Tableau: A High-Throughput and Predictable VM Scheduler for High-Density Workloads

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MAX PLANCK INSTITUTE
FOR SOFTWARE SYSTEMS

MAX-PLANCK-GESELLSCHAFT

Many small VMs packed onto few cores

How to support

high-density

VM workloads

Why High Density?

Competitive market driving datacenter efficiency

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High-Density VM Packing

Consolidating small, cheap VMs to use fewer resources.

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Challenge

Must continue to provide consistent throughput and predictable latency tails.

Competitive market drivin

VM Scheduling Crucial for High-Density

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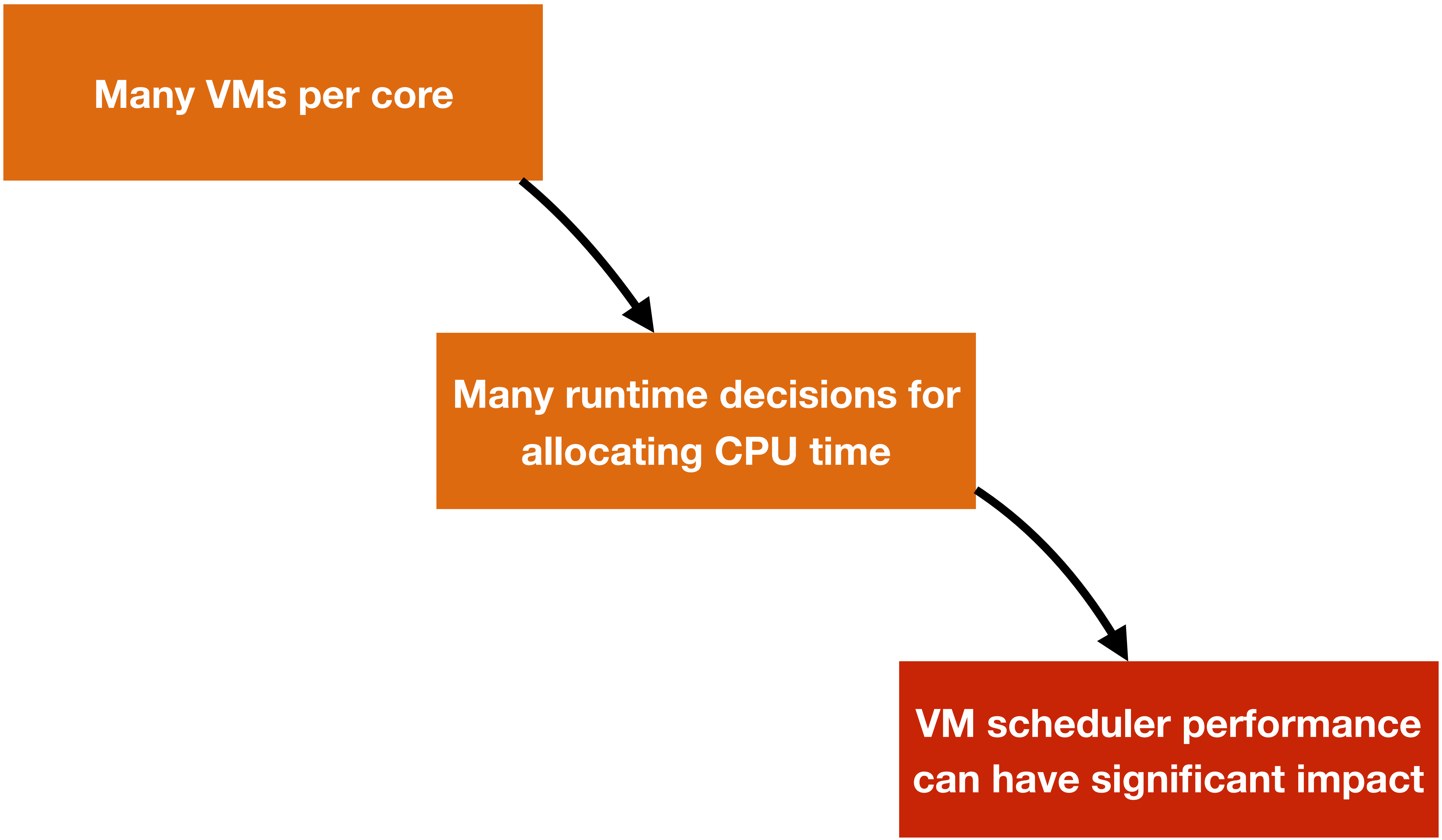

Case Study: VM Scheduling in Xen

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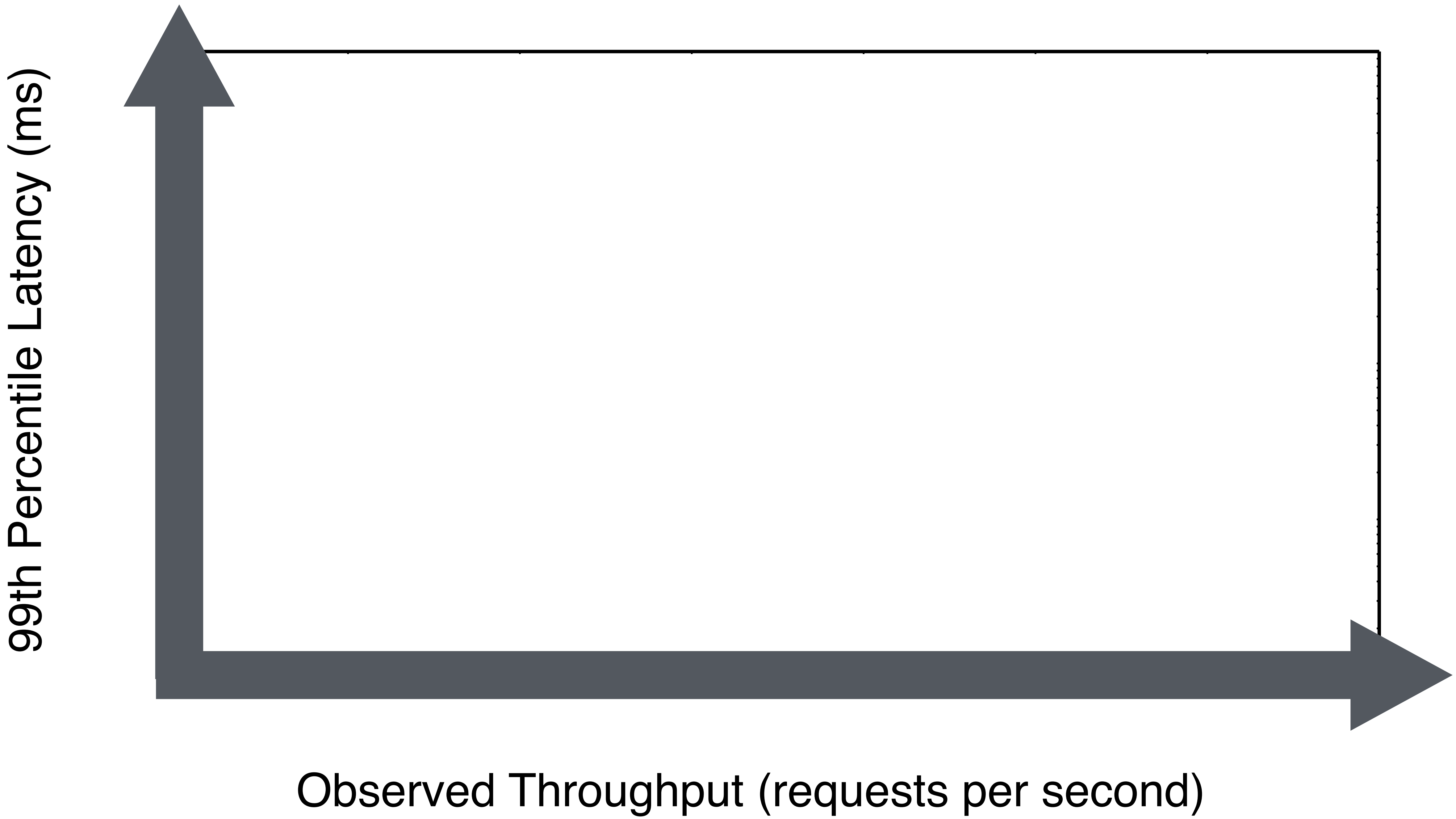
- **Four** VMs per core, 16-core server
- Intel(R) Xeon(R) CPU E5-2667 v4 @ 3.20GHz.
- Measure **HTTPs performance** of one VM
- All other VMs running **I/O-bound stress workload**.

Case Study: VM Scheduling in Xen



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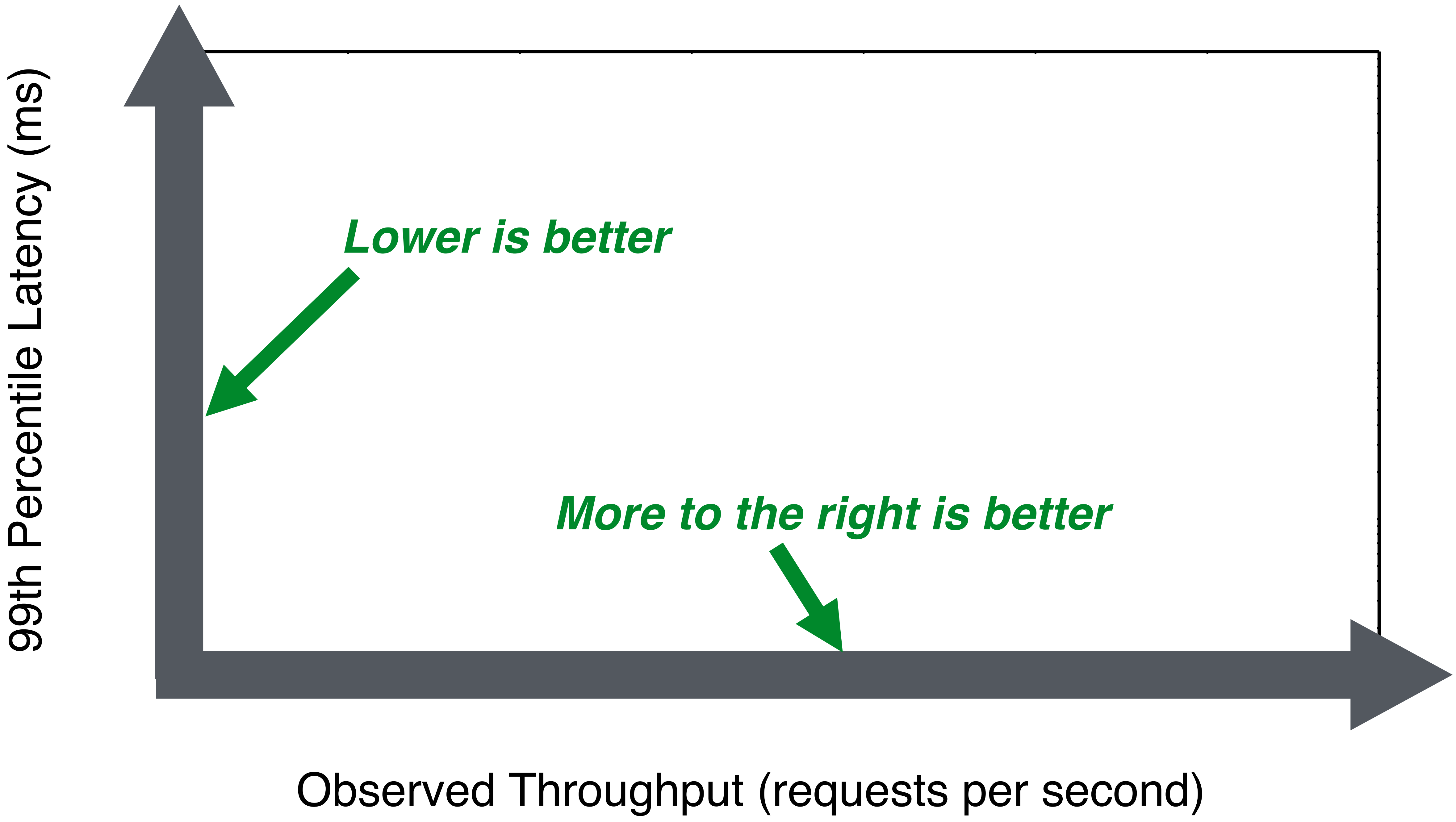

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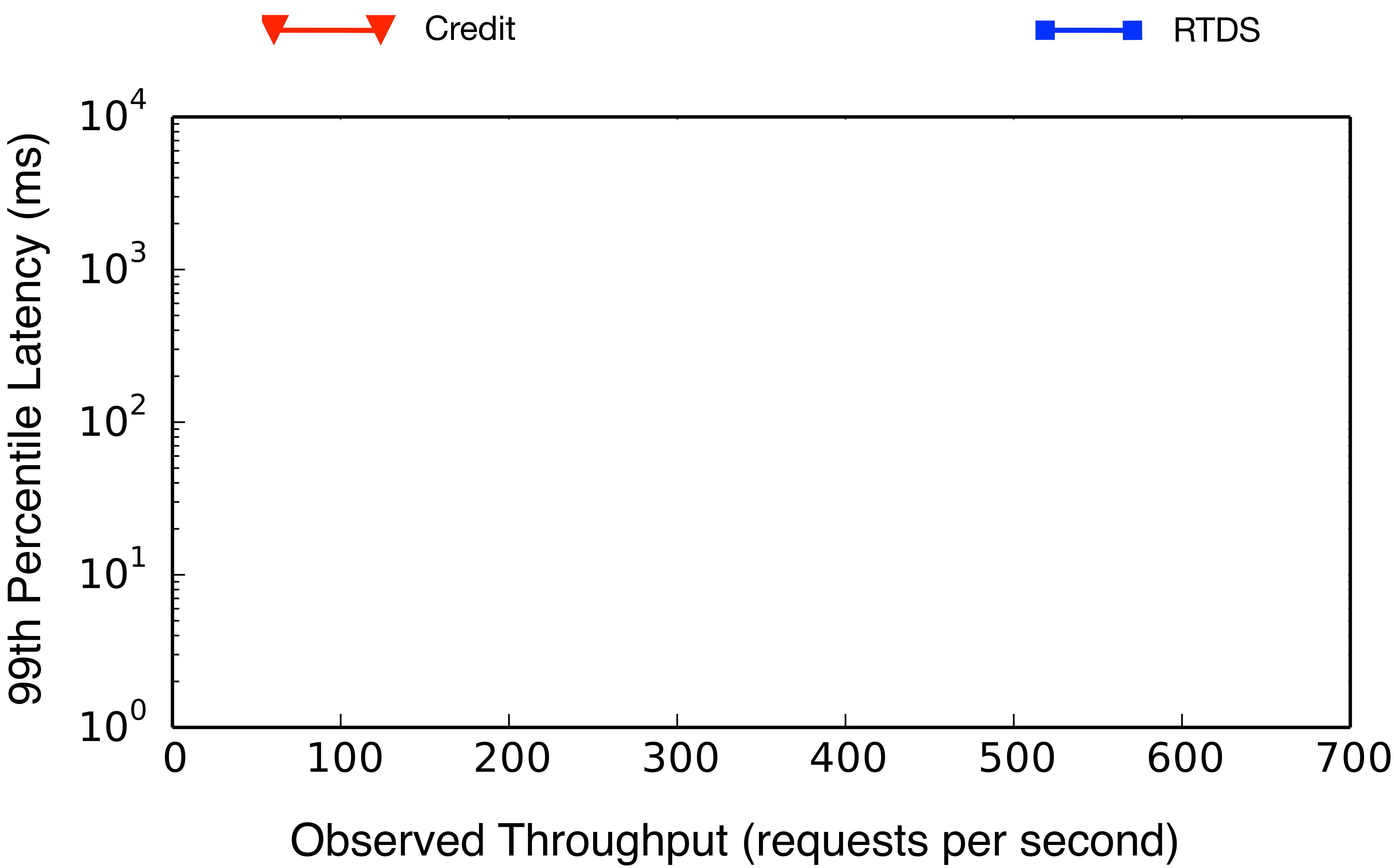

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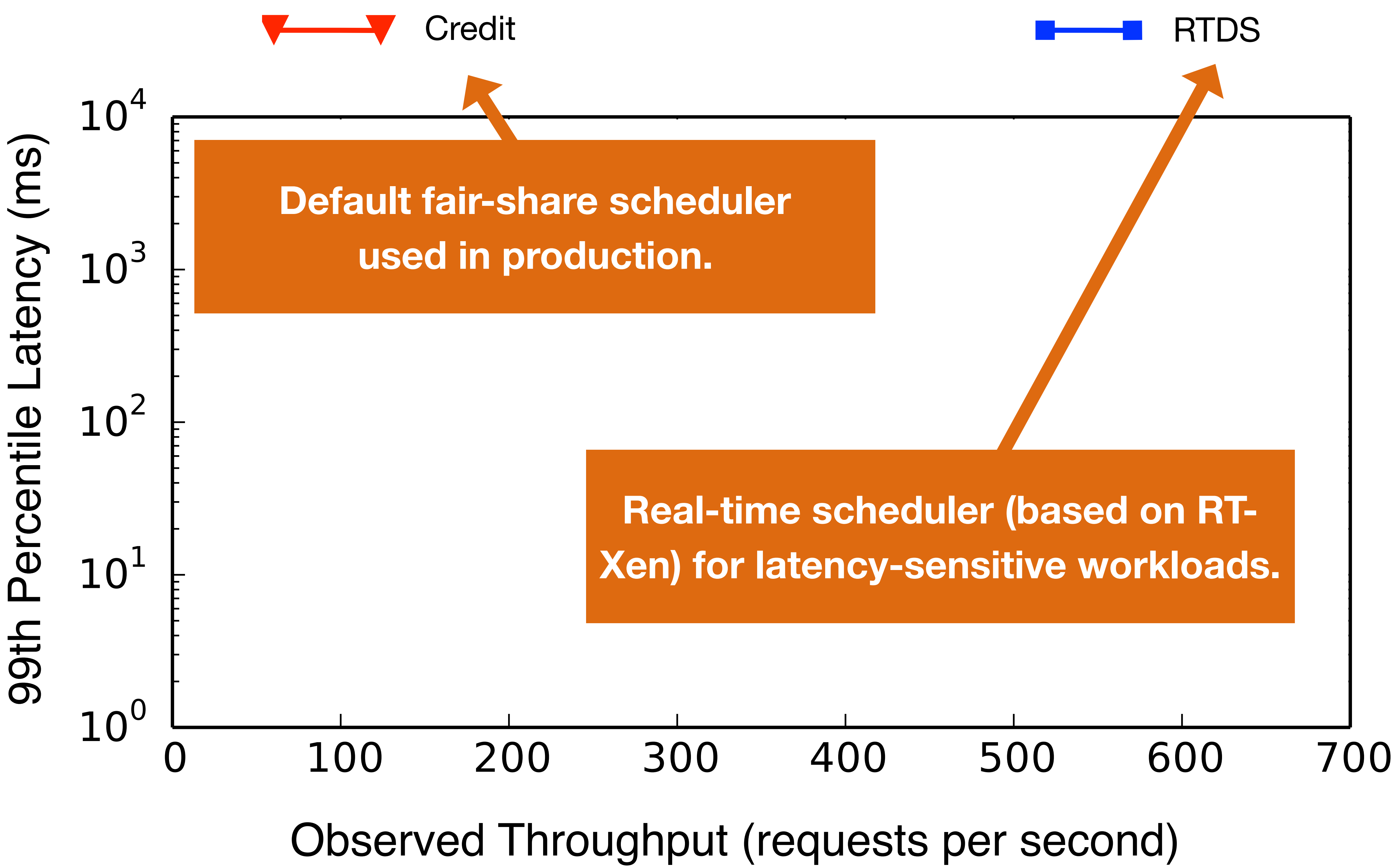

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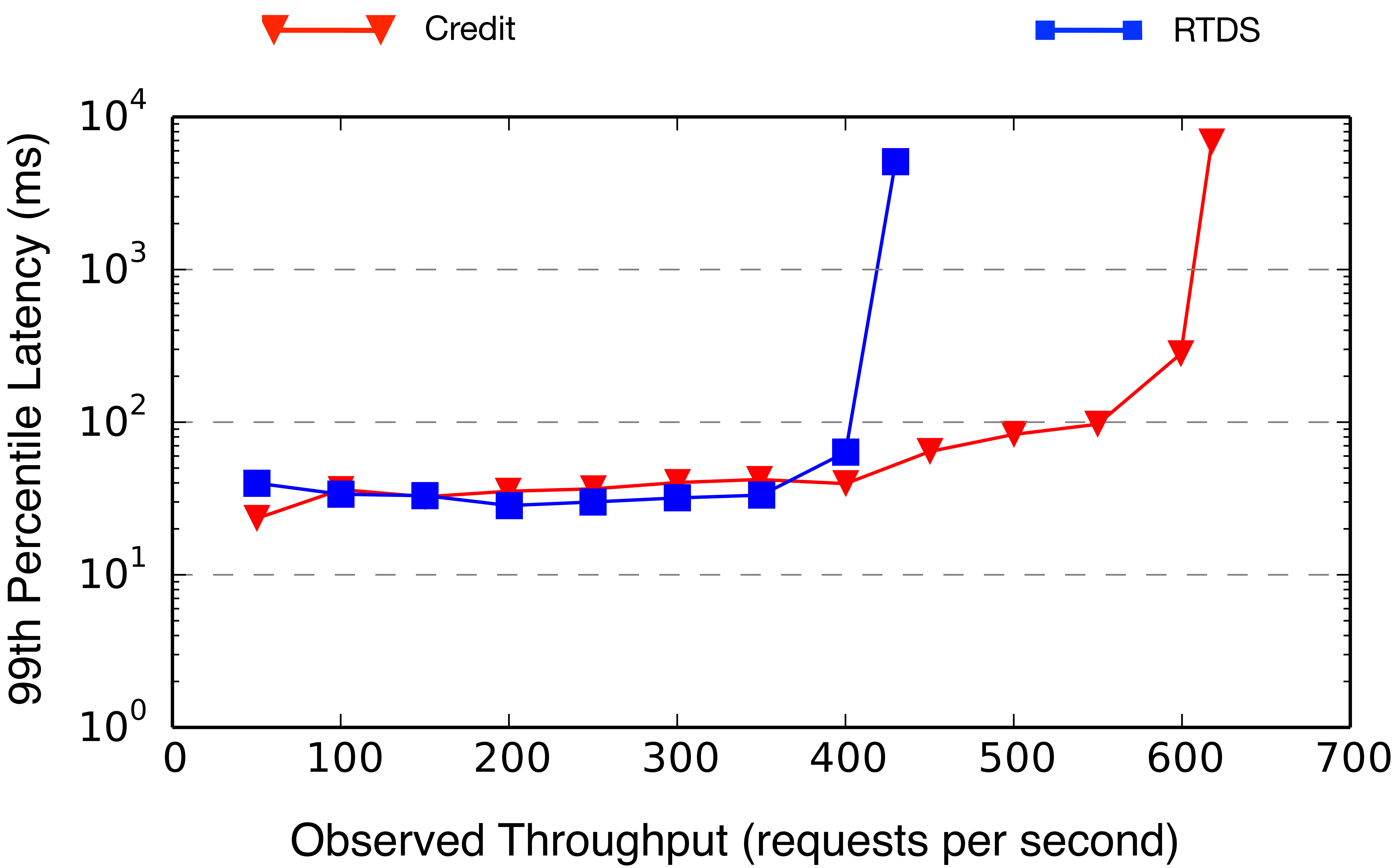

Requesting random 100K-sized files, with I/O background workload

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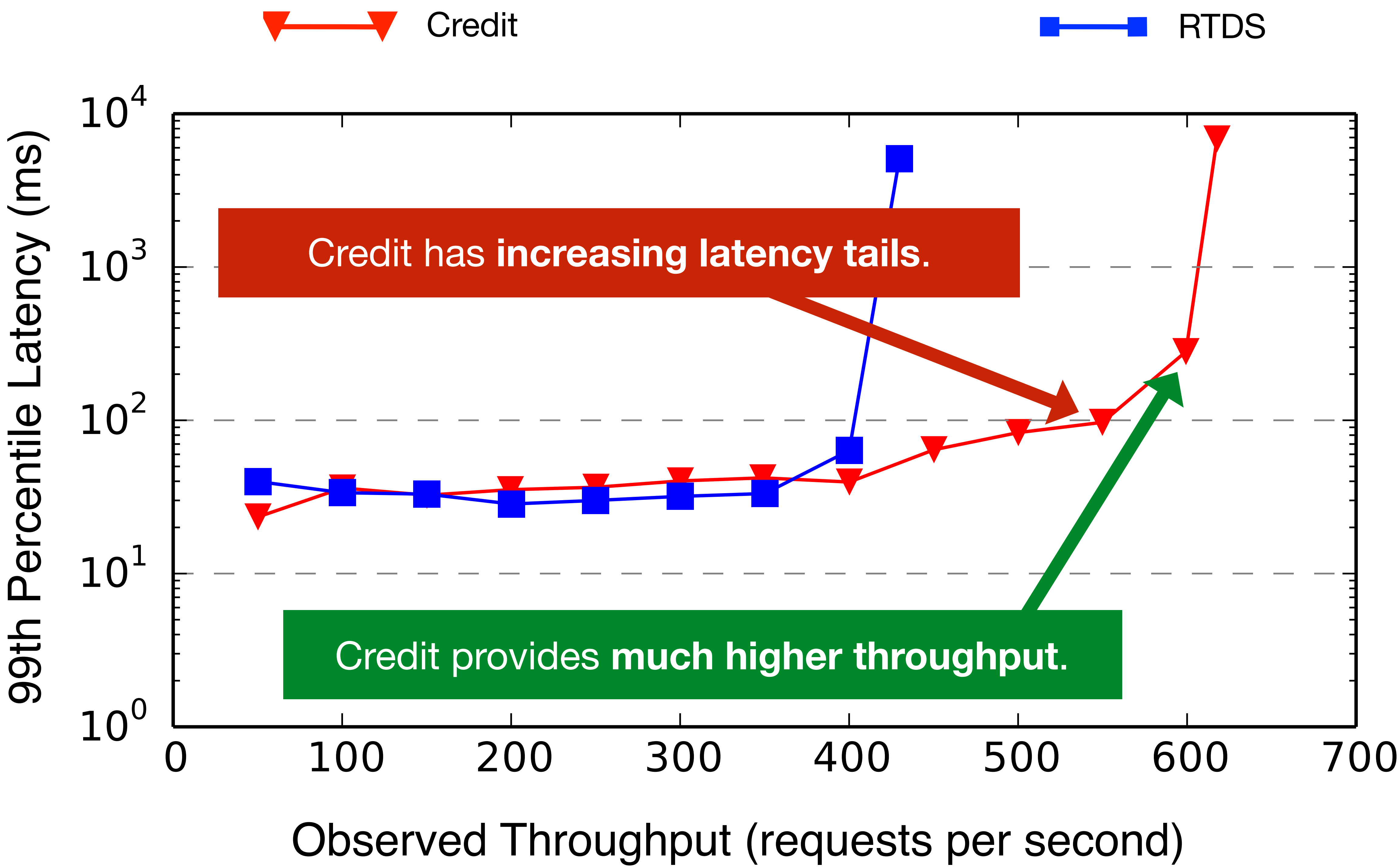

