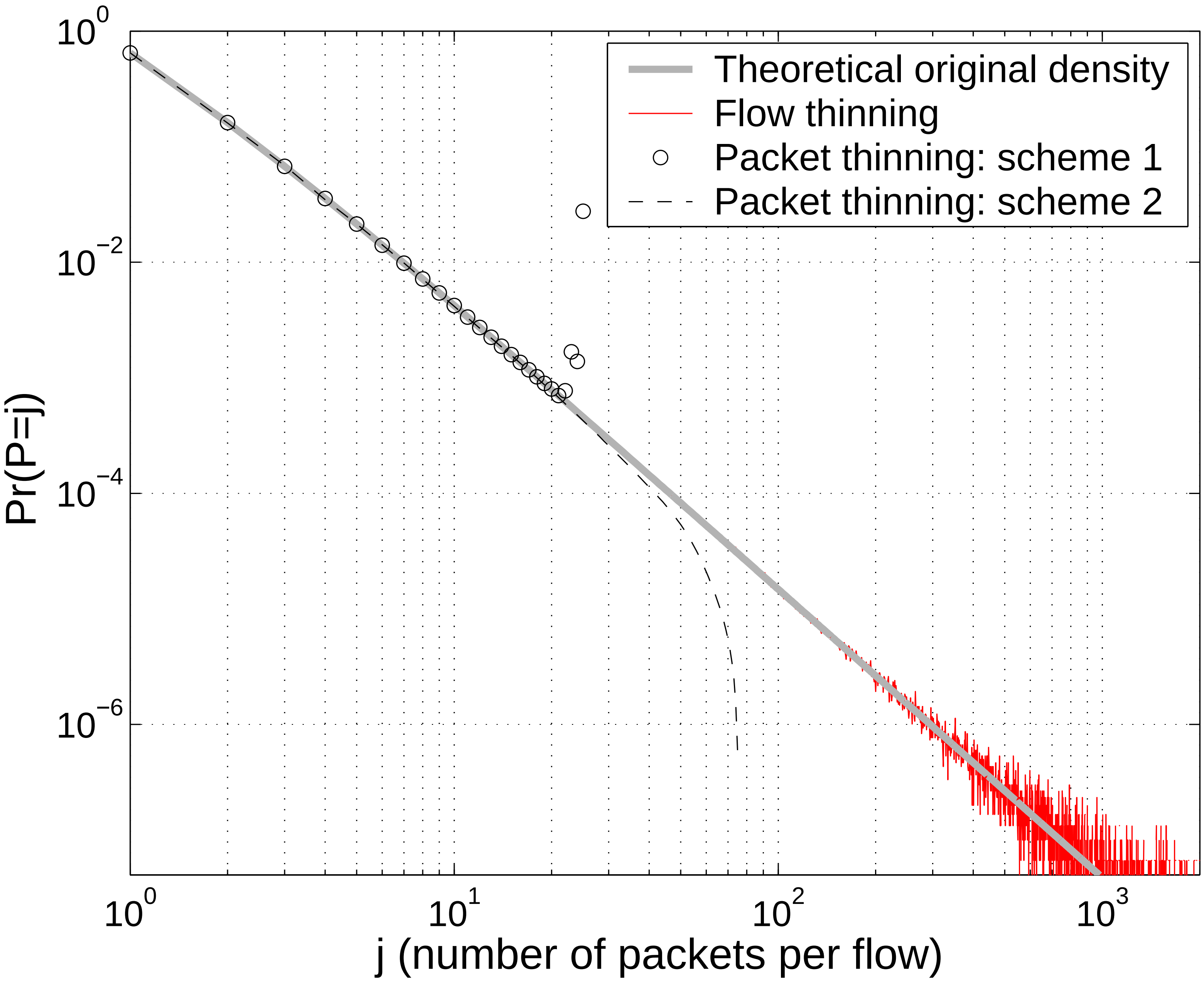
Scheme 2: Cauchy Integral

$$p_j = \oint_{\mathcal{S}} \frac{G_P(z)}{z^{j+1}} dz, \qquad (3)$$

- $\mathcal{S}$: any closed contour containing the origin, for instance $\mathcal{D}(0,1)$.
- Inversion methods work well when G_{P} can be **directly evaluated** on $\mathcal{S}$
- Values of G_{P} on $\mathcal{D}(0,1)$ are **unknown** : obtained with **Padé Approximants**