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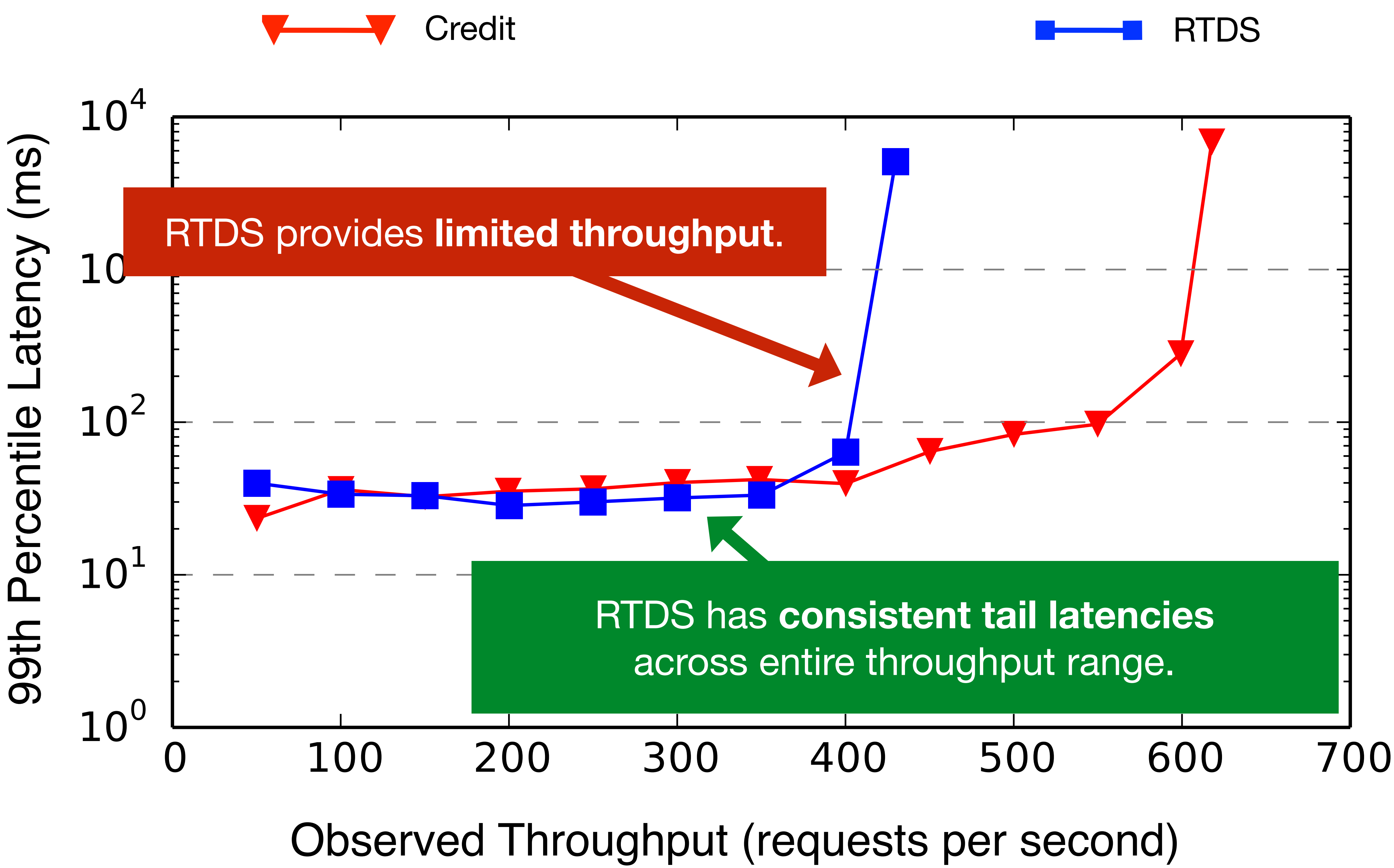
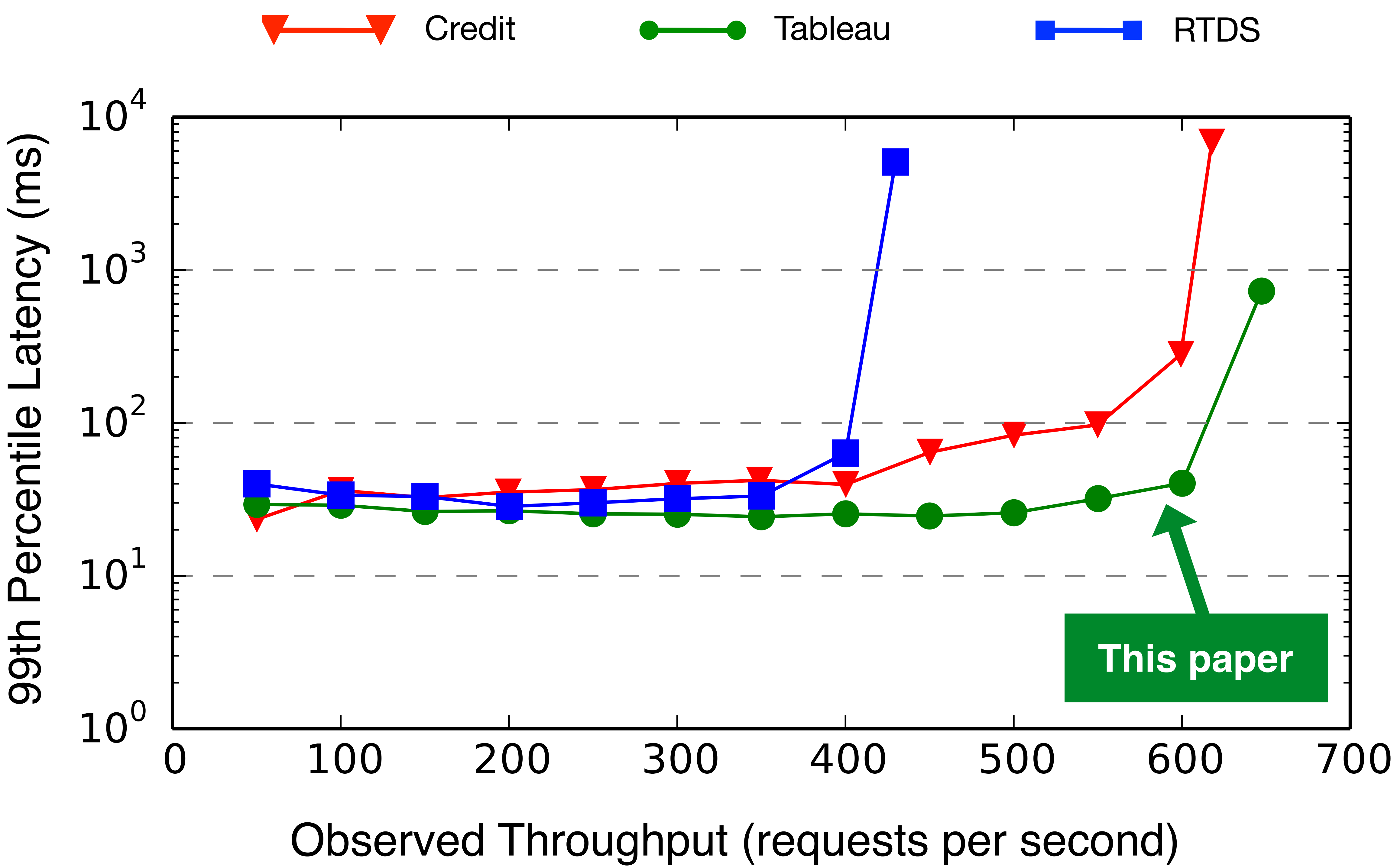


Requesting random 100K-sized files, with I/O background workload

The Tableau VM Scheduler



Requesting random 100K-sized files, with I/O background workload

Contributions

Tableau

An **unorthodox scheduling approach** tailored for high-density public clouds.

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Efficient

Incurs low overheads

Predictable

Accurate control over scheduling latency.

High-throughput

Provides high SLA-aware throughput.

This Talk

- Tableau
- Evaluation
- Conclusion

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What Do We Want From a VM Scheduler?

- **Requirement 1**: Be as "invisible" as possible.
- **Requirement 2**: Guarantee utilization and ensure predictable scheduling latency for every VM.

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Attempting to enforce requirement 2 **at runtime** conflicts with requirement 1.

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Attempting to enforce requirement 2 **at runtime** conflicts with requirement 1.

How do we overcome these conflicting requirements?

The Tableau Approach

Exploit one key property of VM environments

VM churn on a single server is low [1]

[1] Cortez et al., *Resource Central: Understanding and Predicting Workloads for Improved Resource Management in Large Cloud Platforms*, SOSP 2017

The Tableau Approach

Requirement 1
As invisible as possible.
Fast, Low overhead

Requirement 2
Guarantee utilization and
scheduling latency

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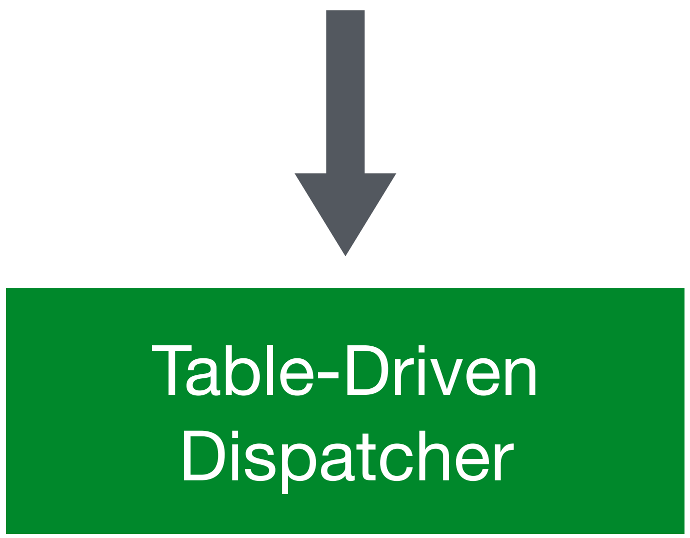

Requirement 2
Guarantee utilization and
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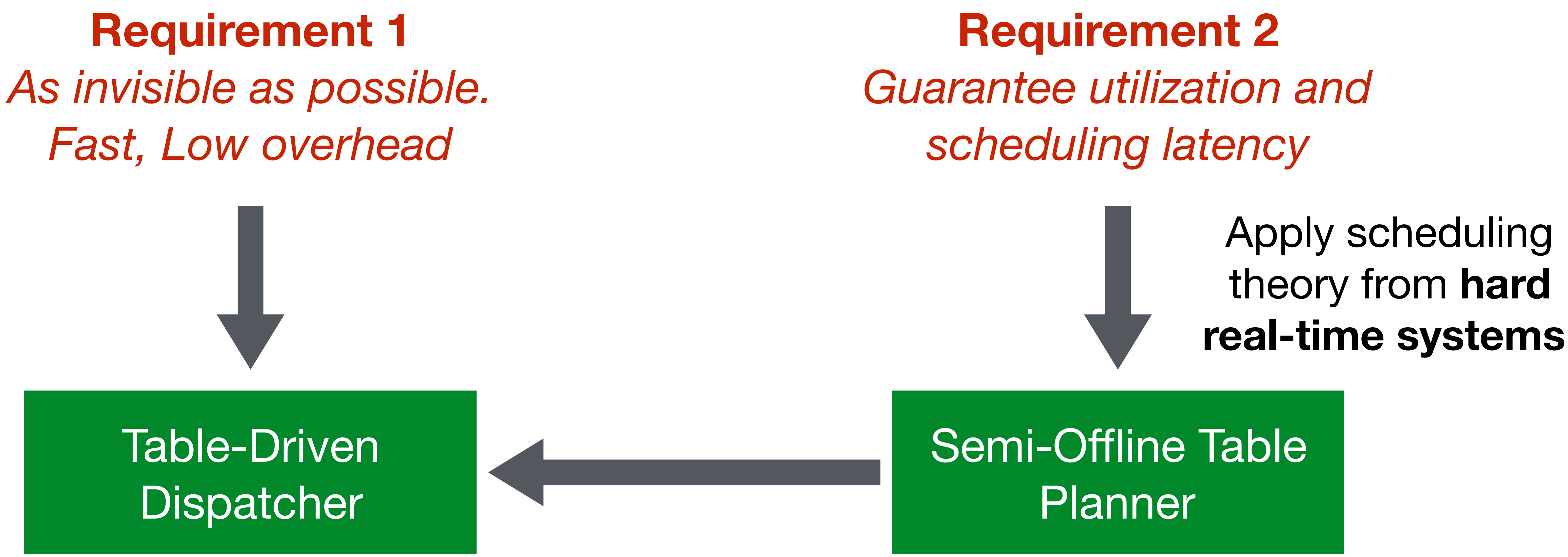
The Tableau Approach



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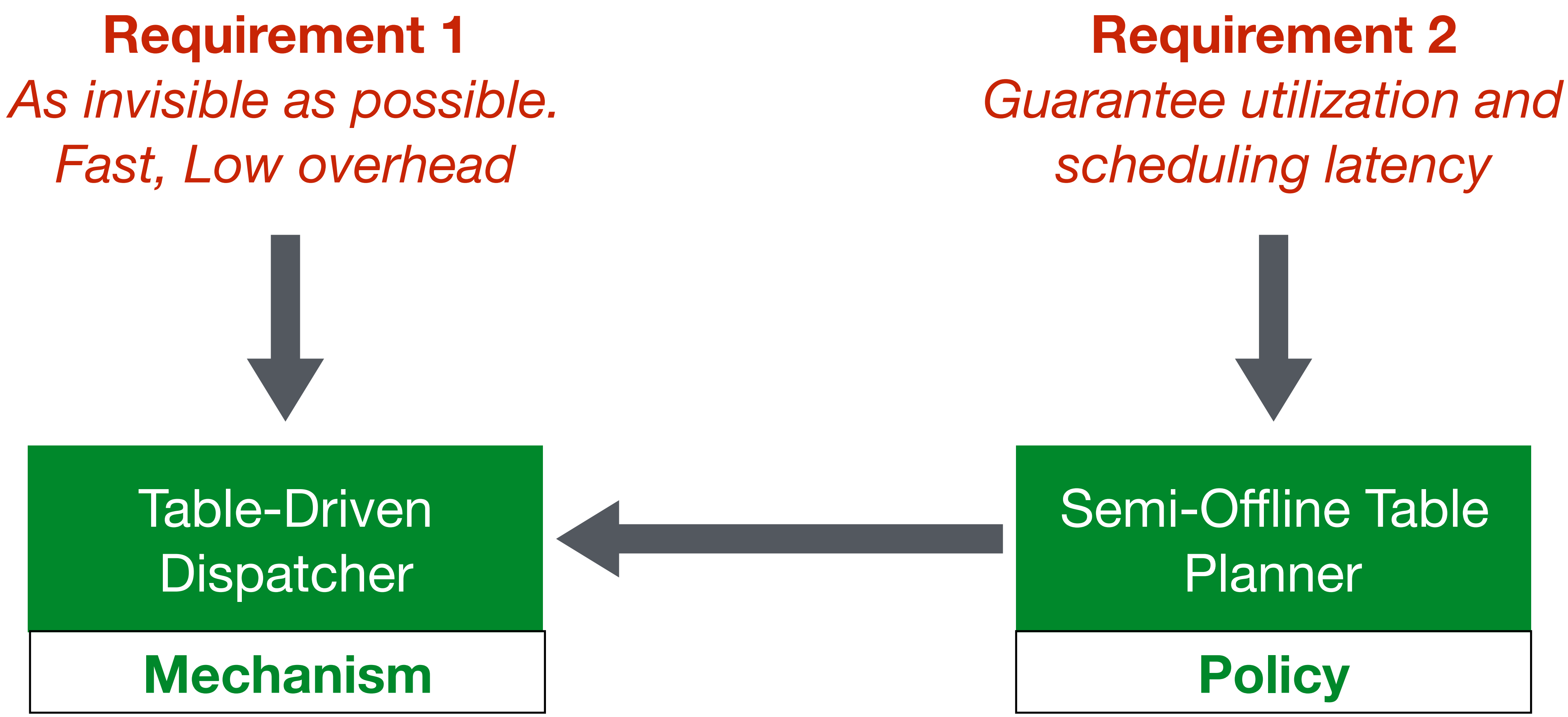

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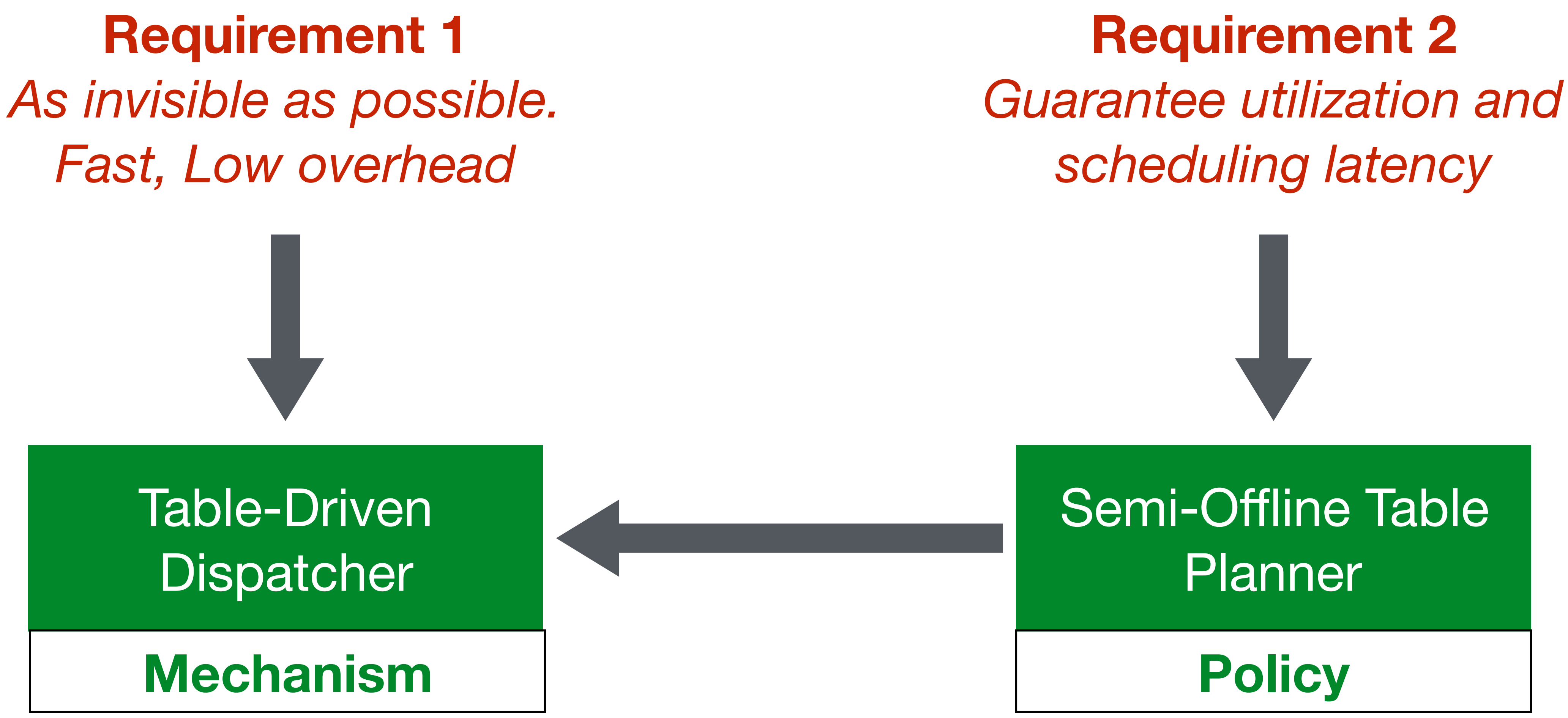

Dispatcher is **completely unaware** of VM-specific requirements!

The Tableau Approach

Requirement 1
As invisible as possible.
Fast, Low overhead

Table-Driven Dispatcher

Mechanism

Dispatcher is **completely unaware** of VM-specific requirements!

Requirement 2
Guarantee utilization and scheduling latency

Semi-Offline Table Planner

Policy

Easy to extend using **high-level** languages, tools, and libraries.

The Tableau Approach

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As invisible as possible.
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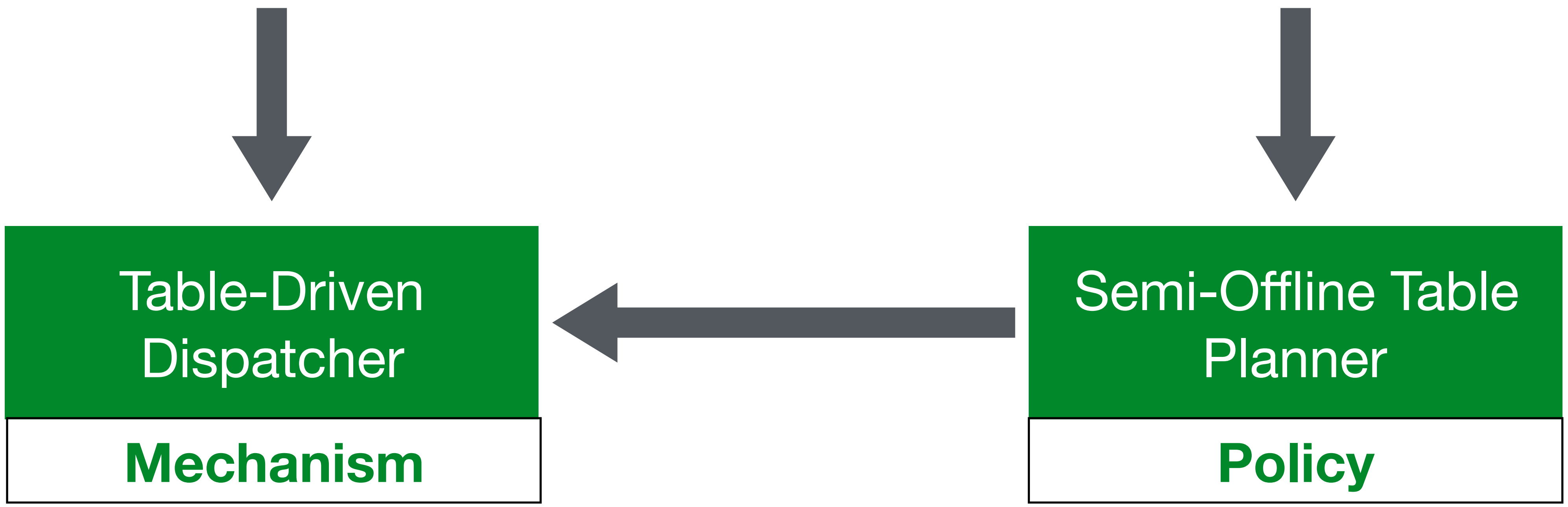
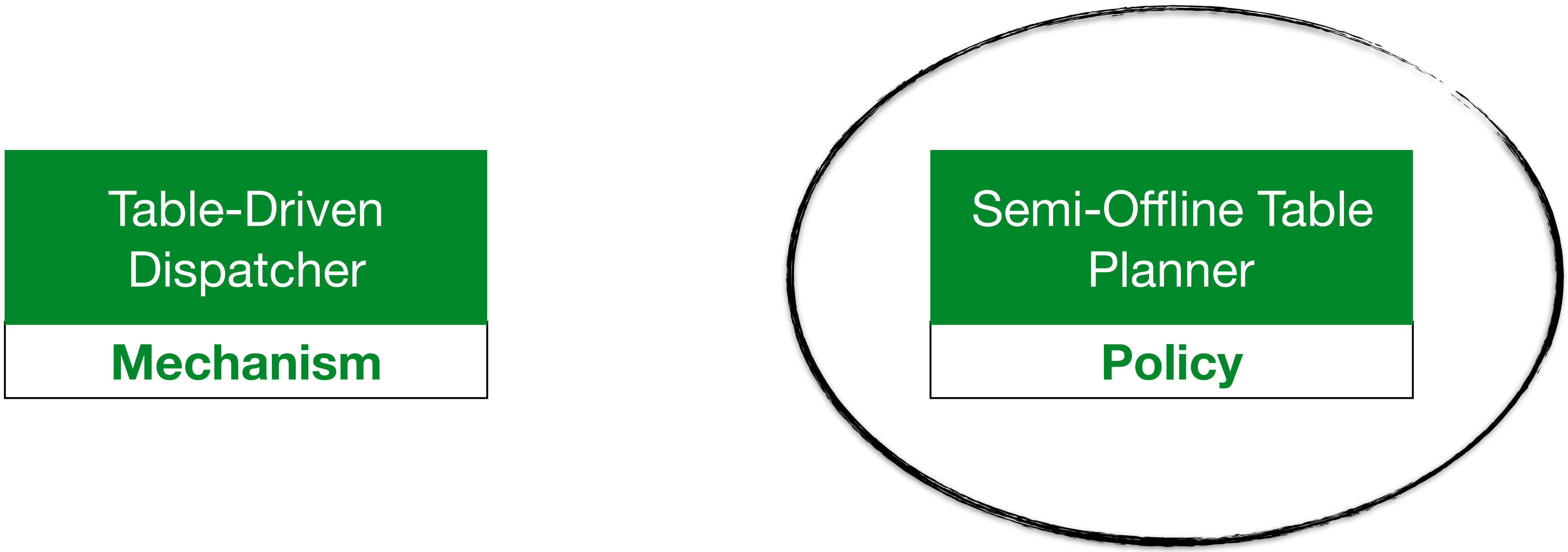


Dispatcher is **completely unaware** of VM-specific requirements!