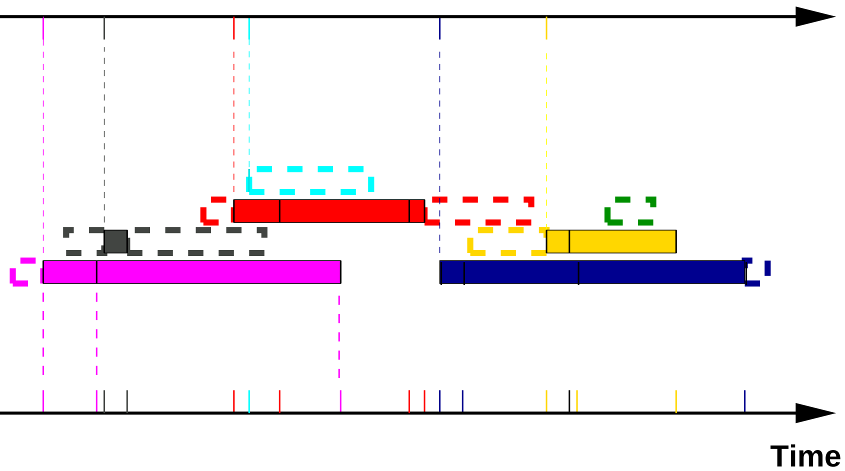
Distribution of number of packets per flow

$q = 0.6$

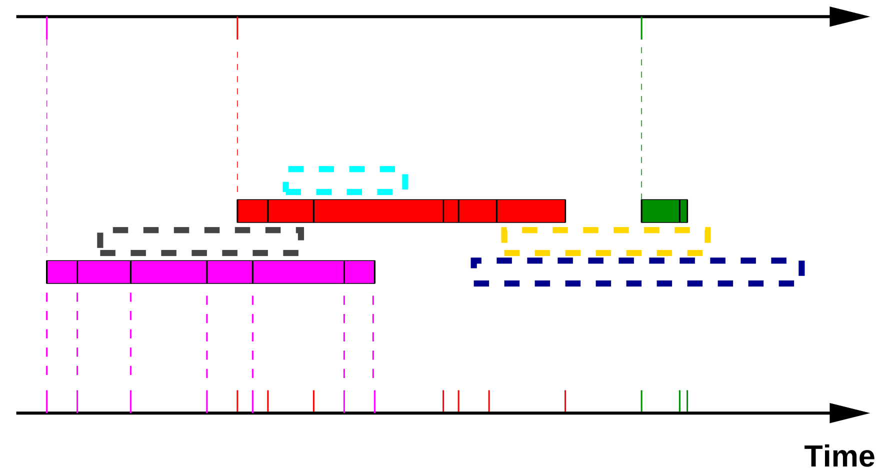


Distribution of number of packets per flow

Packet sampling



Flow Sampling

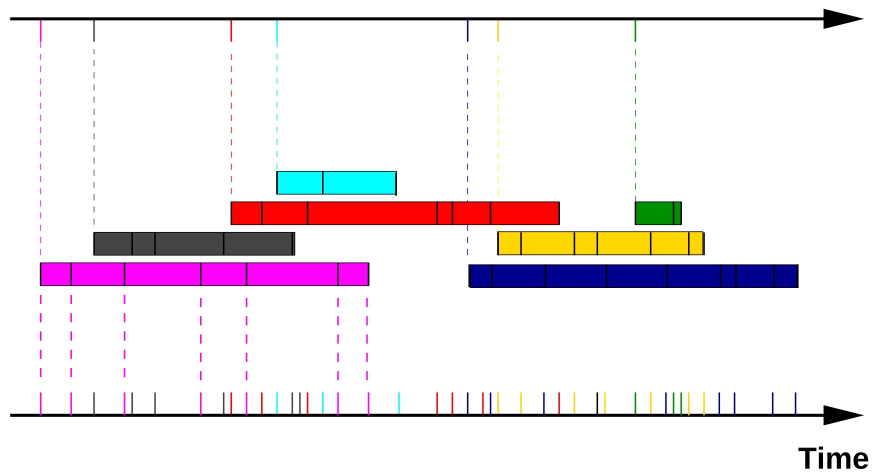


- ➕ Easy to implement,
- ➖ Need for consistent flow definition for sampled traffic (new timeout T_0),
- ➖ Problems to estimate $p_0^{(q)}$ from sampled data,
- ➖ Severe numerical issues to recover the packet distribution (**“impossible” for $q < 0.5$!**),

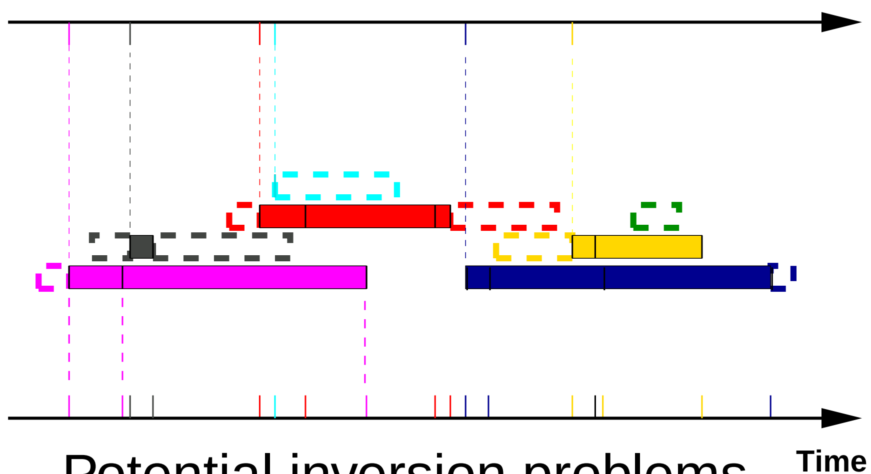
- ➖ Need on-line processing to create flows.
- ➕ No need to change flow definition,
- ➕ No inversion to recover packet distribution,
- ➕ q plays no theoretical role. Only the remaining number of flows matters for the estimation,

Spectral density of packet arrival process

Original traffic

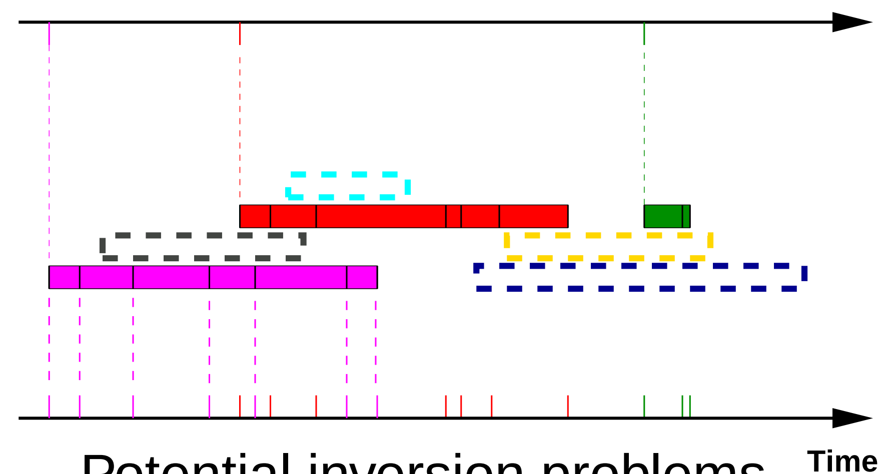


Packet sampling



Potential inversion problems

Flow Sampling



Potential inversion problems

Spectral density of packet arrival process

$\Gamma_X(\omega)$: spectral density of original traffic

$\Gamma_X^{(q)}(\omega)$: spectral density of sampled traffic

Packet sampling

Results from theory of thinned point processes give direct inversion

$$\Gamma_X(\omega) = \frac{1}{q^2}\left(\Gamma_X^{(q)}(\omega) - (1-q)\lambda^{(q)}\right)$$

Flow sampling

Assumptions needed:

- Flow arrivals follow a **Poisson process**,
- Flows are **uncorrelated**.

$$\Gamma_X(\omega) = \frac{1}{q}\Gamma_X^{(q)}(\omega)$$

Study Second Order Structure

Analysis tools: **Discrete Wavelet Transform**

Definition:

Comparison of a signal $X(t)$ with a family of functions $\psi_{j,k}$ by means of inner products $d_X(j,k) =< X, \psi_{j,k} >$, where $\psi_{j,k} = 2^{-j/2}\psi(2^{-j}t - k)$, and ψ is the mother wavelet, localised both in time and frequency.