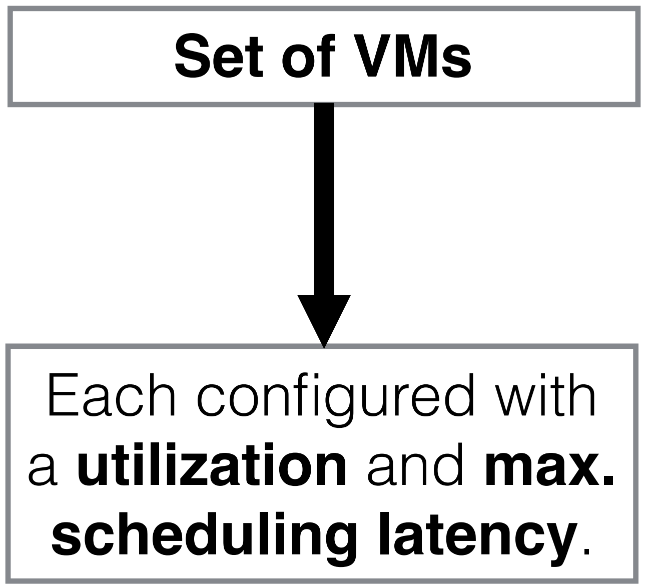
Easy to extend using **high-level** languages, tools, and libraries.

Can be **pre-generated** or generated on a **separate machine**.

The Tableau Approach



Generating Tables Quickly



Generating Tables Quickly

Set of VMs

Each configured with a **utilization** and **max. scheduling latency**.

No more information than existing schedulers *(e.g., Credit requires a relative weight and timeslice)*

Generating Tables Quickly

Set of VMs

Each configured with a **utilization** and **max. scheduling latency**.

Model each VM as a **periodic task**[1].

[1] Liu, Layland, Scheduling algorithms for multiprogramming in a hard-real-time environment. Journal of the ACM (JACM), 20(1), pp.46-61, 1973

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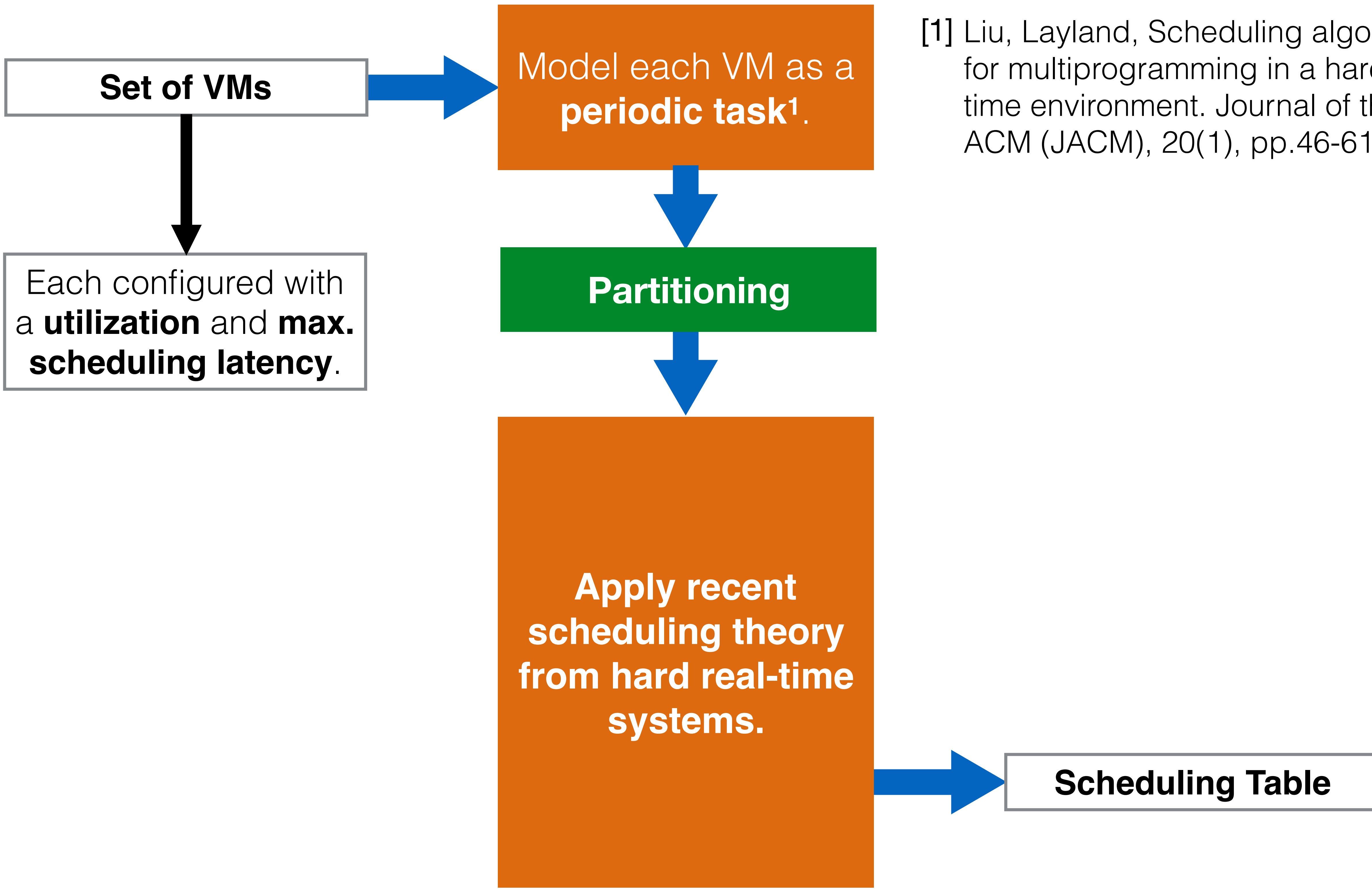

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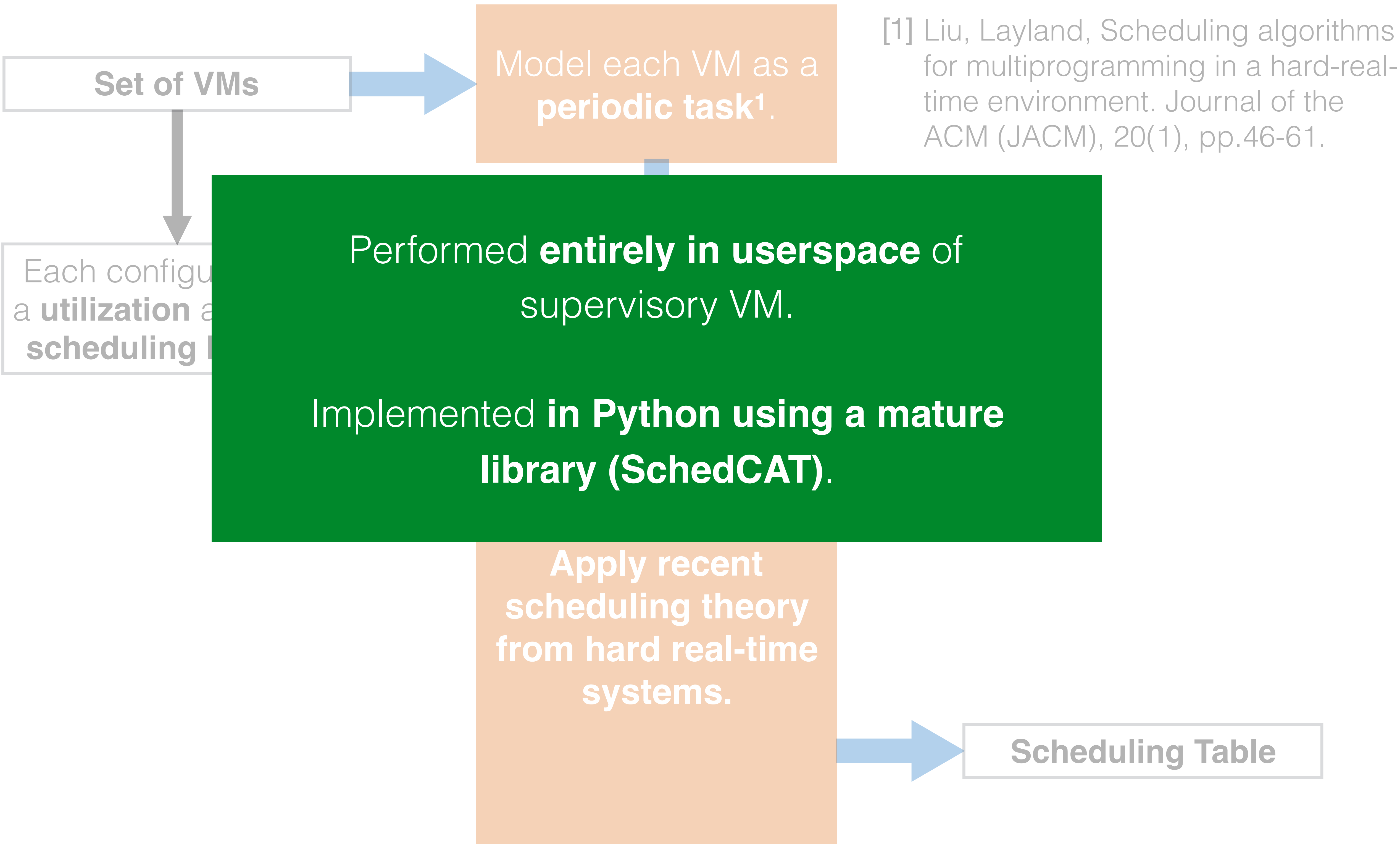

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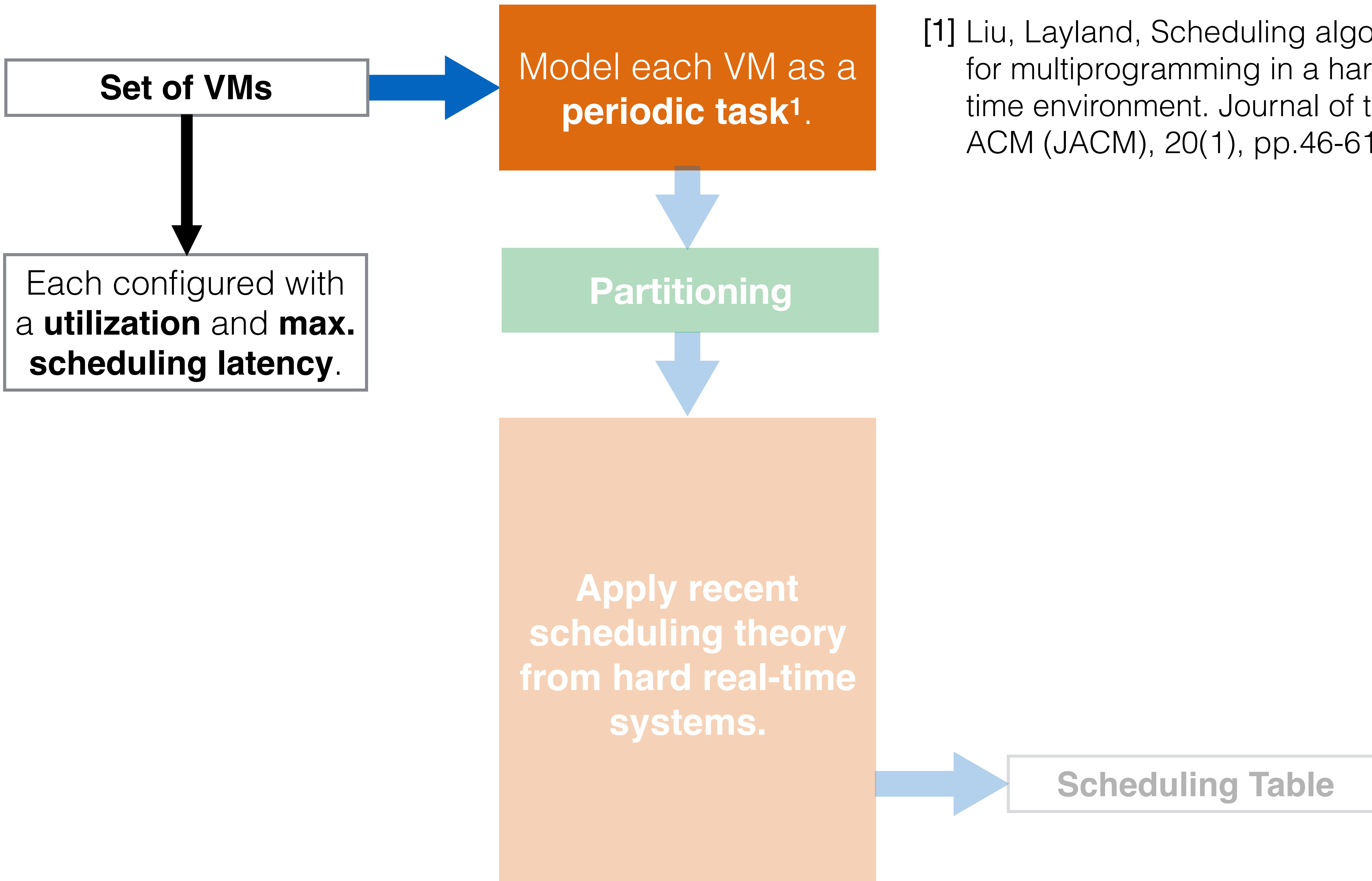

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Modeling VMs as Periodic Tasks

VM (vCPU)

Utilization (U)
A percentage of CPU time reserved for VM.

Max Sched. Delay (L)
An upper bound on scheduling delay.

↓

Periodic Task

Budget (C)

Period (T)

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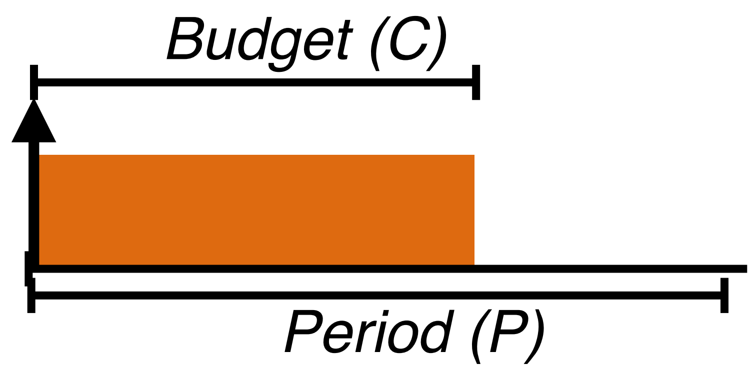

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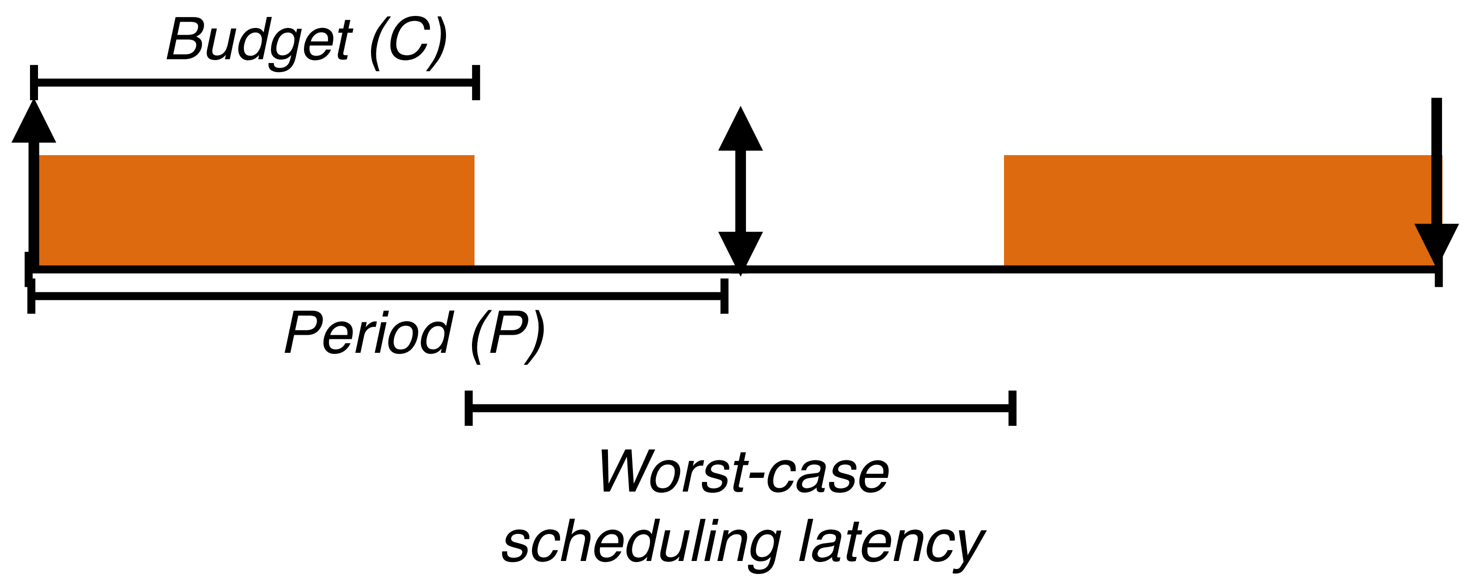

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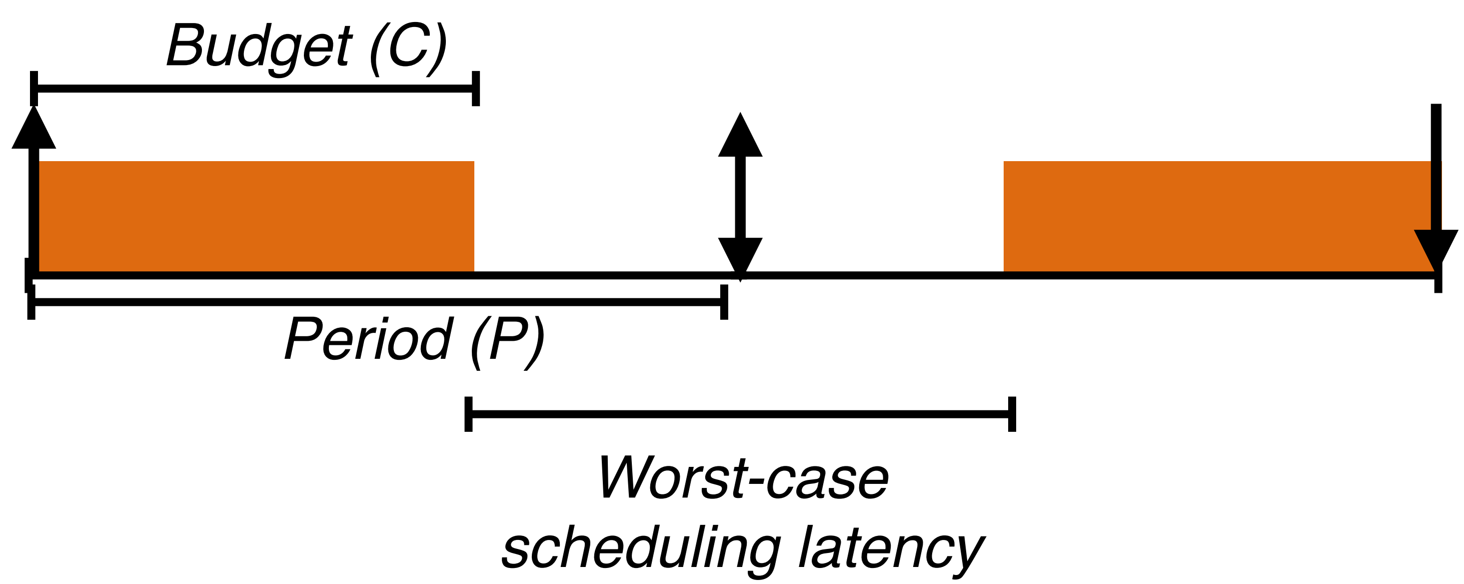

2 x (P - C)

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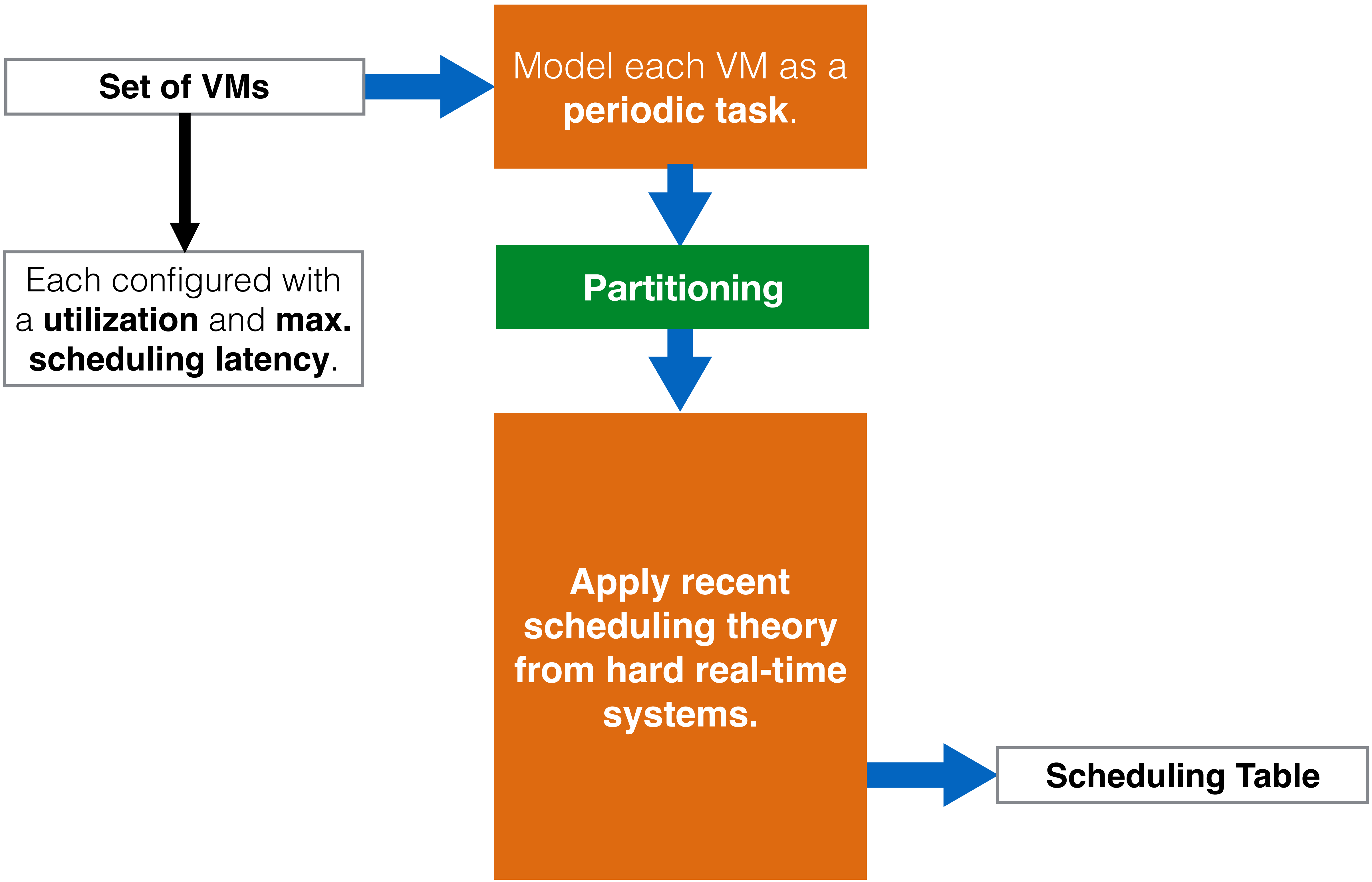
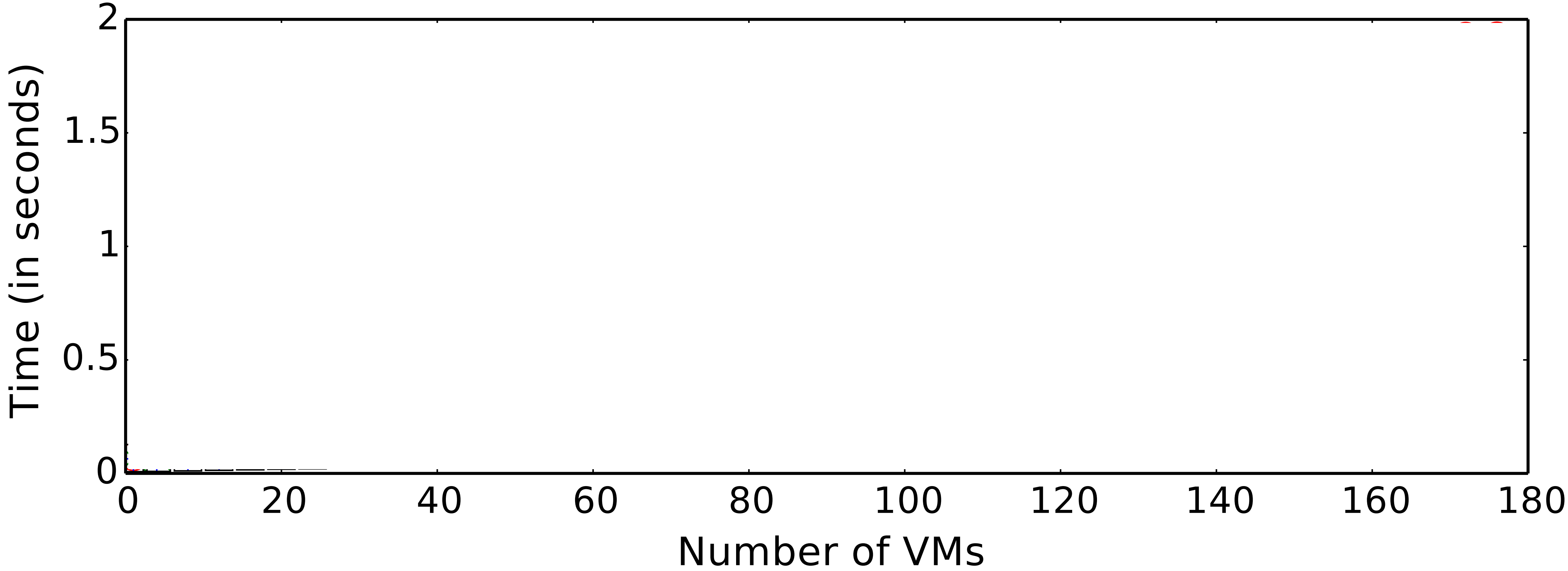