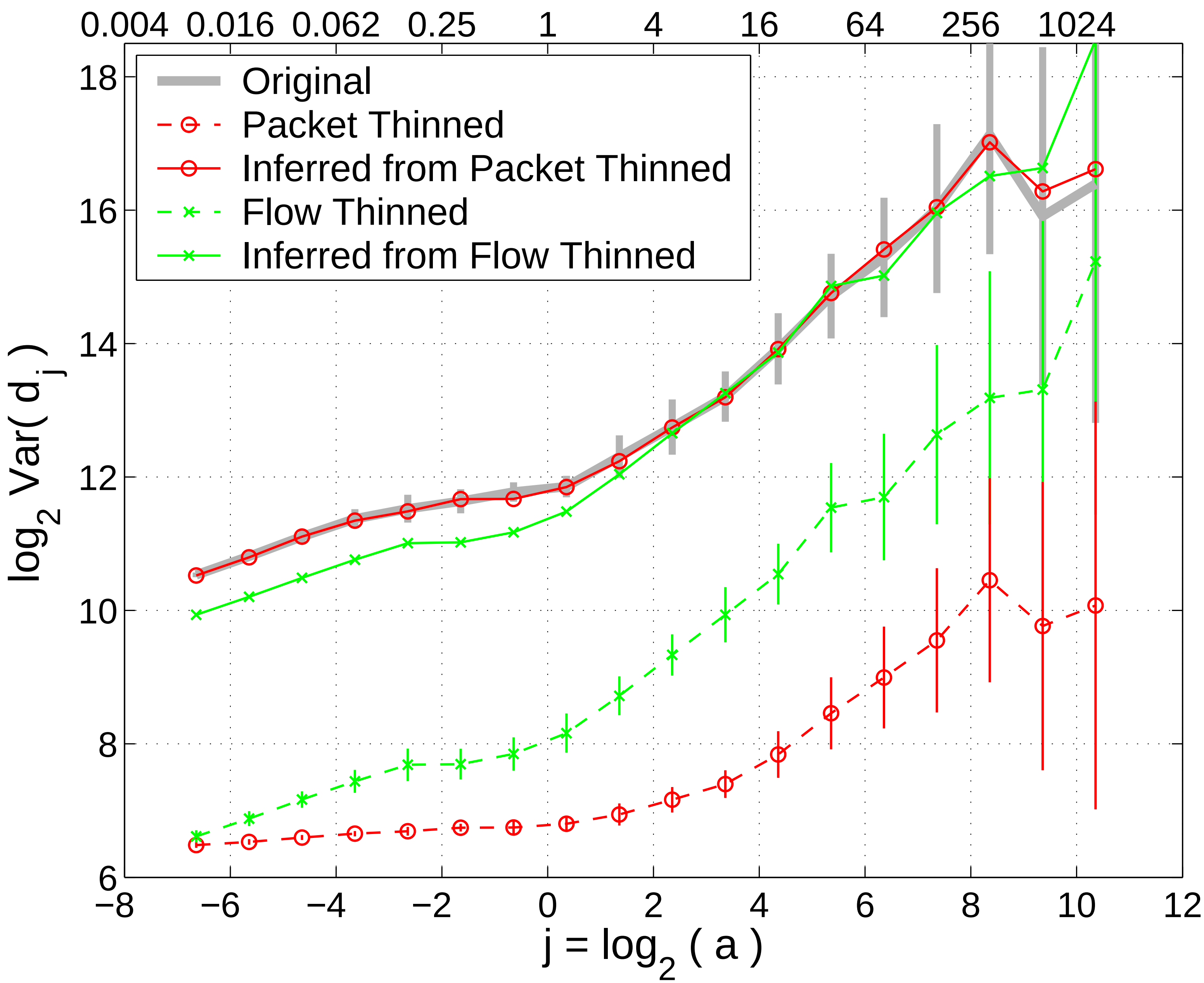
Properties:

- $\{d_X(j,k), k \in \mathcal{Z}\}$ is **stationary** and **short range dependent** for j fixed,
- variance(j) $=$E$|d_X(j,k)|^2$
- For scaling processes: E$|d_X(j,k)|^2 = 2^{j\alpha}E|d_X(0,k)|^2$,
- For LRD processes: E$|d_X(j,k)|^2 \sim 2^{j\alpha}E|d_X(0,k)|^2$ for large j.

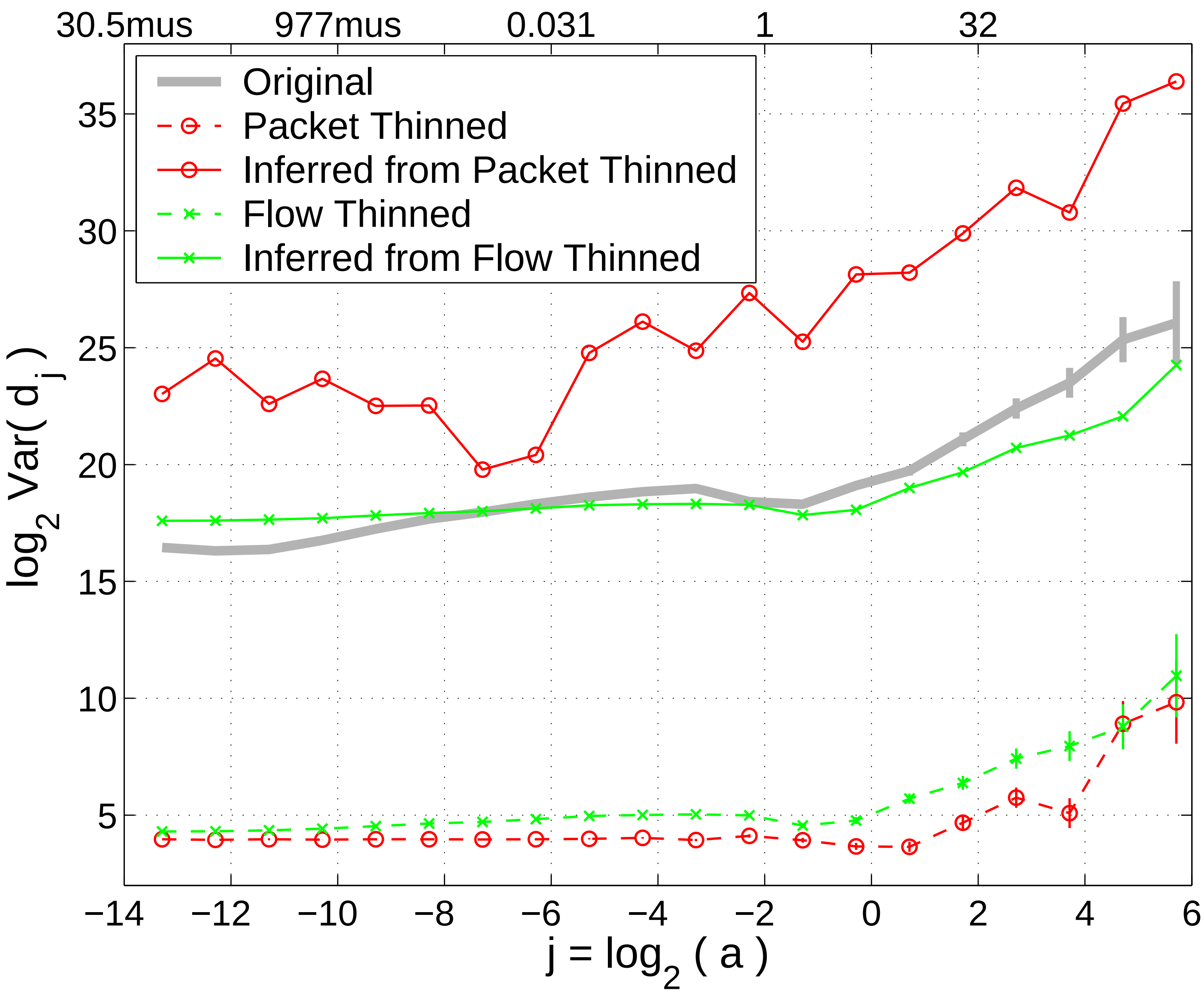
Wavelet Spectrum Estimate: $\log_2\left[\frac{1}{n_j}\sum_k |d_X(j,k)|^2\right]$ vs j

Link with power spectral density: E$|d_X(j,k)|^2 = \int \Gamma_X(\nu) 2^j |\Psi(2^j\nu)|^2 d\nu$

Spectral density: $q = 0.1$



Spectral density: $q = 0.001$



Conclusions

Packet Sampling

- Easy to implement,
- Need for consistent flow definition for sampled traffic (new timeout T_0),
- Problems to estimate $p_0^{(q)}$ from sampled data,
- Severe numerical issues to recover the packet distribution (“impossible” for $q < 0.5$!),
- Inaccurate estimation of the spectrum from sampled traffic for small q.