Table-Generation Times



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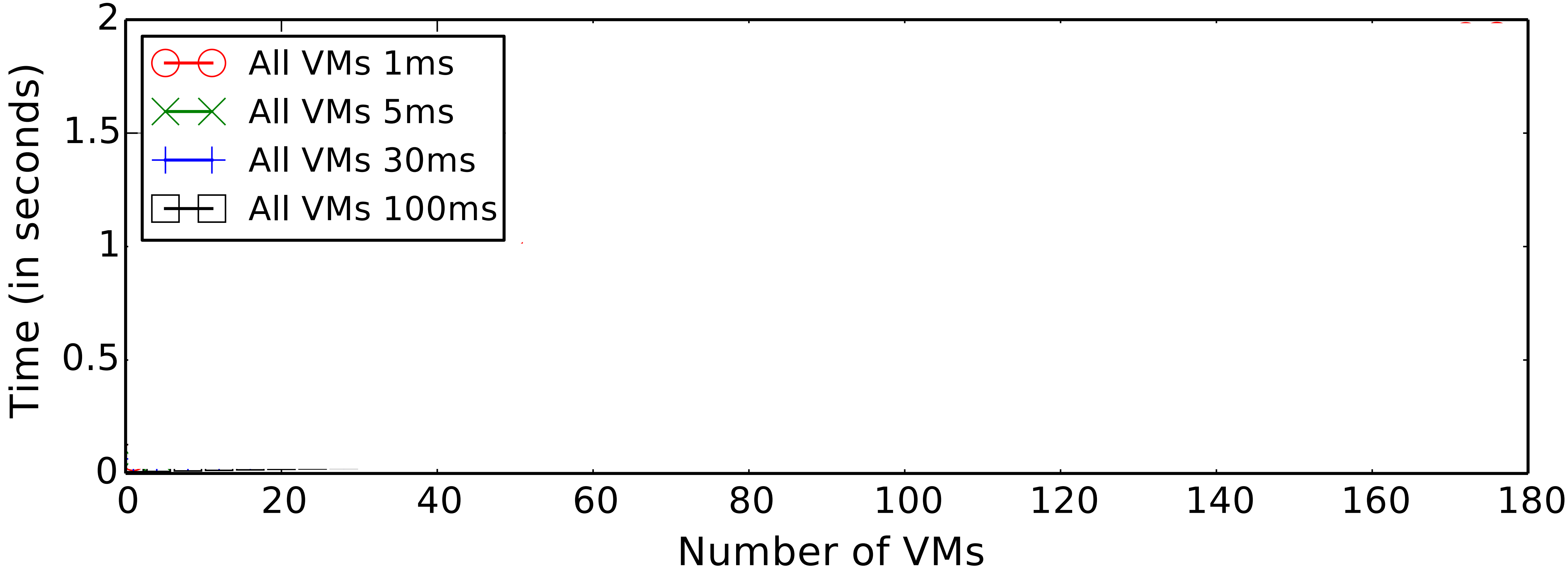

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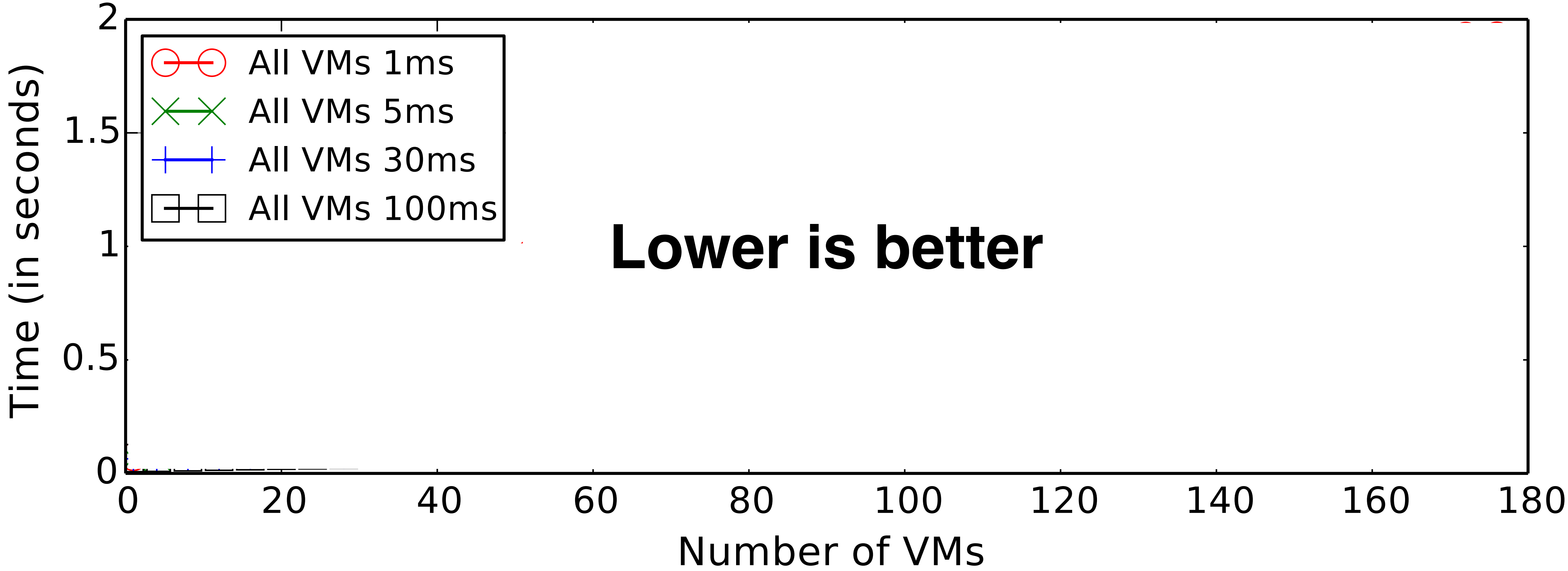

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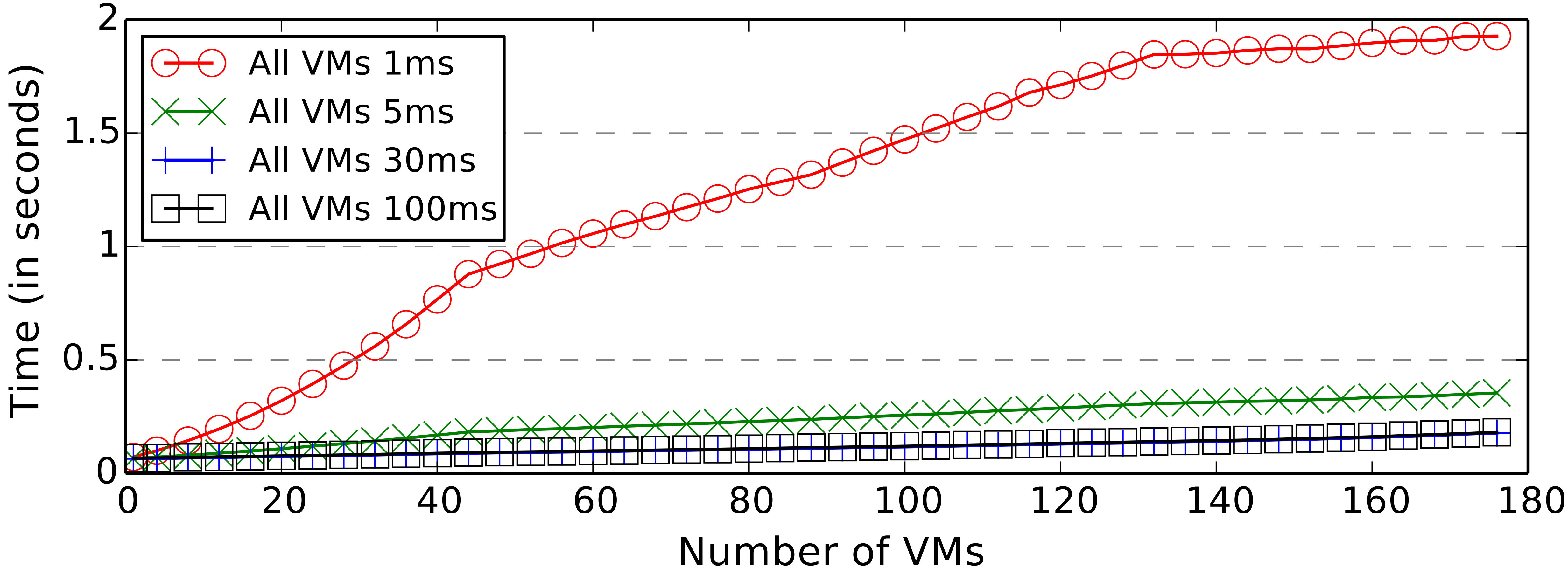

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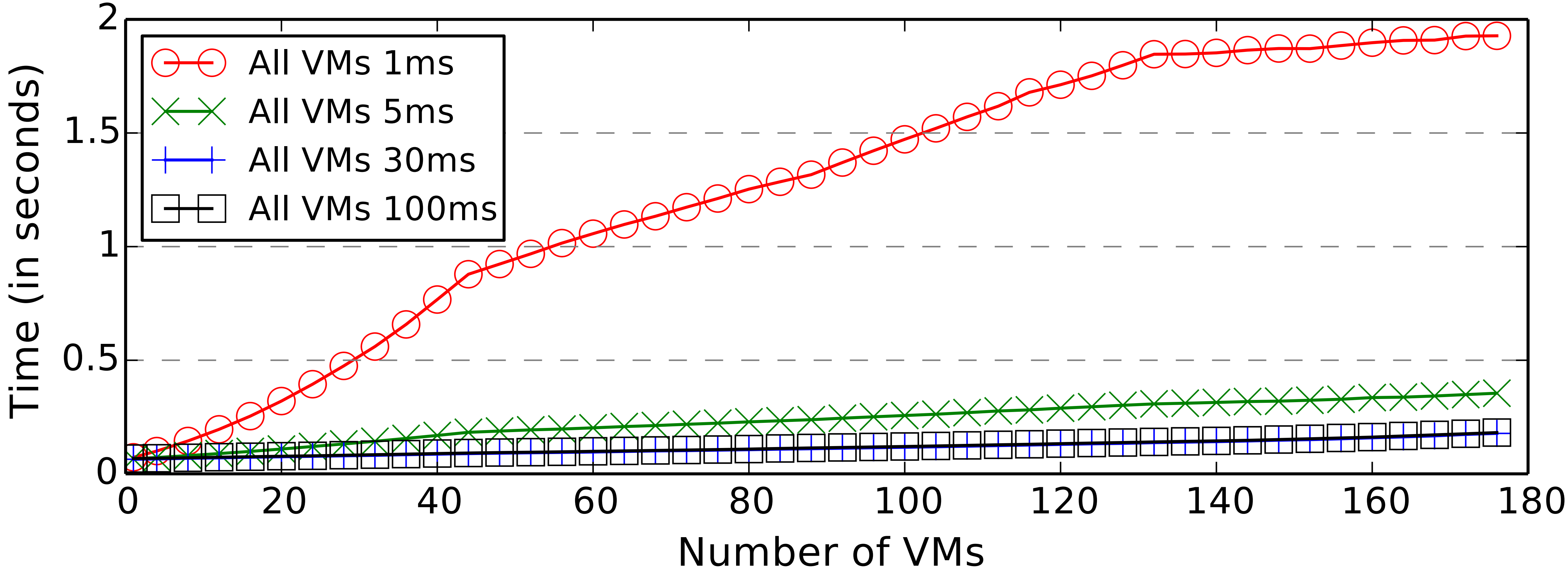


Table generation times are reasonable compared to VM creation and teardown times.

The Tableau Approach

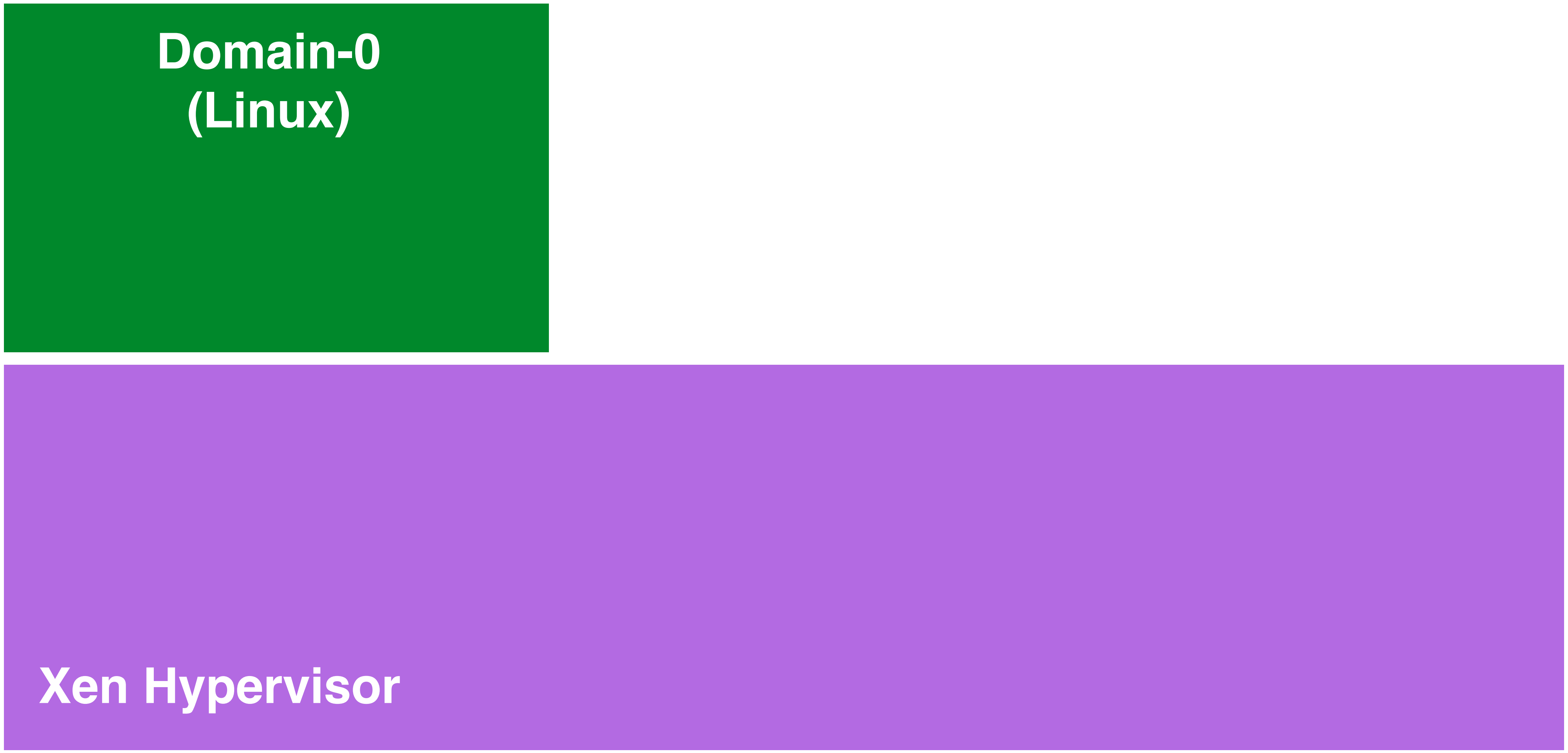
Table-Driven Dispatcher

Mechanism

Semi-Offline Table Planner

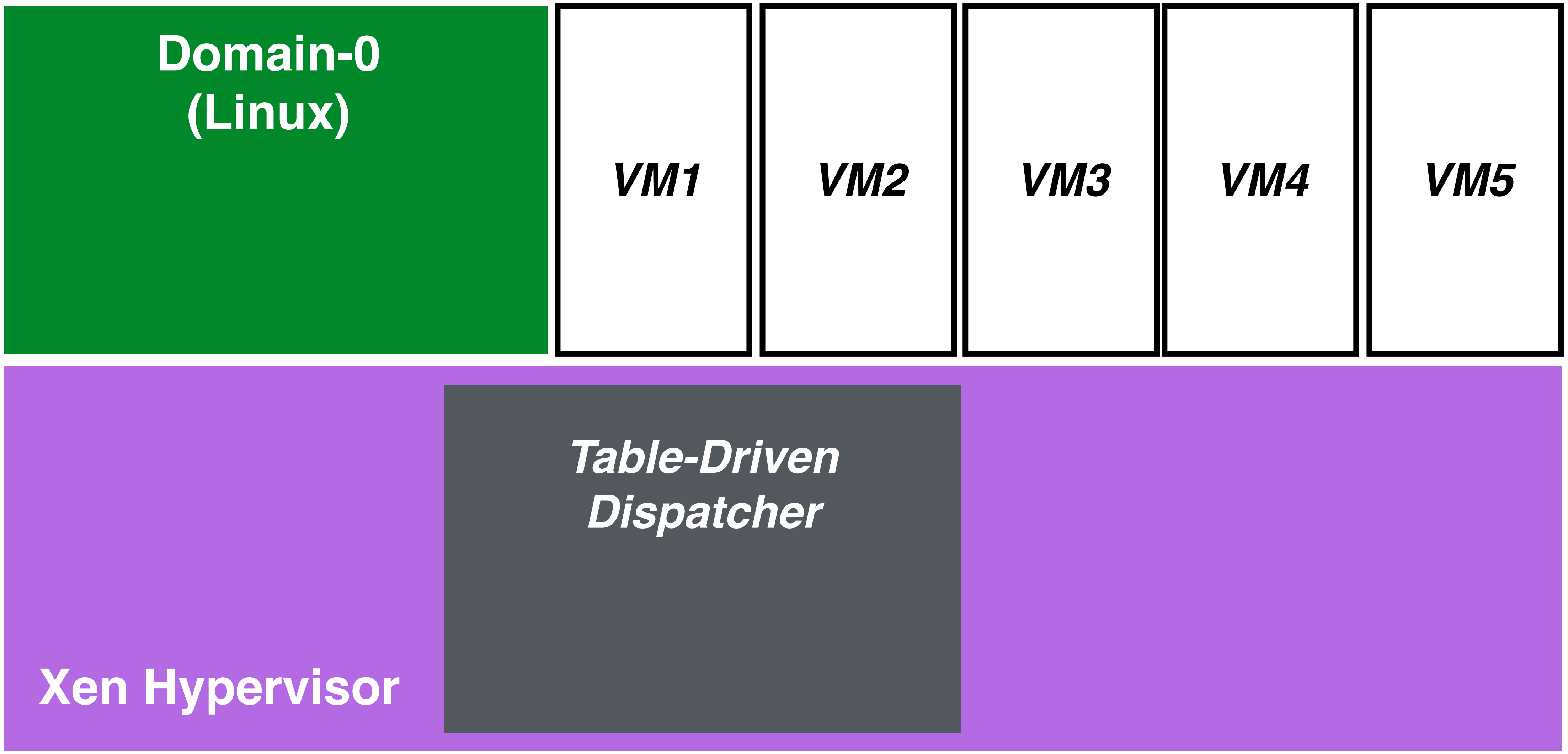
Policy

Implementation in Xen



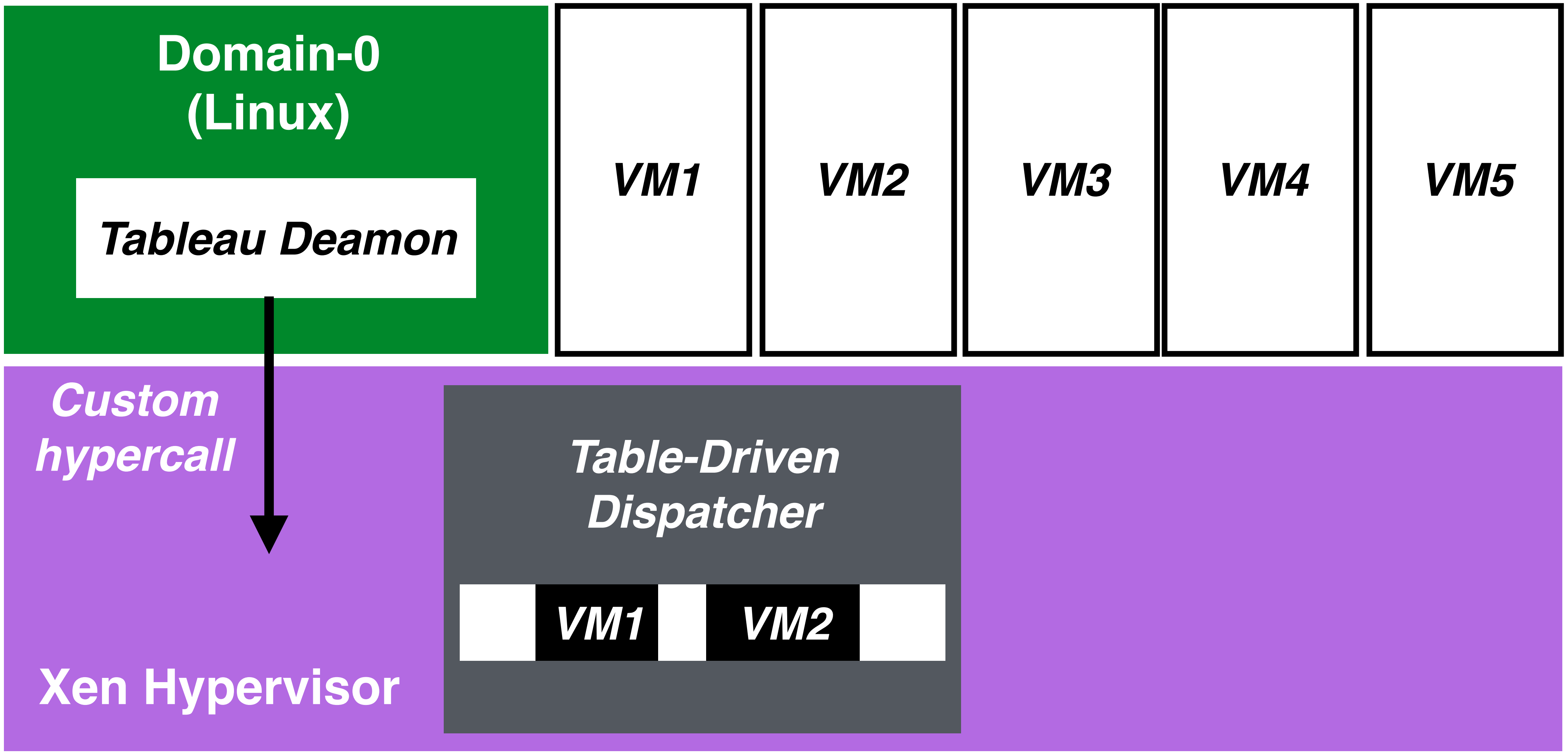
- Popular open-source hypervisor (Amazon AWS)
- Supervisory VM (domain-0) created at boot time.

Implementation in Xen



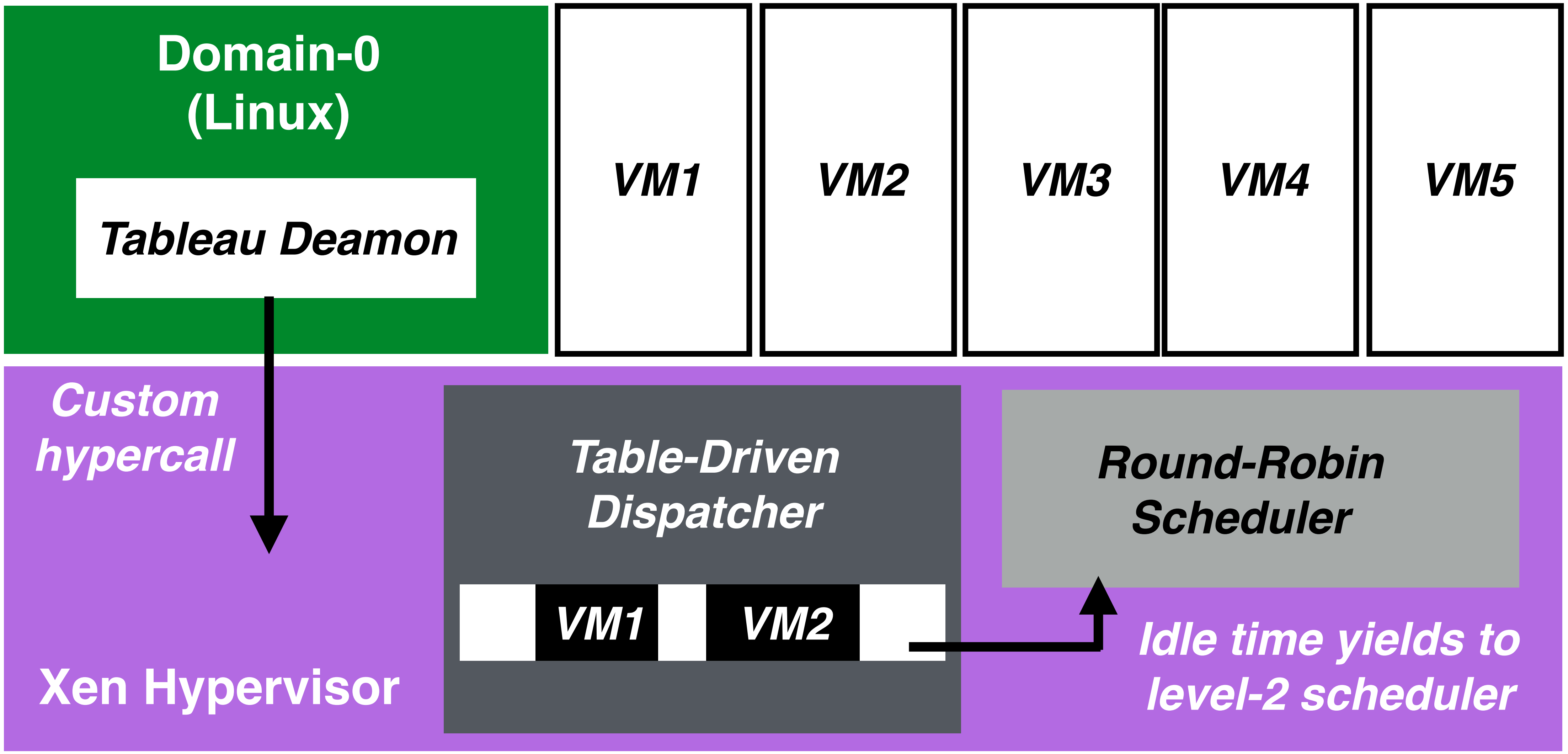
- Simple, table-driven dispatcher implemented within the hypervisor.