Flow Sampling

- Need on-line processing to create flows.
- No need to change flow definition,
- No inversion to recover packet distribution,
- q plays no theoretical role. Only the remaining number of flows matters for the estimation,
- Accurate spectrum estimation,

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Application to traffic modelling

Aim

- Fit model to sampled traffic,
- Infer model parameters for unsampled traffic.

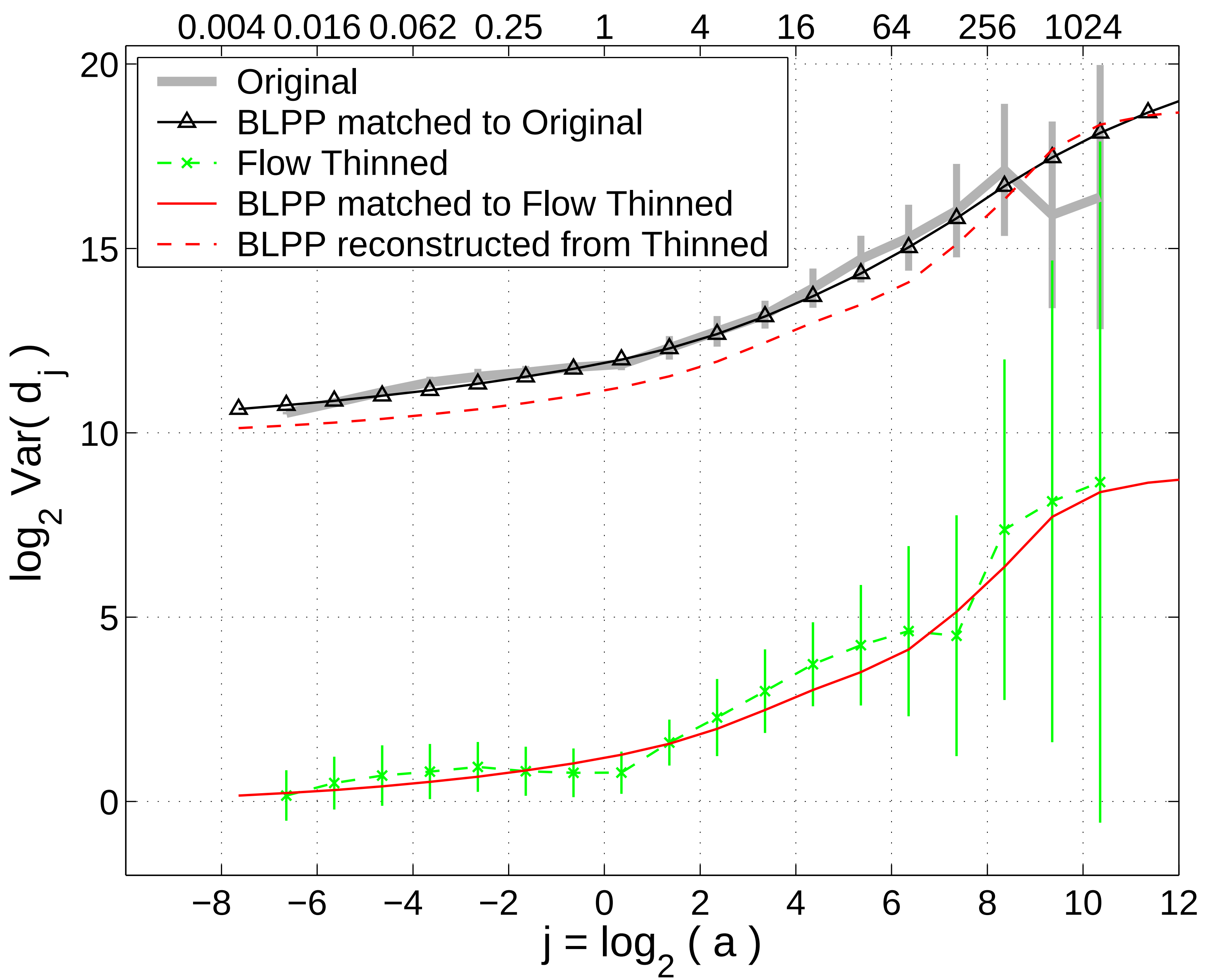
Theory

- Closure properties of the **Bartlett-Lewis Point Process** under both packet and flow sampling.

Practice

- Only flow thinning is applicable.

Sampling the Bartlett-Lewis Point Process



Conclusions

- Packet sampling
  - Easy to implement but hard to infer original statistics beyond first order.
- Flow sampling
  - Harder to implement but leads useful information about original traffic, for both flow and packet level statistics.