Implementation in Xen



- Userspace daemon responsible for re-generating tables whenever a VM is created.
- ~1,600 lines of Python code.

Implementation in Xen



- For work-conserving behavior, idle time in tables (white blocks) yields to round-robin scheduler. Picks runnable core-local VMs to schedule.

This Talk

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Summary of Results

Tableau **incurs lower runtime overheads** compared to the other evaluated Xen schedulers

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Tableau achieves **higher SLA-aware application throughput**.

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See our paper for details!

Tableau enables **accurate control over scheduling latency**.

Tableau achieves **higher SLA-aware application throughput.**

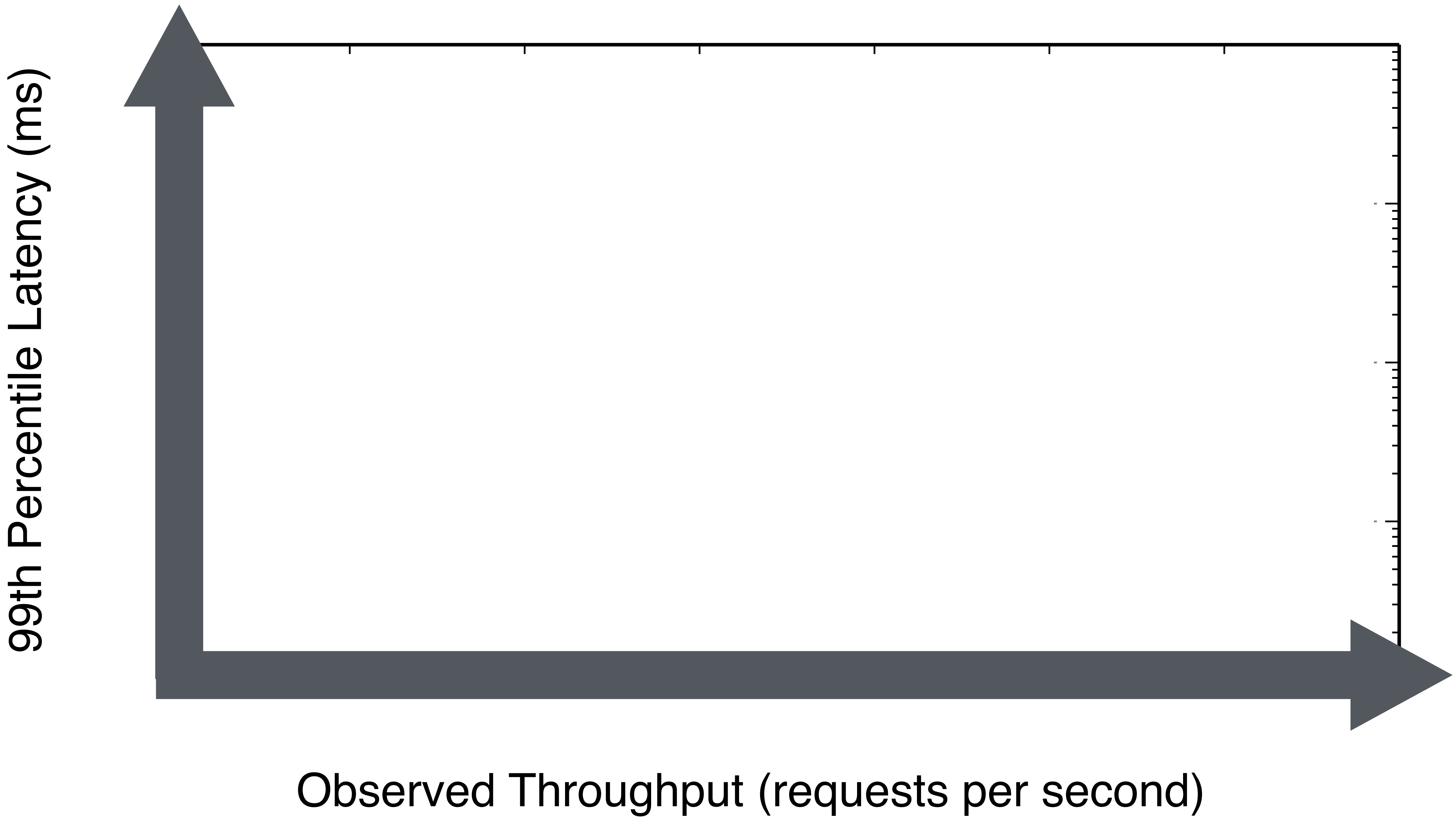
Platform

- Server machine:
  - 16 cores (2 sockets), 512 GiB RAM
  - Intel(R) Xeon(R) CPU E5-2667 v4 @ 3.20GHz
  - Ubuntu 16.04.3
  - Xen 4.9
- Load generation machine:
  - Identical machine connected via 10G ethernet.

Experimental Setup

- We simulate a multi-tenant datacenter environment.
  - 4 VMs/core (25% utilization each).
  - 1 **vantage** VM, rest **background** VMs
  - Background VMs run different workloads based on **stress-ng** tool.
- Schedulers configured based on best practices:
  - 5ms timeslice in Credit.
  - Equivalent configuration in Tableau and RTDS (max 20ms scheduling latency)

SLA-Aware Throughput



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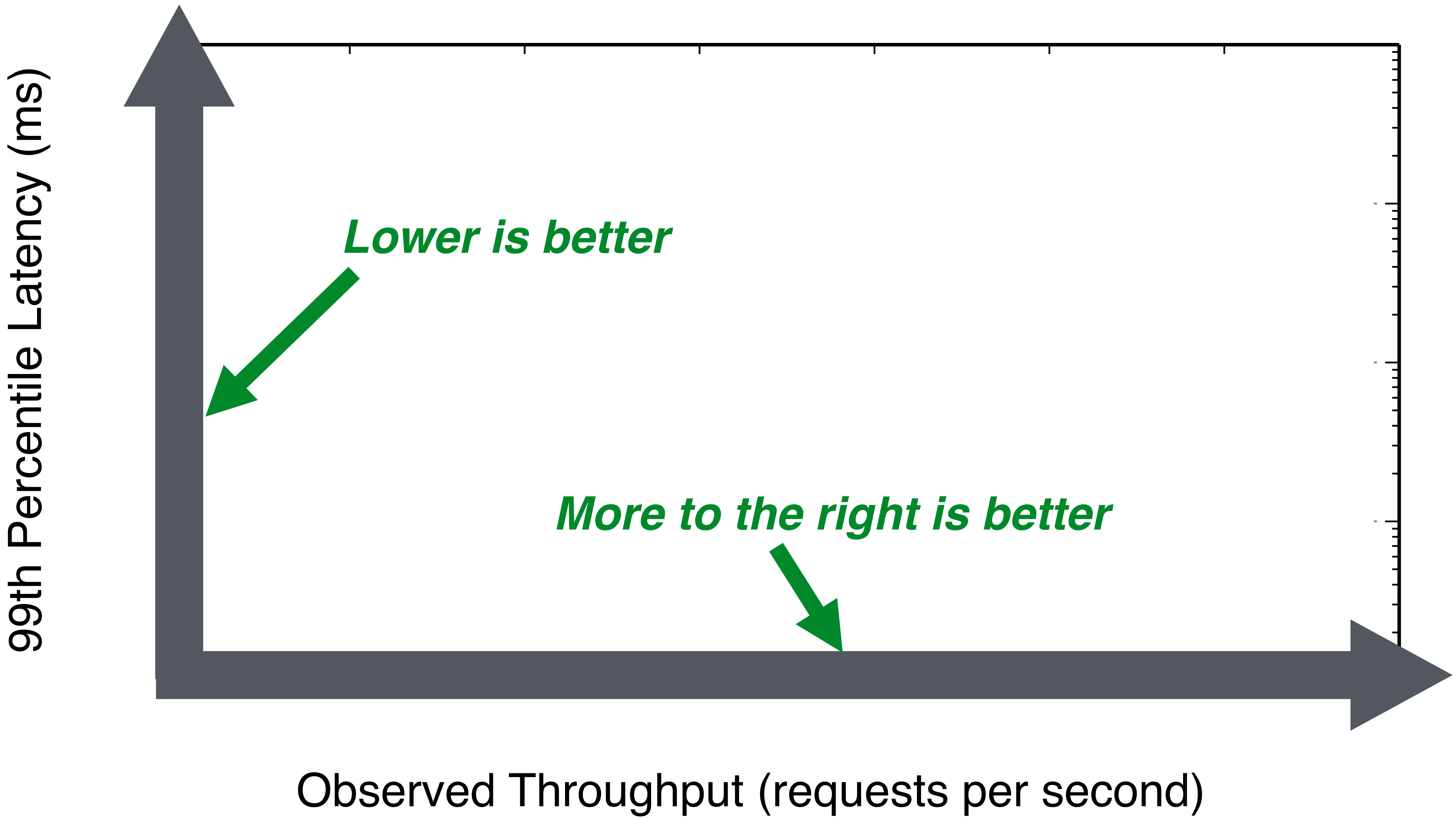
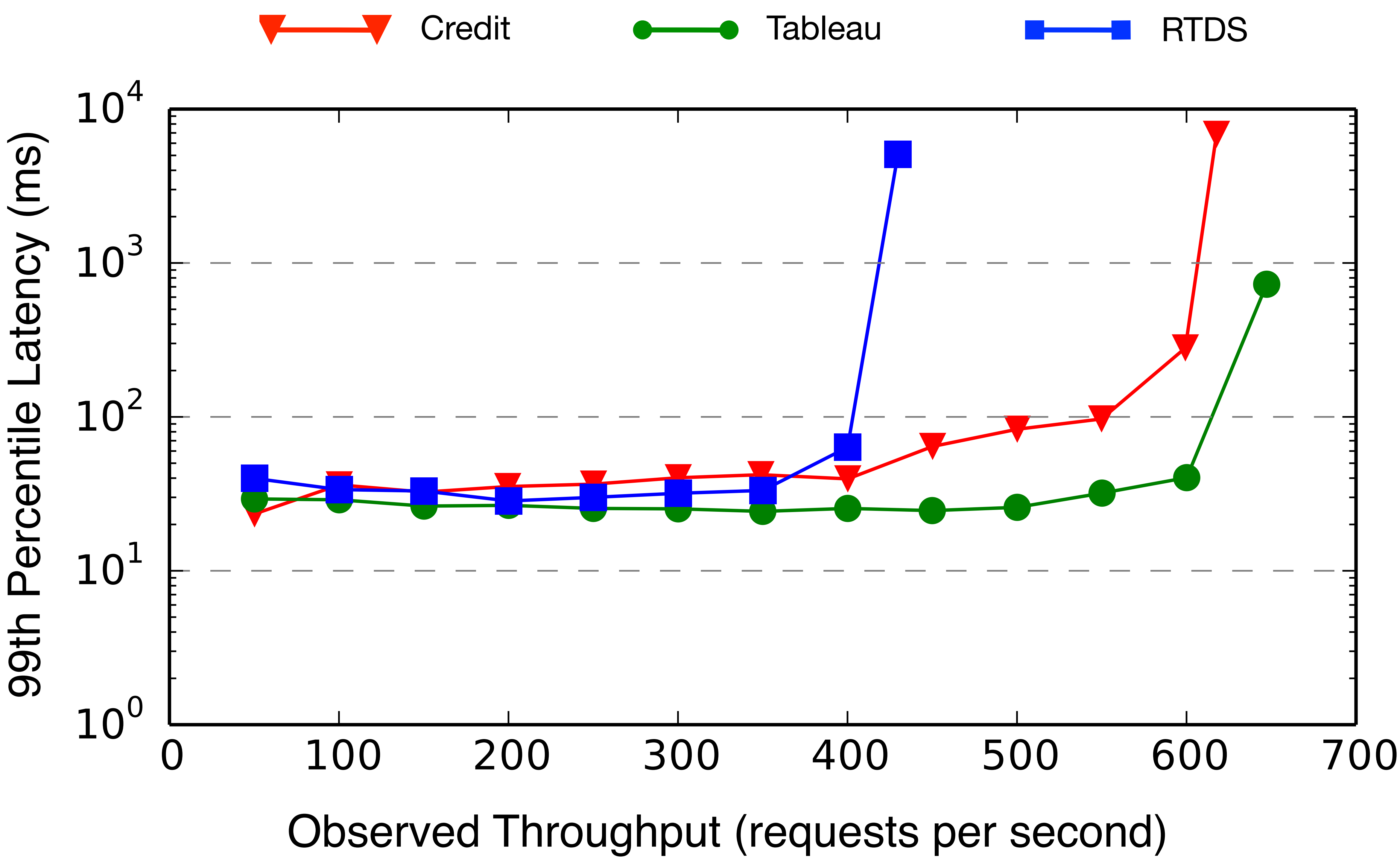


Peak Throughput



VMs Capped at 25%, 100K files, I/O background workload

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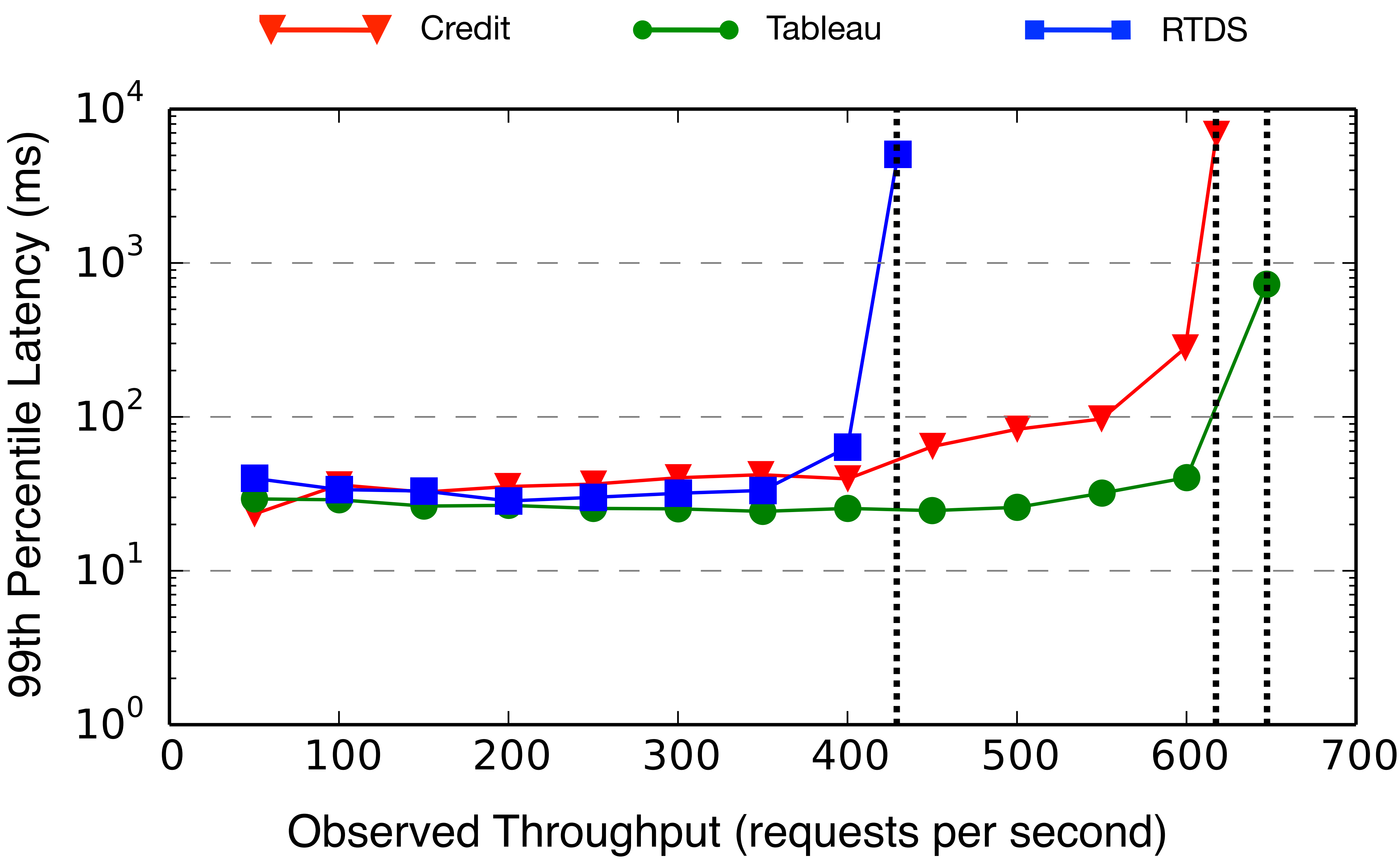

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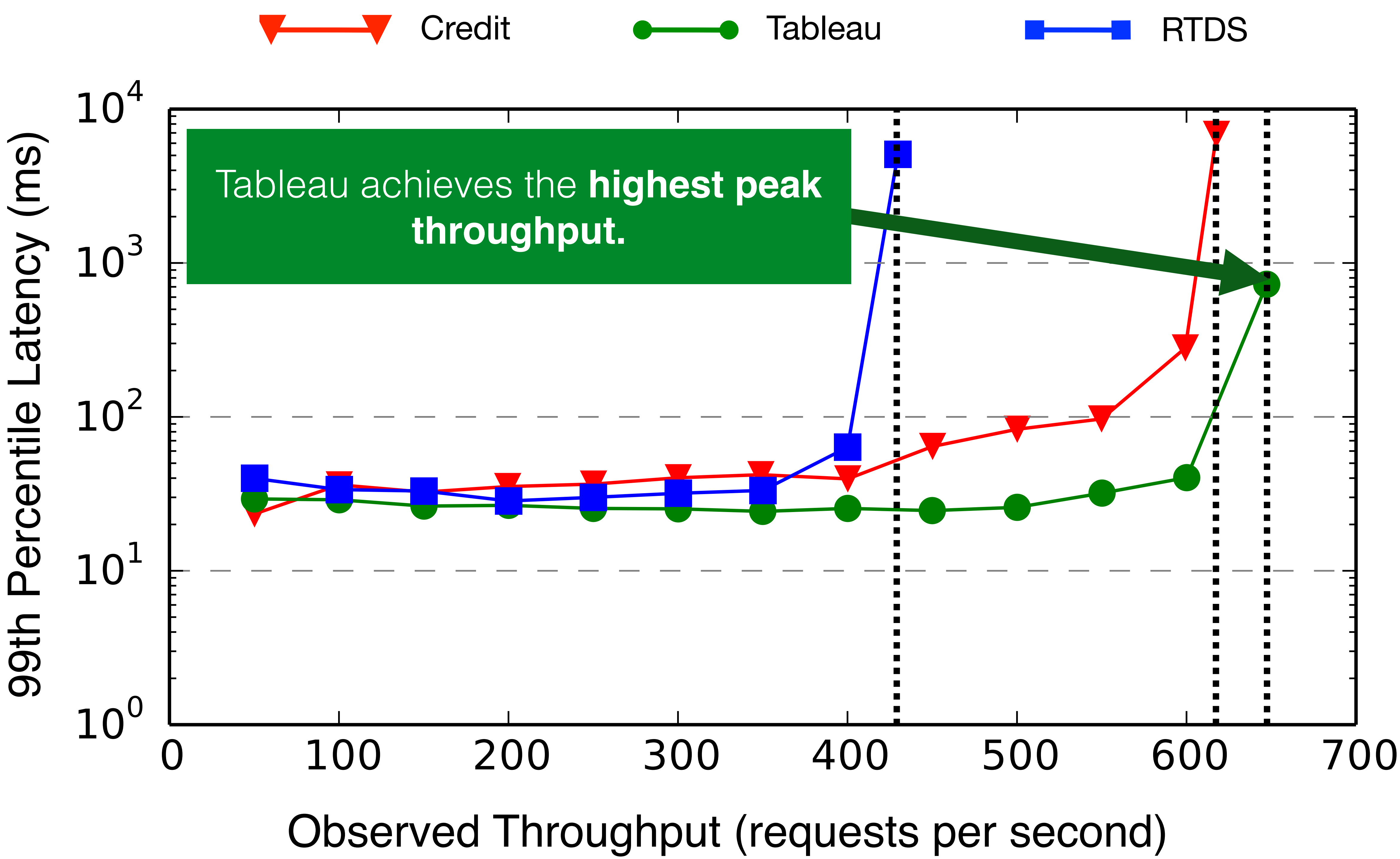

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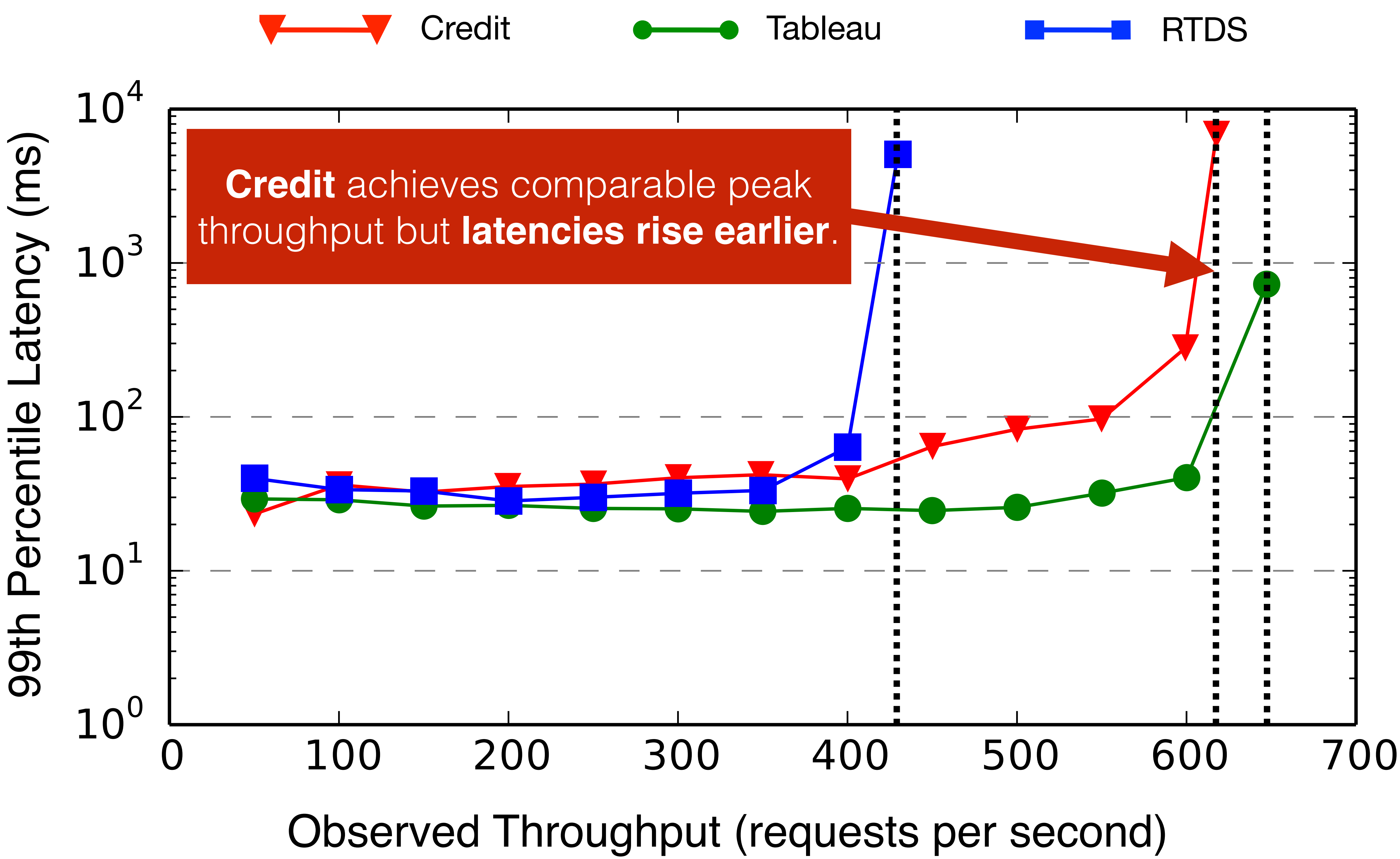

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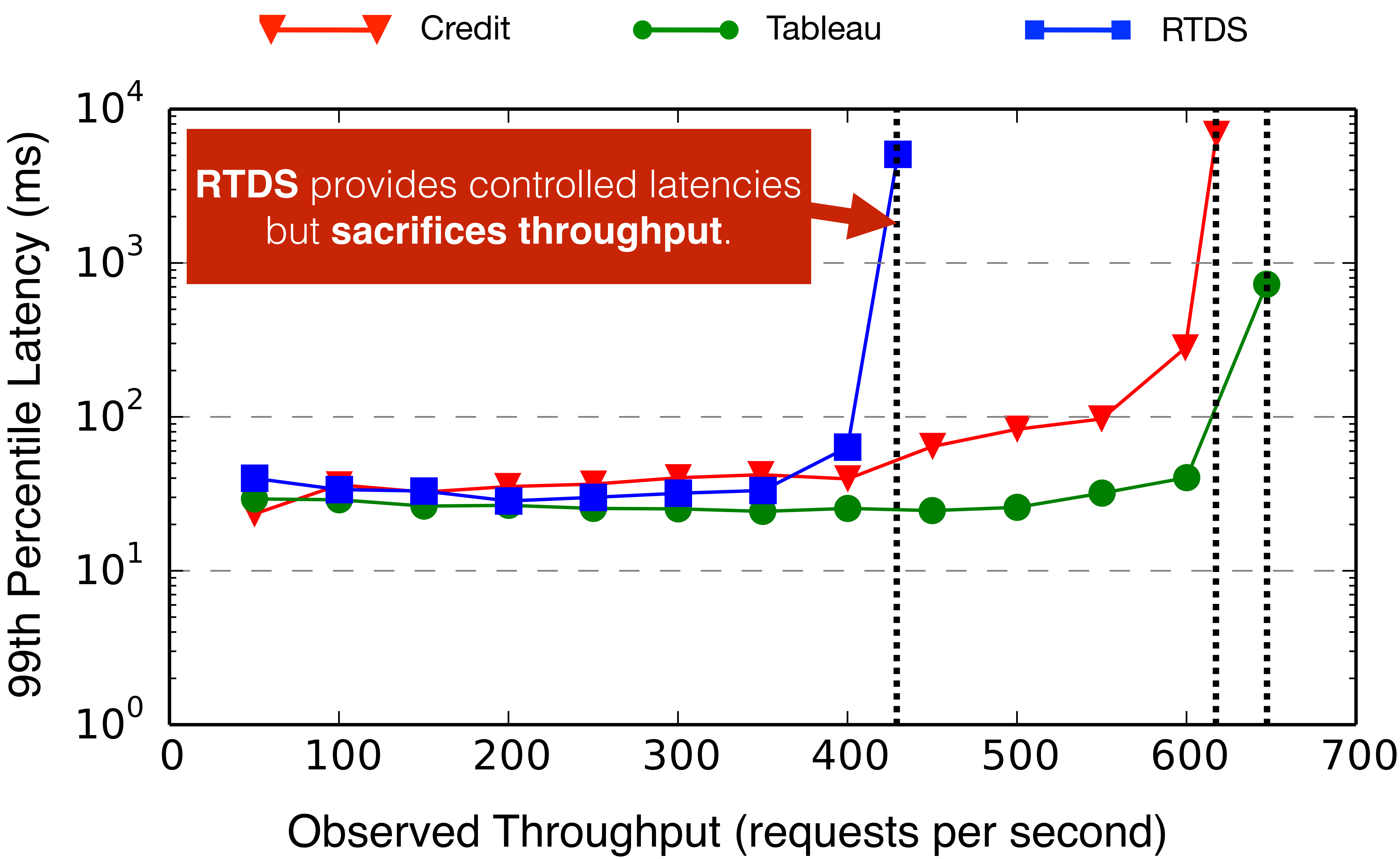

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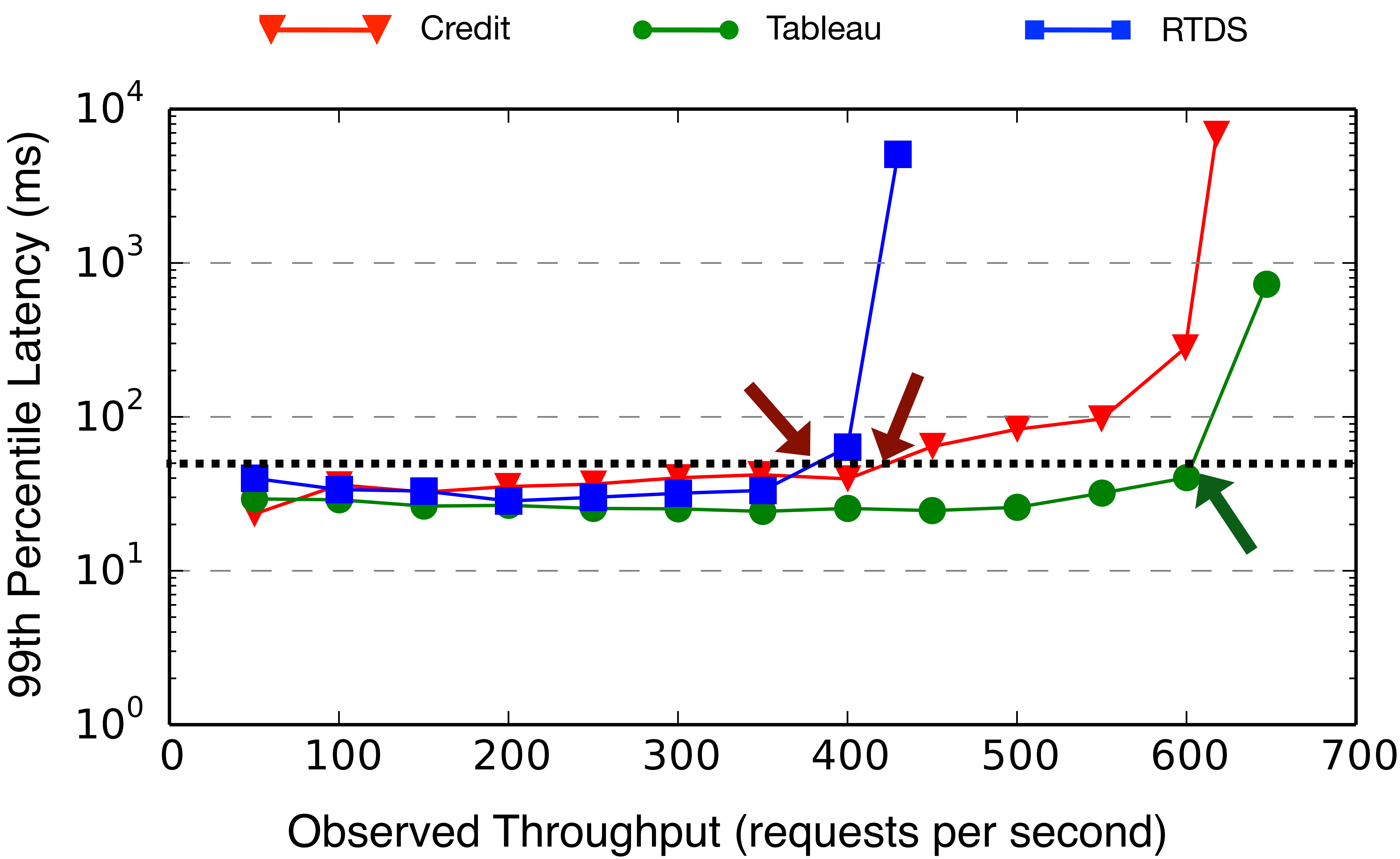

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SLA-Aware Throughput (Capped Scenario)

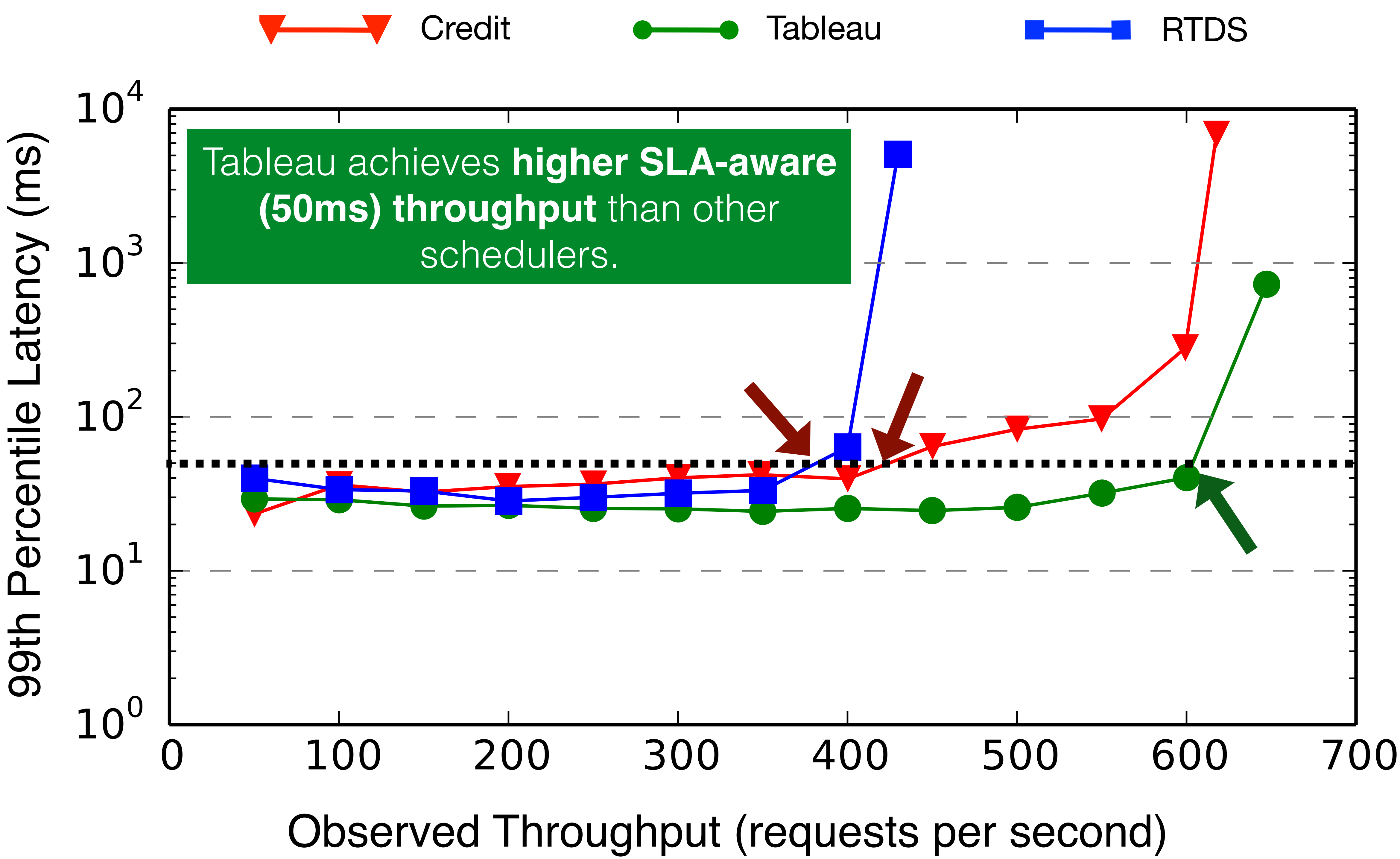

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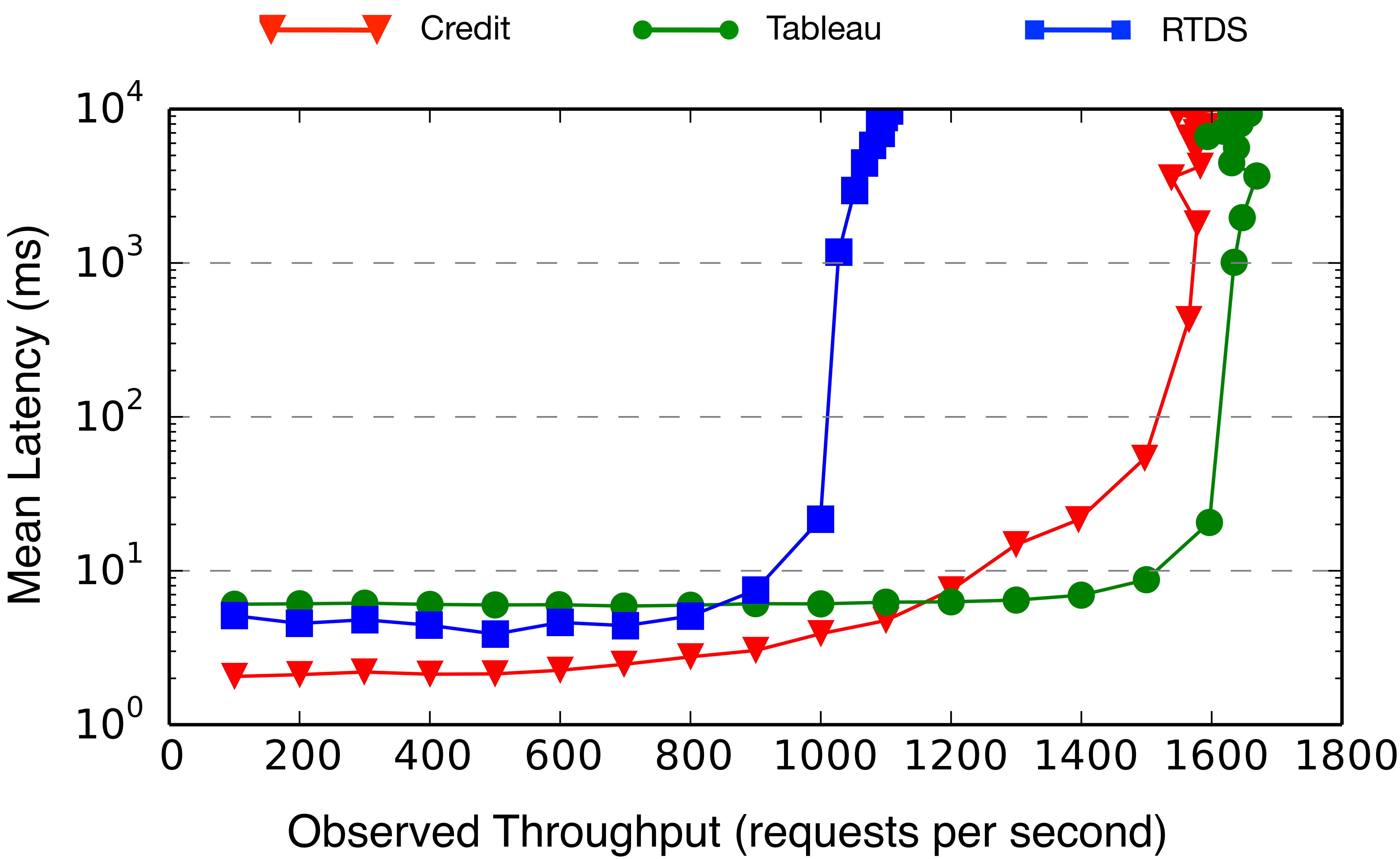
Tableau Results in Higher Mean Latencies

Hard-capped VMs under Tableau incur
higher mean latencies.

Tableau Results in Higher Mean Latencies



Capped VMs, 1K files, I/O background workload

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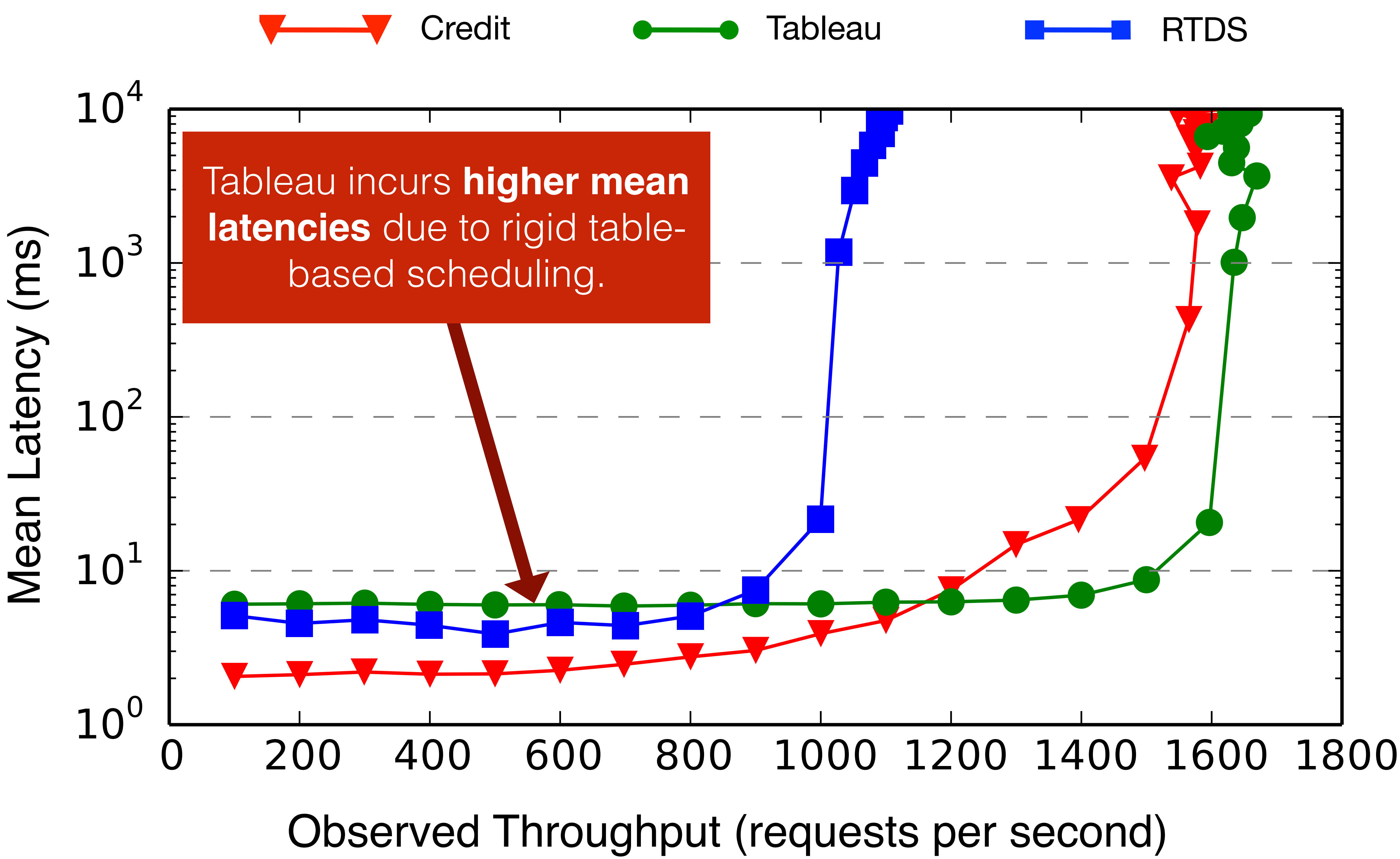

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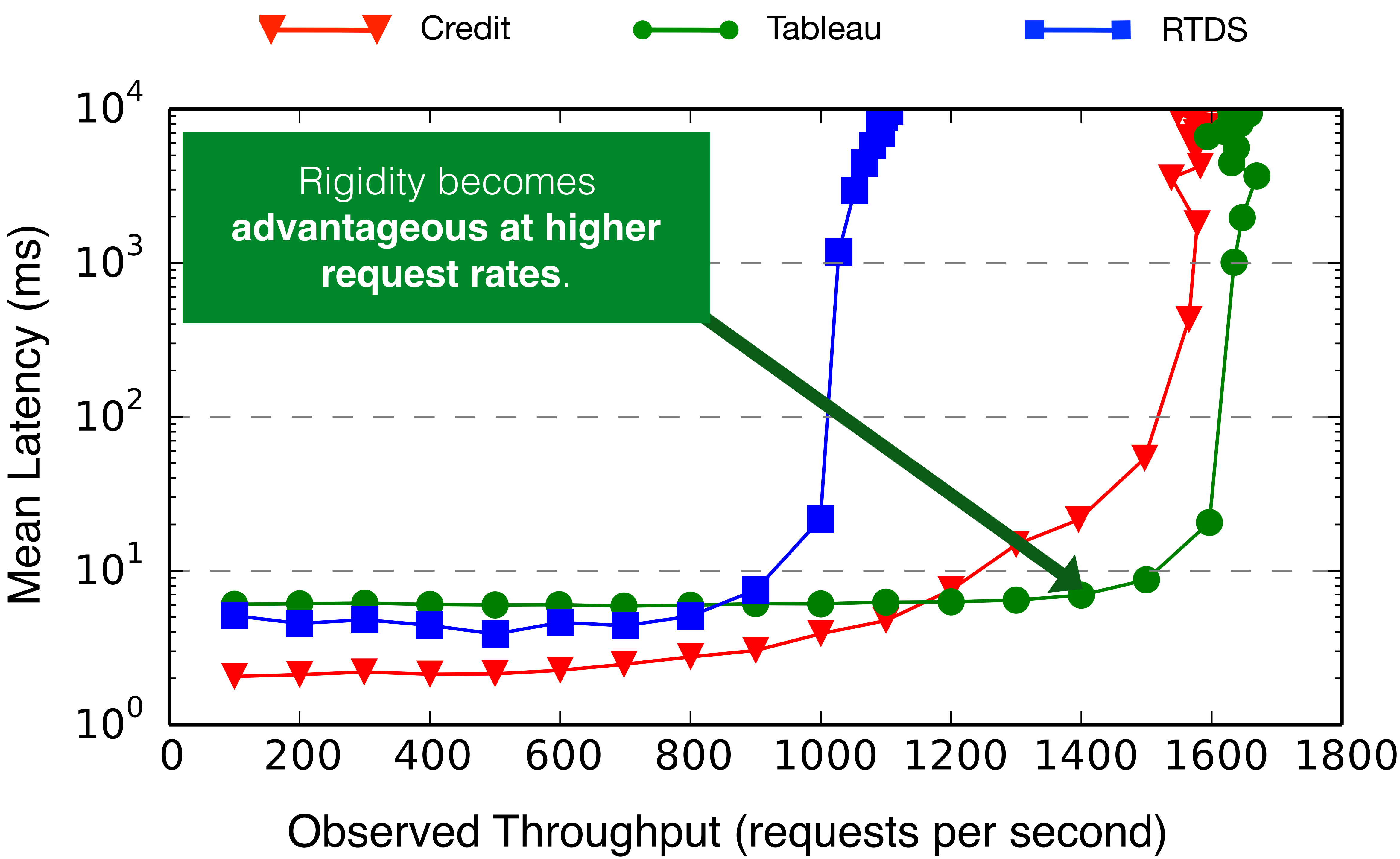

Capped VMs, 1K files, I/O background workload

Summary of Results

Tableau **incurs lower runtime overheads** compared to the other evaluated Xen schedulers

Tableau enables **accurate control over scheduling latency**.

Tableau achieves **higher SLA-aware application throughput.**

Hard capped VMs under Tableau incur **higher mean latency**, but entirely controllable.

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An **unorthodox scheduling approach** tailored for high-density public clouds.

Efficient

Incurs low overheads

Predictable

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High-throughput

Provides high SLA-aware throughput.

Thanks!

Source-code available at:

http://tableau.mpi-sws.org/

Scheduling Overheads on 48-Core Server

	Credit	RTDS
Schedule	16.40	4.39
Wakeup	7.07	19.16
Migrate	0.42	168.62

Overheads (in μs) of key scheduler operations on a 48-core server.

Overview of Table Generation Procedure

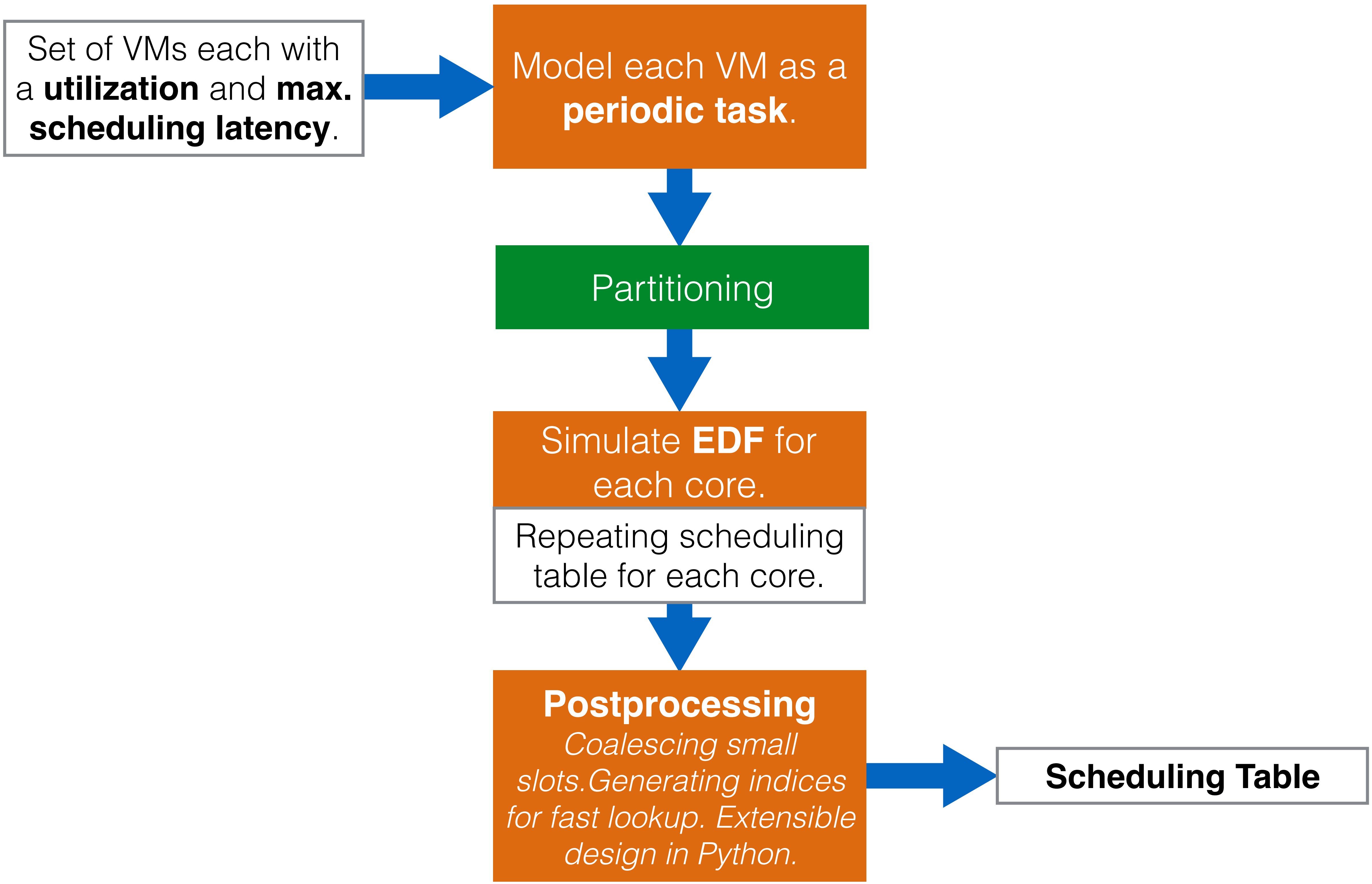


Table Sizes

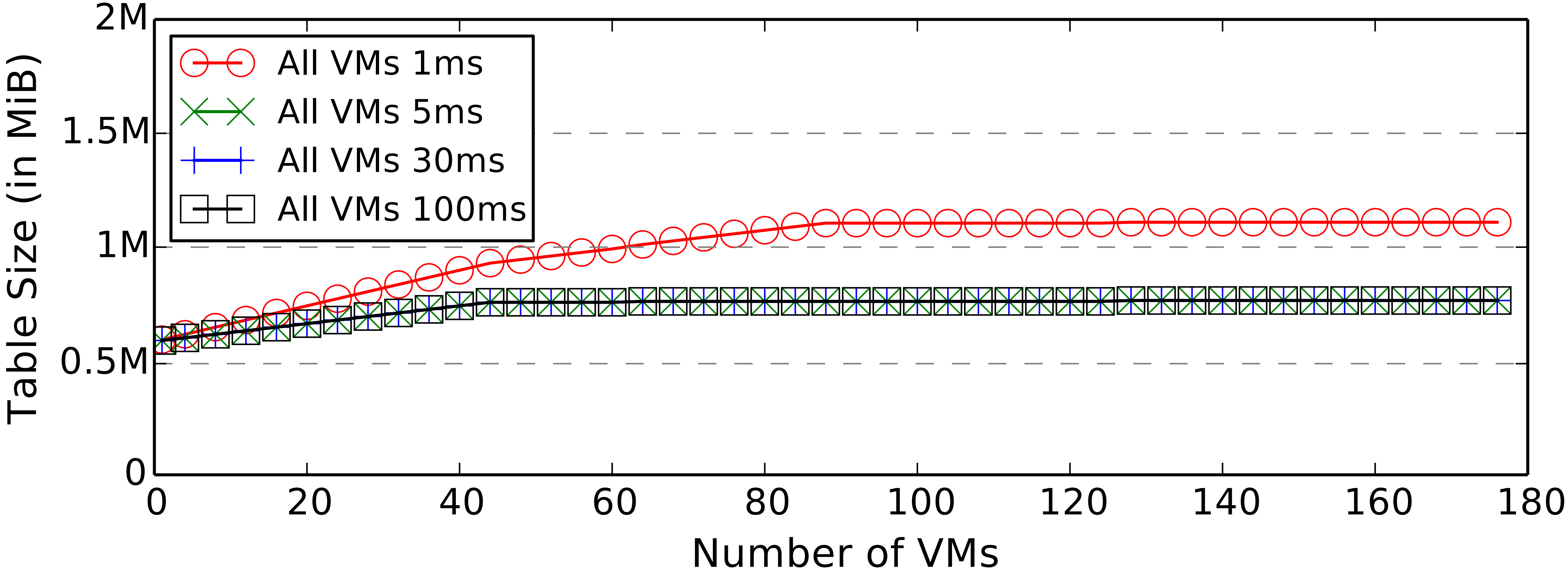
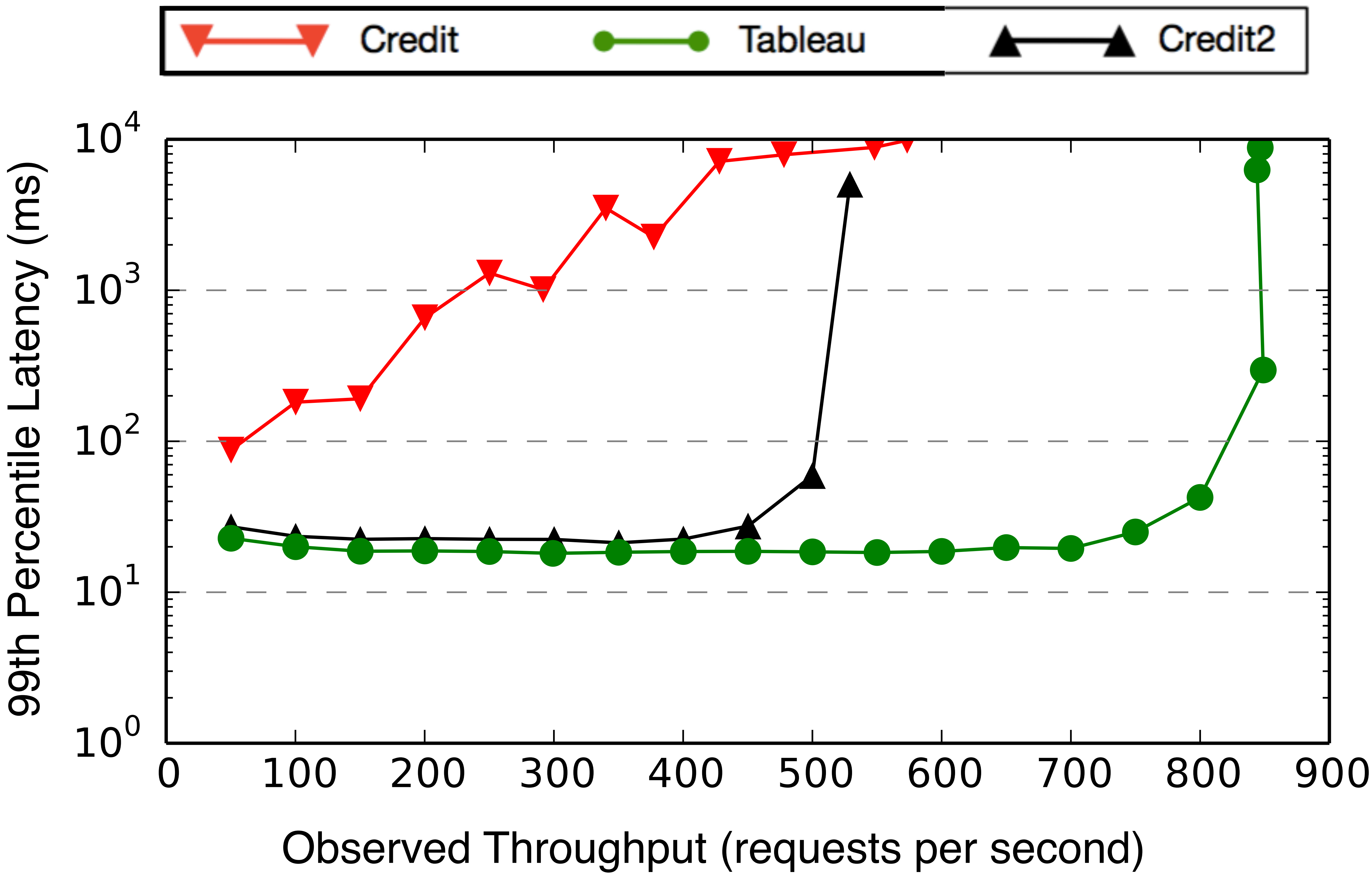


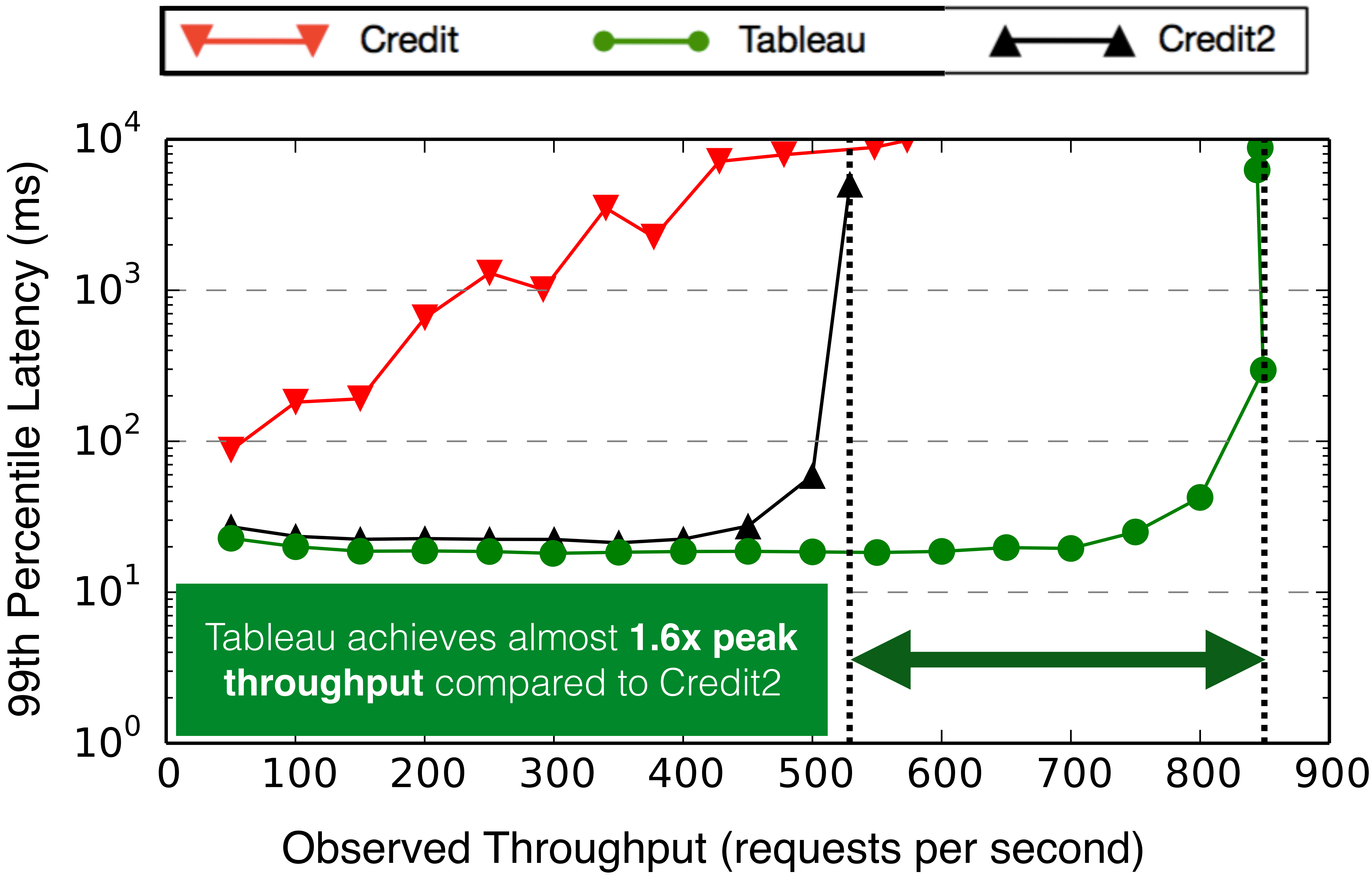
Table Size (in MiB)
2M
1.5M
1M
0.5M
0
0
20
40
60
80
100
120
140
160
180
Number of VMs
All VMs 1ms
All VMs 5ms
All VMs 30ms
All VMs 100ms

SLA-Aware Throughput (Uncapped Scenario)



Uncapped VMs, 100K files, I/O background workload

SLA-Aware Throughput (Uncapped Scenario)



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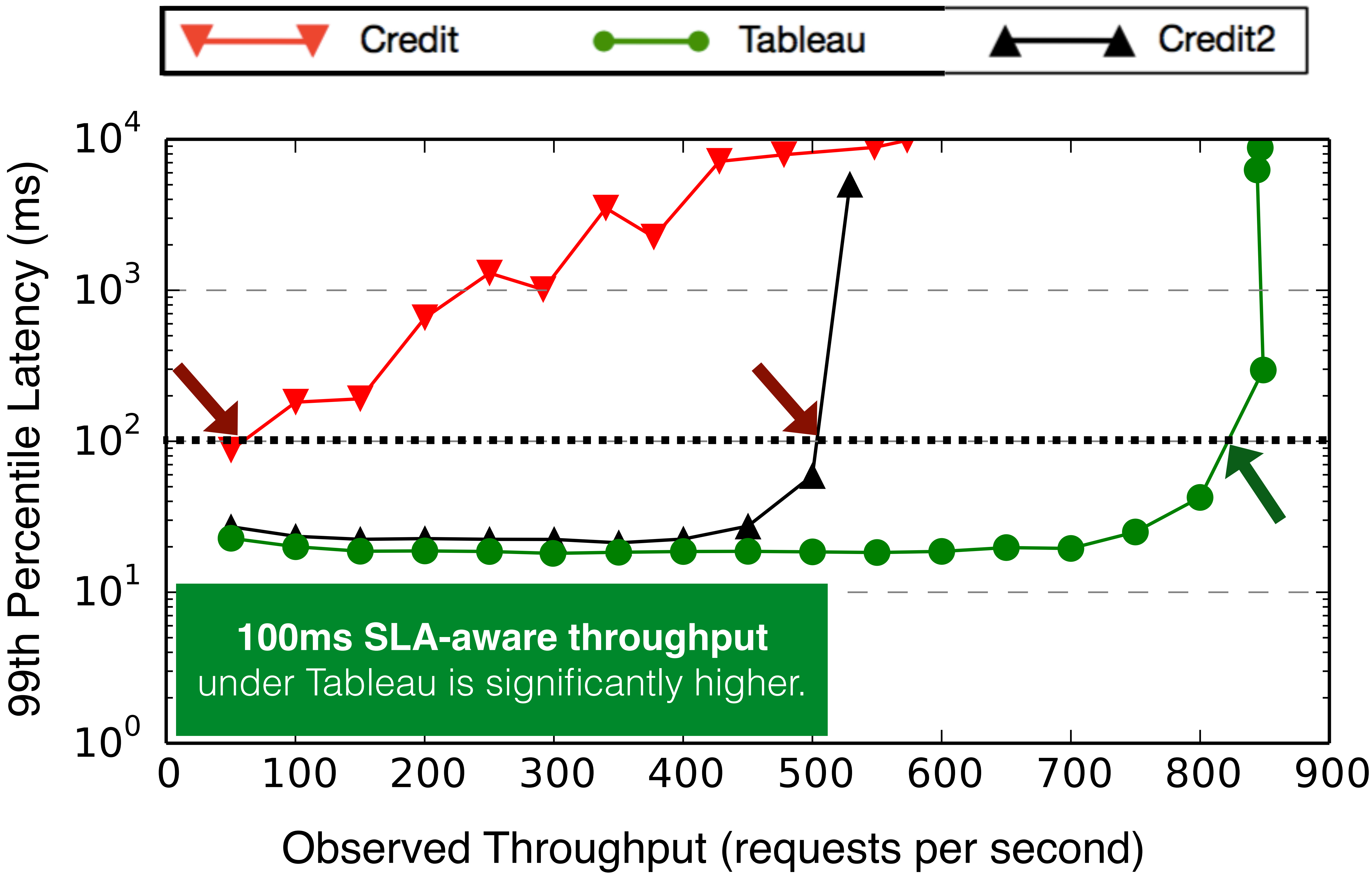

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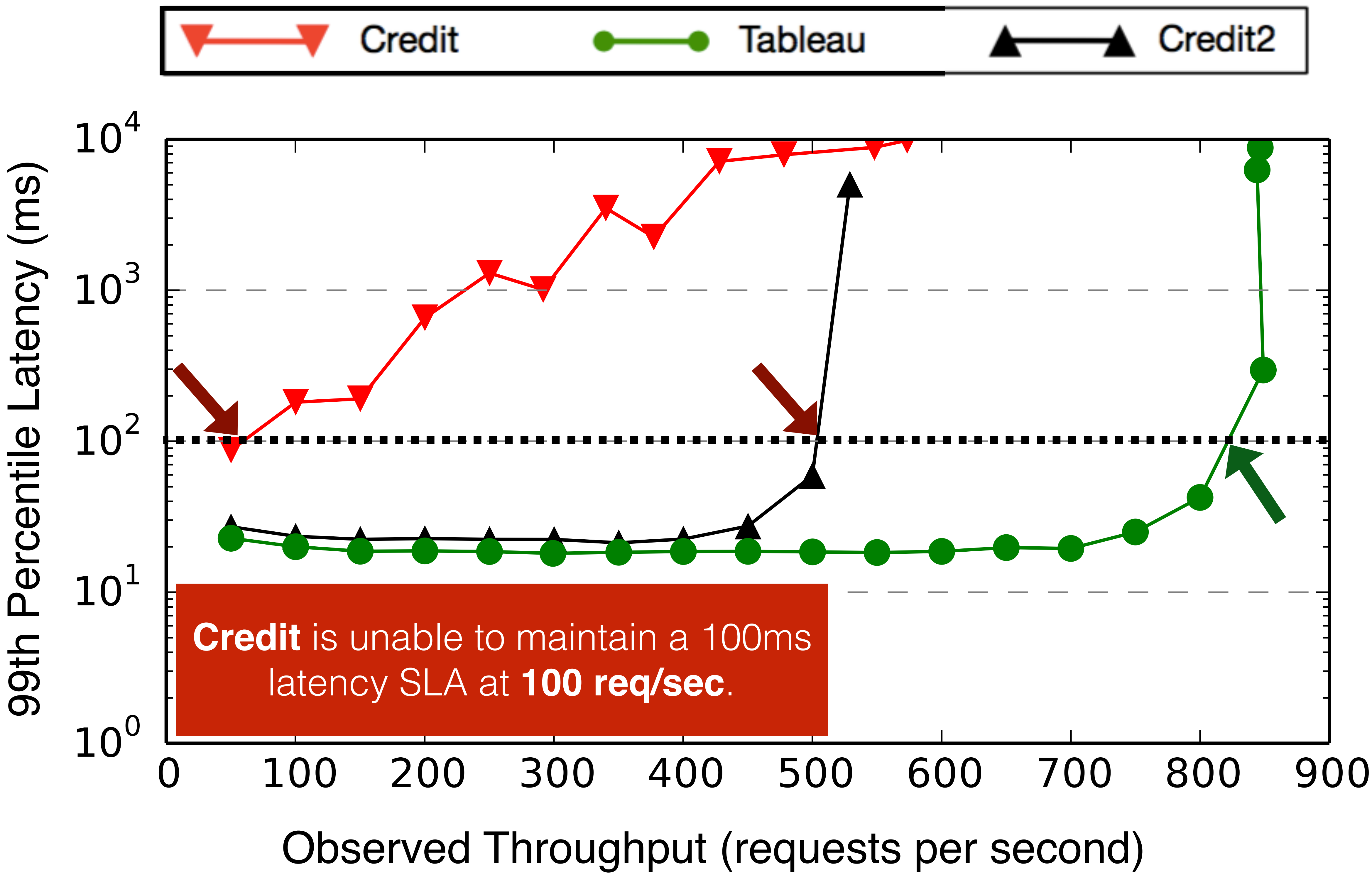


Uncapped VMs, 100K files, I/O background workload

Partitioning & Semi-Partitioning

Partitioning → **Assign VMs to individual cores** using bin-packing heuristic.

Semi-Partitioning → **Split any VMs that couldn't be assigned** to multiple cores.

Optimal Scheduling → **Guaranteed to find a schedule**. Results in many preemptions.

Included for completeness, but unnecessary in practice.

Modelling VMs as Periodic Tasks

VM (vCPU)

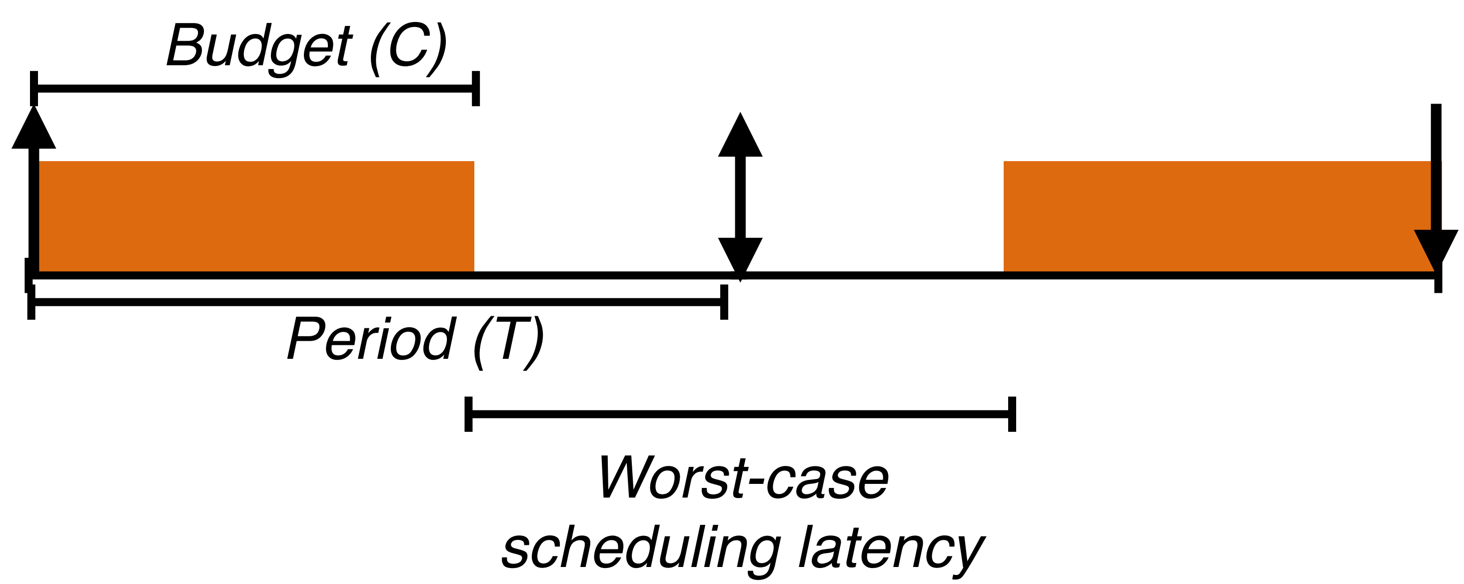
Utilization (U)
A percentage of CPU time reserved for VM.

Max. Latency (L)
An upper bound on scheduling delay.

Periodic Task

Budget (C)

Period (T)



$$2 \times (T - C)$$

$$= 2 \times (1 - U) \times T$$

Pick any T such that $2 \times (1 - U) \times T <= L$

Schedule repeats after hyperperiod (common multiple of all task periods)

Choosing T indiscriminately can result in exponential hyperperiod.

Modelling VMs as Periodic Tasks

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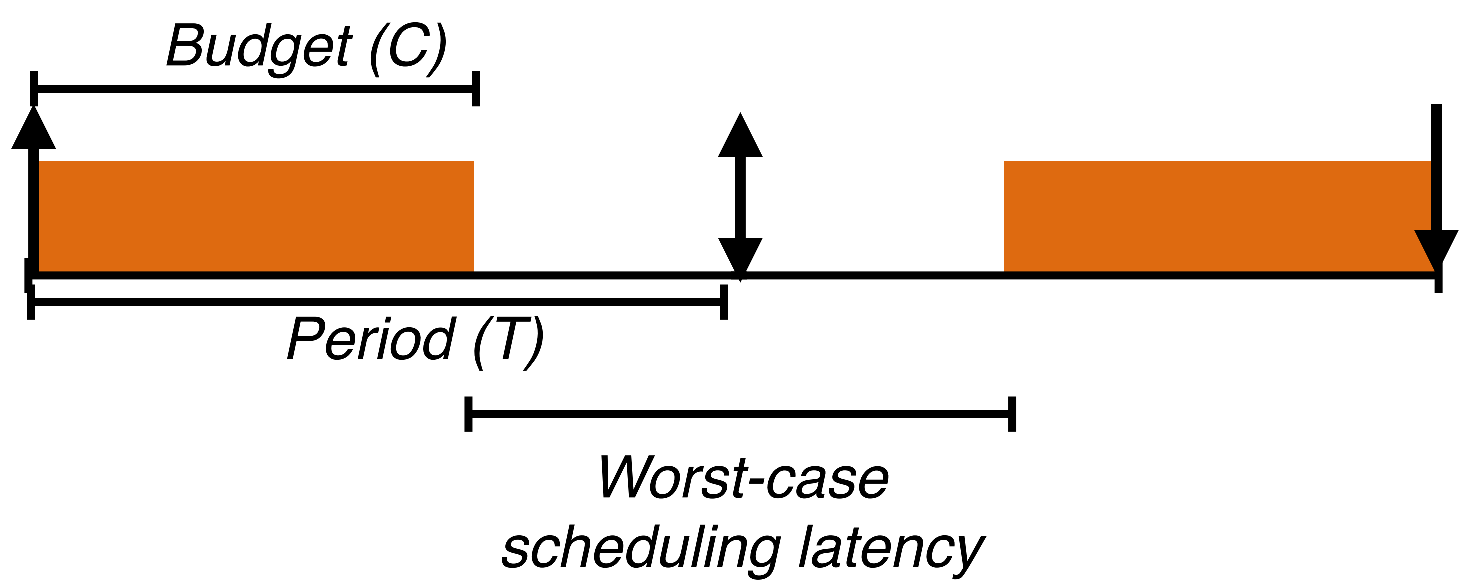

$$2 \times (T - C)$$

$$= 2 \times (1 - U) \times T$$

Pick largest T ∈ F $2 \times (1 - U) \times T <= L$

(F is the set of all integer divisors of 102,702,600)

Pick periods from a set of candidate periods with a known hyperperiod (102,702,600 ns = ~102ms) to ensure **bounded table length**.

Summary of Results

Tableau **incurs lower runtime overheads** compared to the other evaluated Xen schedulers

Tableau enables **accurate control over scheduling latency**.

Tableau achieves **higher SLA-aware application throughput**.

Scheduler Overheads

	Credit	RTDS	Tableau
Schedule			
Wakeup			
Migrate			

Overheads (in μs) of key scheduler operations on 16-core server.

Scheduler Overheads

Picking the next VM to schedule

	Credit	RTDS	Tableau
Schedule			
Wakeup			
Migrate			

Unblocking a VM

Overheads (in us) of key scheduler

Migrating de-scheduled VM to idle core.

Scheduler Overheads

	Credit	RTDS	Tableau
Schedule	8.08	2.86	1.43
Wakeup	2.12	3.90	1.06
Migrate	0.32	9.42	0.43

Overheads (in μs) of key scheduler operations on 16-core server.

Scheduler Overheads

Heuristics and decision-making.

	Credit		RTDS	Tableau
Schedule	8.08	3.51	2.86	1.43
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Overheads (in μs) of key scheduler operations on 16-core server.

Poor scalability

Scheduler Overheads

Heuristics and decision-making.

	Credit	RTDS	Tableau
Sc	3.51	2.86	1.43
	5.19	3.90	1.06
		9.42	0.43

…f key scheduler
…-core server.

	RTDS
Schedule	4.39
Wakeup	19.16
Migrate	168.62

RTDS Overheads on 48-core server

Poor scalability

Scheduler Overheads

Heuristics and decision-making.

	Credit		RTDS	Tableau
Schedule	8.08	3.51	2.86	1.43
Wakeup	2.12	5.19	3.90	1.06
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Overheads (in μs) of key scheduler operations on 16-core server.

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Overheads (in μs) of key scheduler operations on 16-core server.

Significant reduction in runtime overheads

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Significant reduction in runtime overheads

Inherently scalable

Summary of Results

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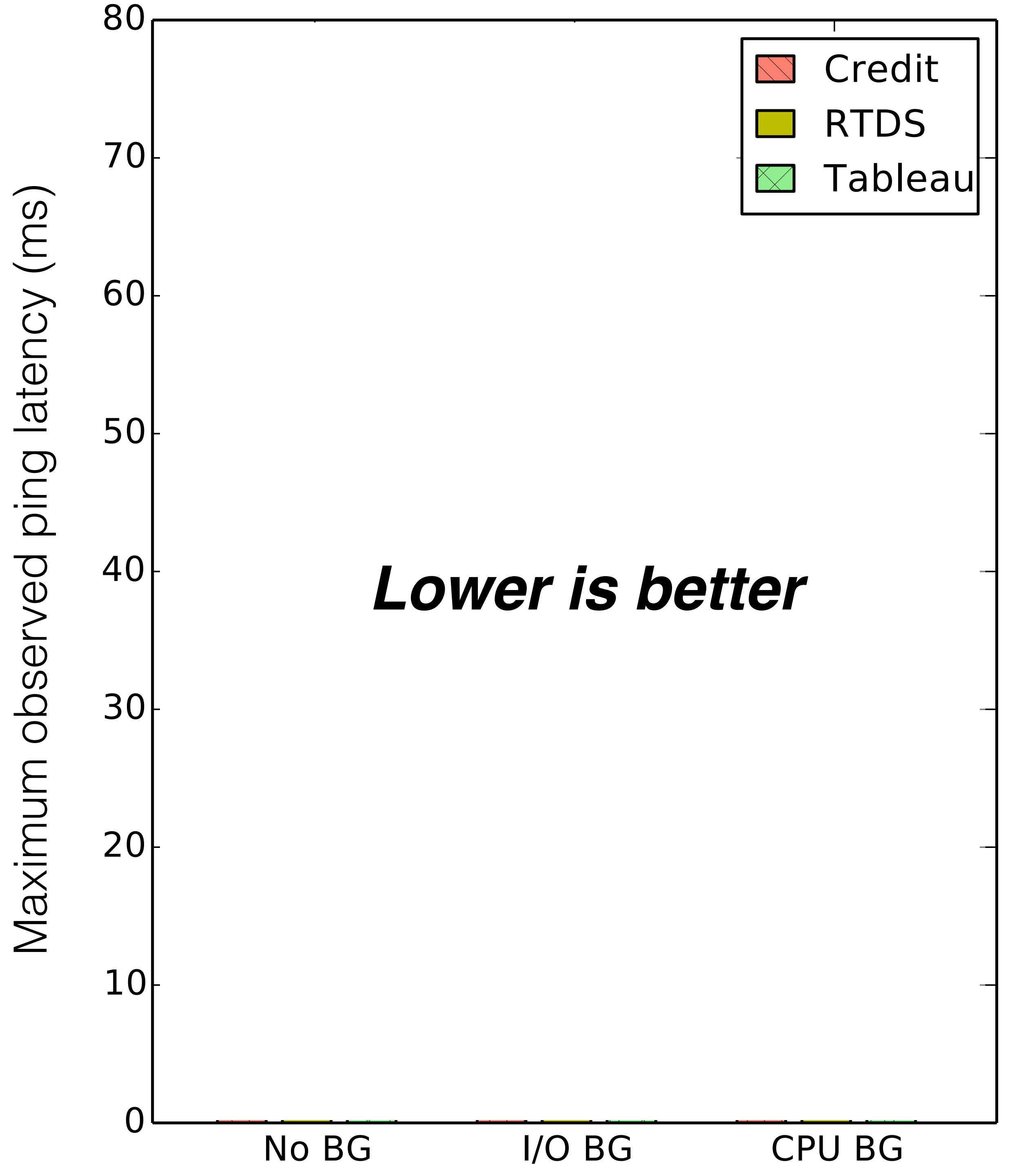
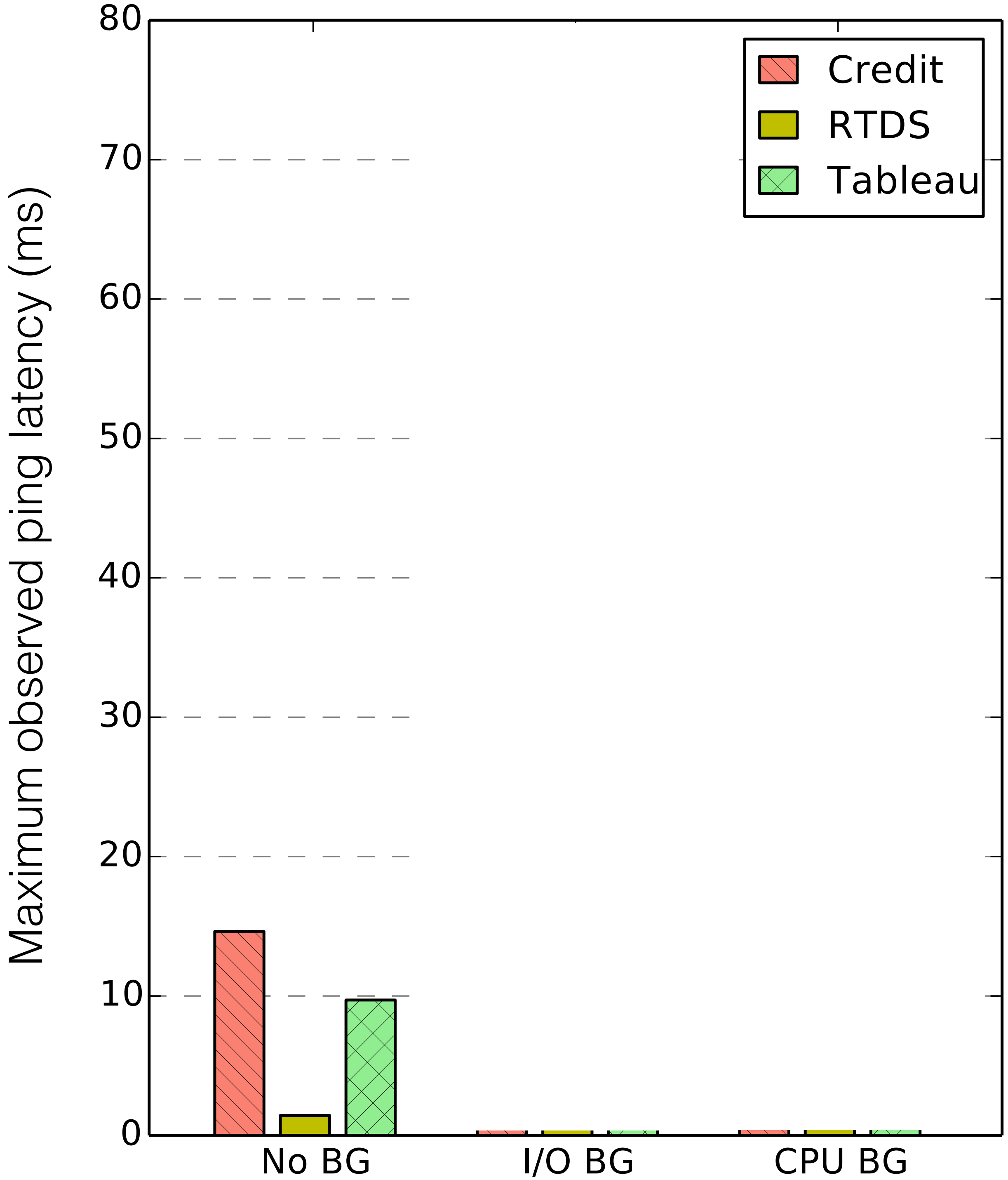
Scheduling Latency



VMs Capped at 25%

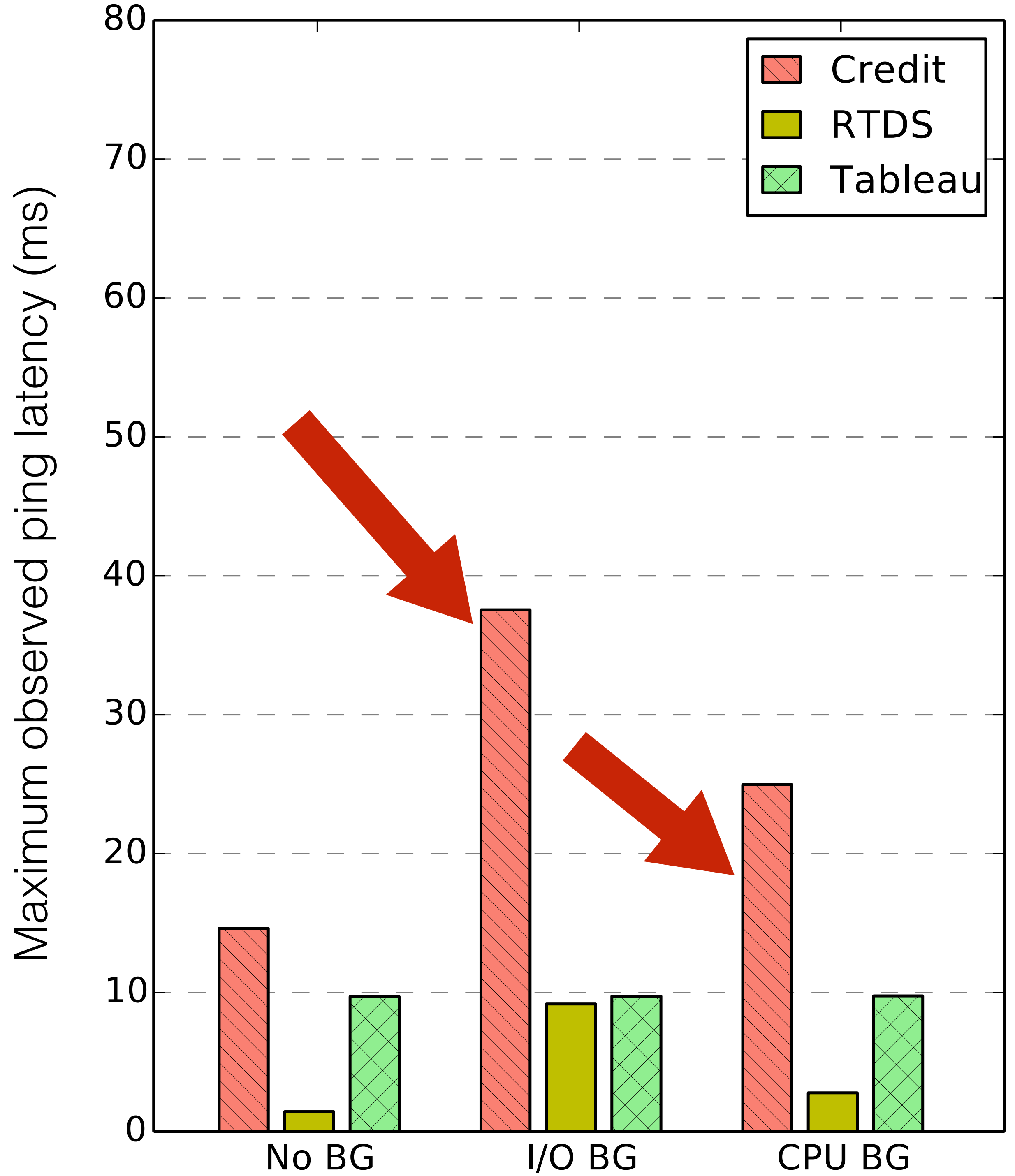
Scheduling Latency



VMs Capped at 25%

With **idle background**, predictable scheduling delays.

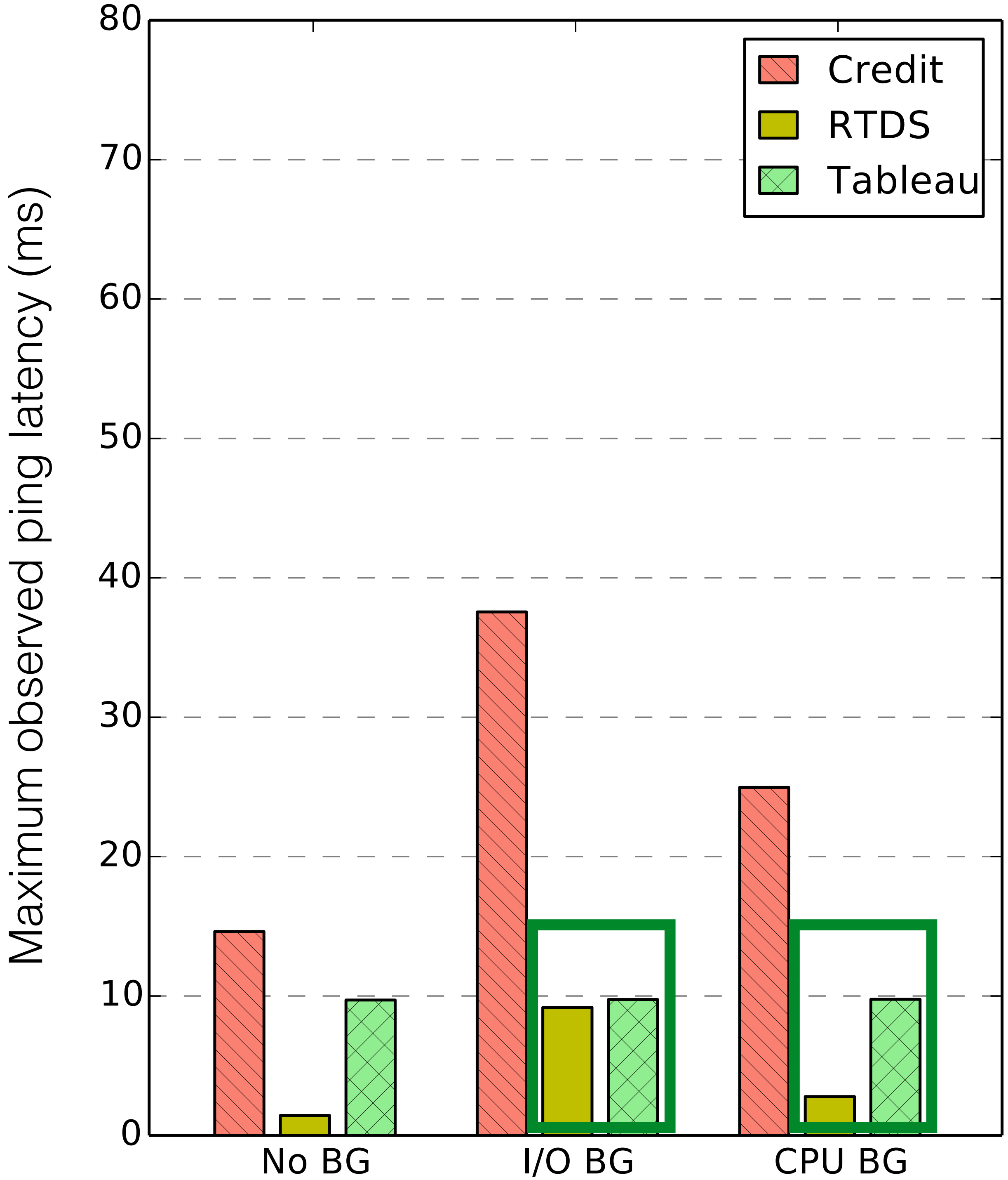
Scheduling Latency



VMs Capped at 25%

With a **I/O or CPU background**, Credit's tail latency increases.

Scheduling Latency



VMs Capped at 25%

With **an I/O or CPU background**, RTDS, and Tableau continue to have predictable scheduling delays.

Limitations

Tableau incurs **higher mean latencies** for low throughputs with hard-capped VMs.

Table-generation **increases VM startup and teardown times**.

Dealing with Table-Generation Time

Cache pre-generated tables

Pre-generate fixed-utilization slots

Generate tables on an external (faster) server

This Talk

- Tableau
- Evaluation
- **Limitations**
- Conclusion

Limitations

Tableau incurs **higher mean latencies** for low throughputs with hard-capped VMs.

Table-generation **increases VM startup and teardown times**.

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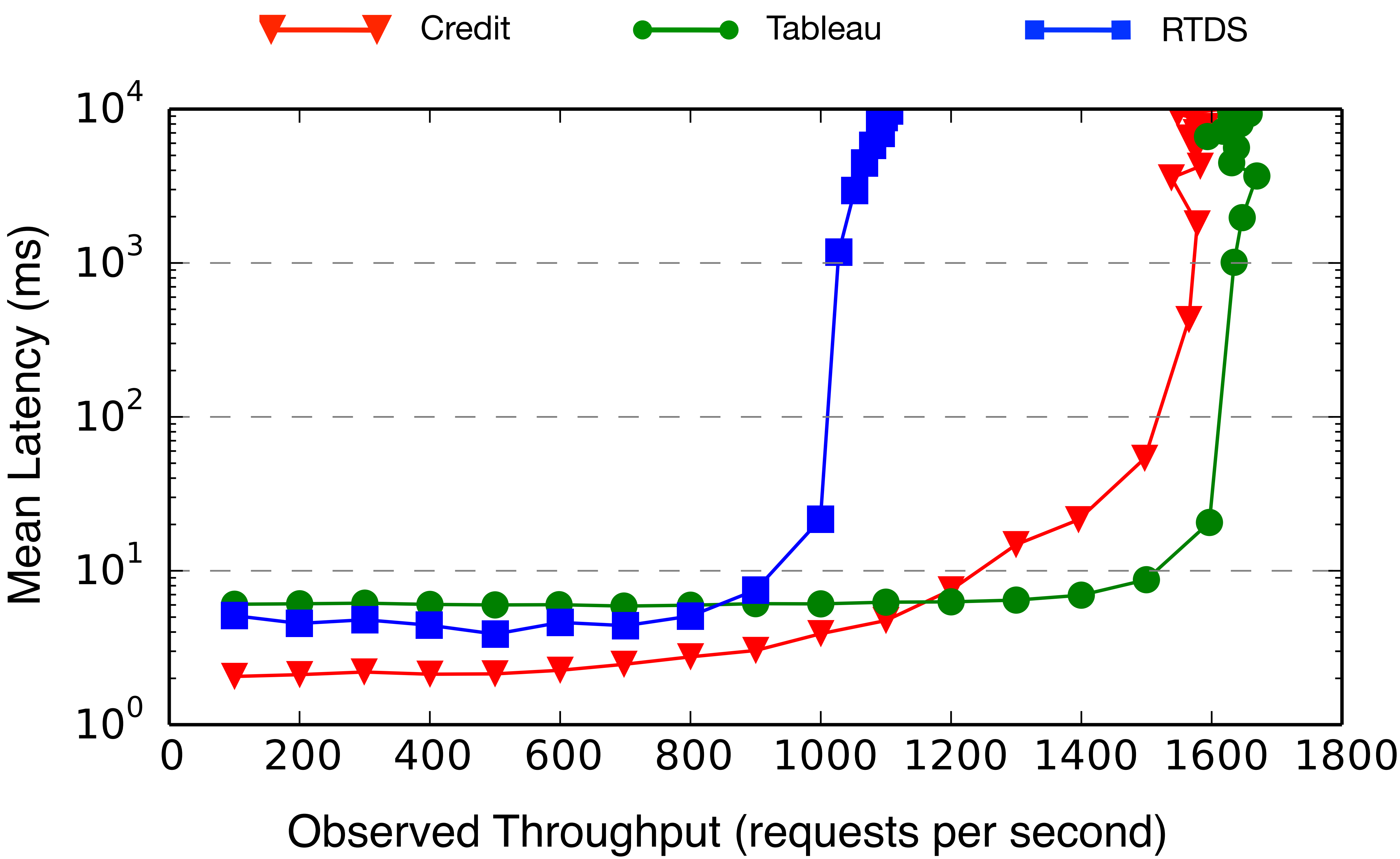
Tableau Results in Higher Mean Latencies



Capped VMs, 1K files, I/O background workload

Tableau Results in Higher Mean Latencies

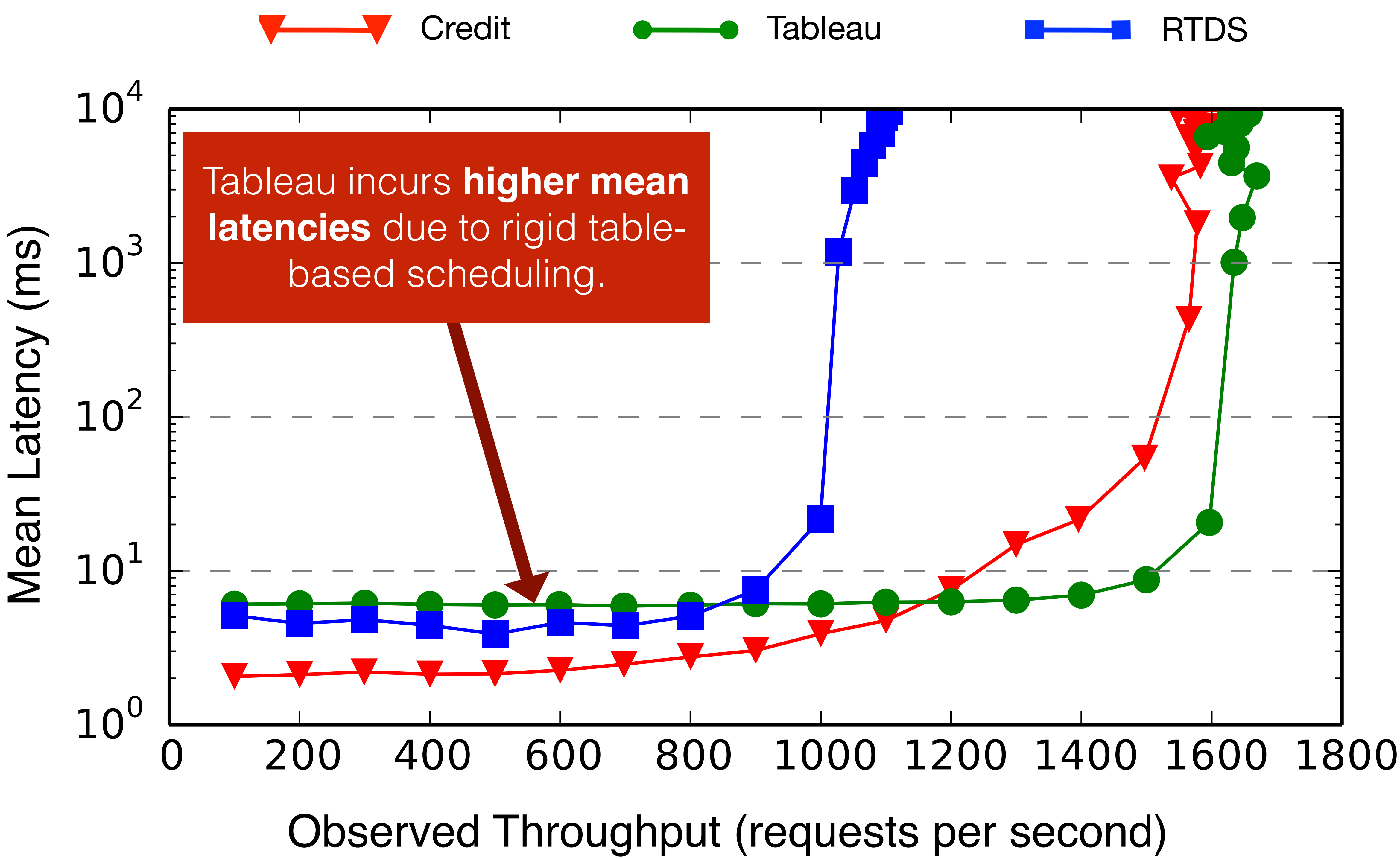


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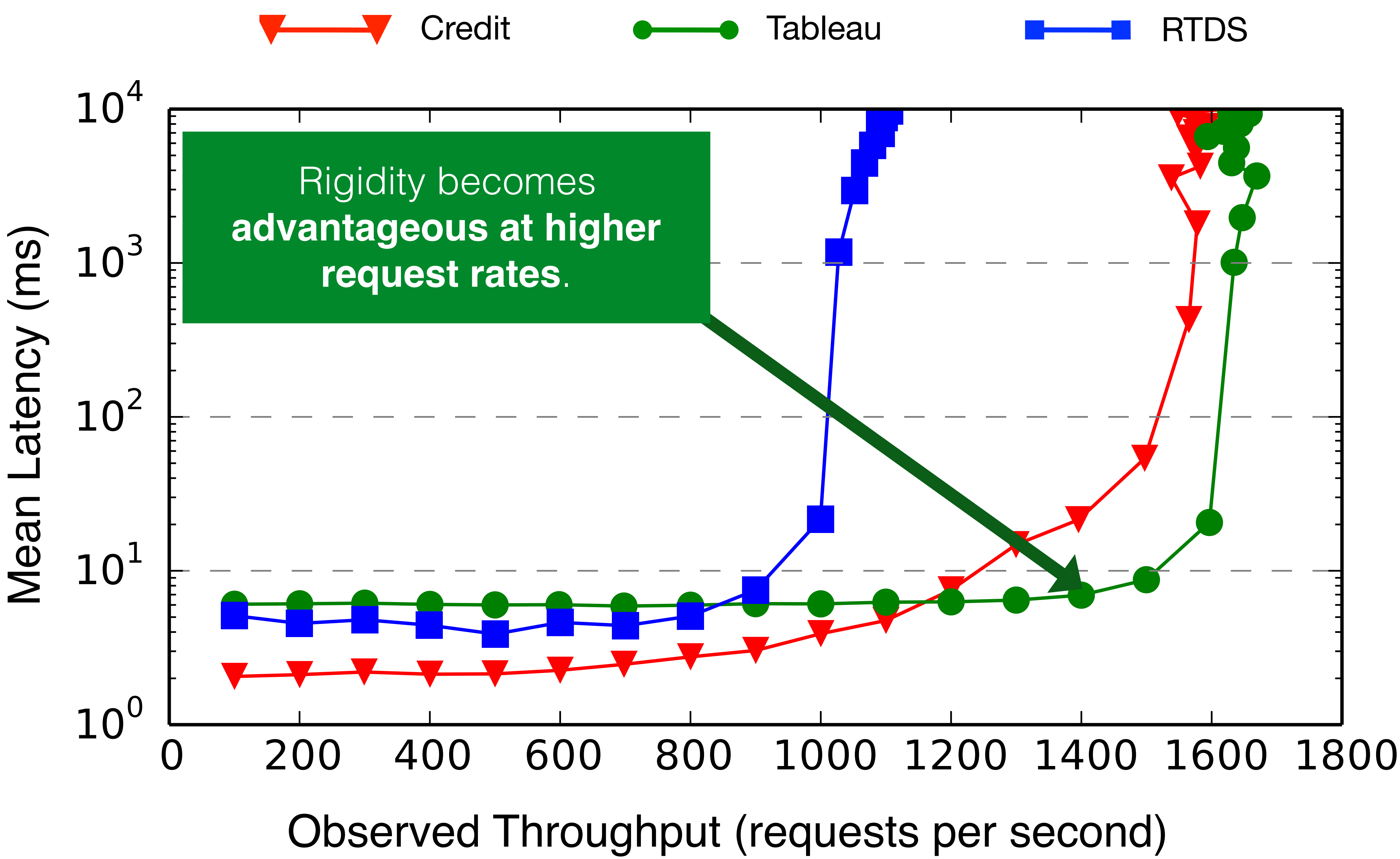
Tableau Results in Higher Mean Latencies



Capped VMs, 1K files, I/O background workload