Max
Planck
Institute
for
Software Systems

A Comparison of Scheduling Latency in Linux, PREEMPT_RT, and LITMUS^{RT}

Felipe Cerqueira and Björn Brandenburg

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Linux as a Real-Time OS

Linux as a Real-Time OS

Optimizing
system
responsiveness

Linux as a Real-Time OS

Optimizing
system
responsiveness

PREEMPT_RT
(Linux)

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Algorithmic changes
based on real-time
systems research

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LITMUS^RT
Linux Testbed for Multiprocessor Scheduling in Real-Time Systems

PREEMPT_RT

- Main real-time branch of Linux
- **Goal:** decrease **scheduling latency** through the use of low-level hacks
  - Convert in-kernel spinlocks into (preemptable) mutexes
  - Limit the extent of non-preemptable sections
- Commonly evaluated with **cyclictest**
  - **Single**, easy-to-compare measure of scheduling latency as output

LITMUS^{RT}

Linux Testbed for Multiprocessor Scheduling in Real-Time Systems

- Testbed for applied real-time systems research
- **Goal**
  - Allow implementation and evaluation of novel multiprocessor schedulers and synchronization protocols
  - **NOT** to reduce scheduling latency
- Evaluated with **Feather-Trace**
  - Flexible, fine-grained measurement of **different** overheads

LITMUS^{RT}

Linux Testbed for Multiprocessor Scheduling in Real-Time Systems

- Testb
- **Goal**
  - A
  - **NOT** to reduce scheduling latency
- Evaluated with **Feather-Trace**
  - Flexible, fine-grained measurement of **different** overheads

How do LITMUS^{RT} and PREEMPT_RT compare?

LITMUS^{RT}

Linux Testbed for Multiprocessor Scheduling in Real-Time Systems

- Testb
- **Goal**
  - A
    s
  - [redacted]
- Eval
  - [redacted]

How do LITMUS^{RT} and PREEMPT_RT compare?

It is not straightforward to compare them!

Objective

LITMUS^{RT}
Linux Testbed for Multiprocessor Scheduling in Real-Time Systems

vs.

PREEMPT_RT (Linux)

Direct comparison of
scheduling latency between
LITMUS^{RT} and PREEMPT_RT

Background

How is LITMUS^{RT} evaluated?

- Evaluated with feather trace

- Lightweight tracing framework for measuring fine-grained overheads (e.g., IPI latency, context-switching overhead, etc.)

- Extensively used (20+ publications)

- Suitable for schedulability analysis

  - Check if a task is going to miss a deadline

How is PREEMPT_RT evaluated?

- Evaluated with **cyclictest**
- **Standard benchmark** for assessing real-time responsiveness

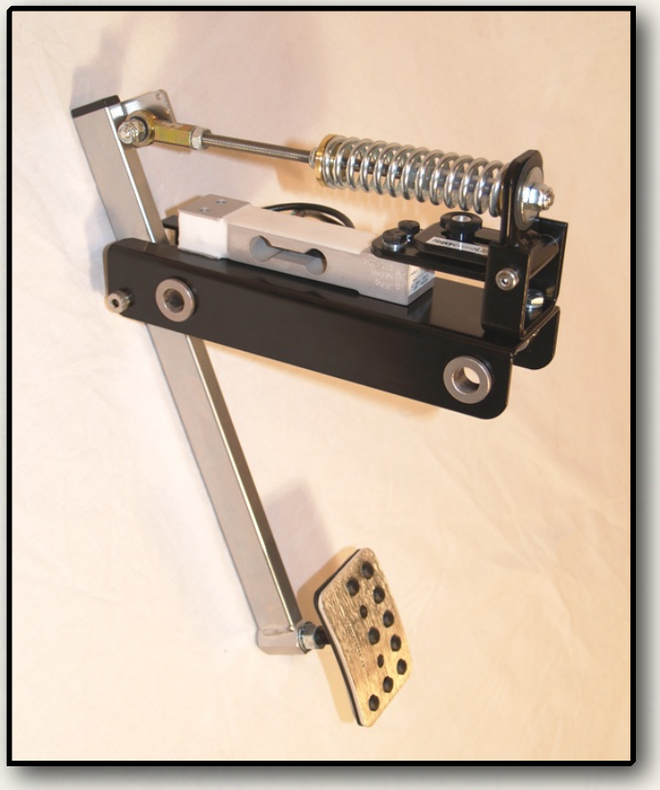
```
# /dev/cpu_dma_latency set to 0us
policy: fifo: loadavg: 0.00 0.01 0.05 1/178 4320

T: 0 ( 4305) P:99 I:1000 C:  13092 Min:      2 Act:    3 Avg:    3 Max:       9
T: 1 ( 4306) P:99 I:1500 C:   8728 Min:      2 Act:    3 Avg:    2 Max:       9
T: 2 ( 4307) P:99 I:2000 C:   6546 Min:      2 Act:    2 Avg:    2 Max:       5
T: 3 ( 4308) P:99 I:2500 C:   5236 Min:      2 Act:    2 Avg:    2 Max:       4
T: 4 ( 4309) P:99 I:3000 C:   4364 Min:      2 Act:    2 Avg:    2 Max:       3
T: 5 ( 4310) P:99 I:3500 C:   3740 Min:      2 Act:    2 Avg:    2 Max:       3
T: 6 ( 4311) P:99 I:4000 C:   3273 Min:      2 Act:    3 Avg:    2 Max:       4
T: 7 ( 4312) P:99 I:4500 C:   2909 Min:      2 Act:    3 Avg:    2 Max:       4
T: 8 ( 4313) P:99 I:5000 C:   2618 Min:      3 Act:    3 Avg:    3 Max:       4
T: 9 ( 4314) P:99 I:5500 C:   2380 Min:      2 Act:    2 Avg:    2 Max:       6
T:10 ( 4315) P:99 I:6000 C:   2182 Min:      2 Act:    4 Avg:    3 Max:       4
T:11 ( 4316) P:99 I:6500 C:   2014 Min:      2 Act:    3 Avg:    2 Max:       4
T:12 ( 4317) P:99 I:7000 C:   1870 Min:      2 Act:    3 Avg:    3 Max:       6
T:13 ( 4318) P:99 I:7500 C:   1745 Min:      2 Act:    3 Avg:    2 Max:       3
T:14 ( 4319) P:99 I:8000 C:   1636 Min:      2 Act:    4 Avg:    3 Max:       4
T:15 ( 4320) P:99 I:8500 C:   1540 Min:      2 Act:    3 Avg:    2 Max:       4
```

- Creator: Thomas Gleixner
  Current maintainer: Clark Williams
- Reports scheduling latency as a single measure
  - Treats hardware and OS as a black-box

Scheduling Latency

Time until the highest-priority task is scheduled



brake sensor
HP task

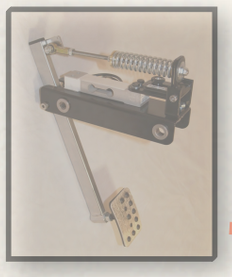
interrupt!

ECU

ISR called

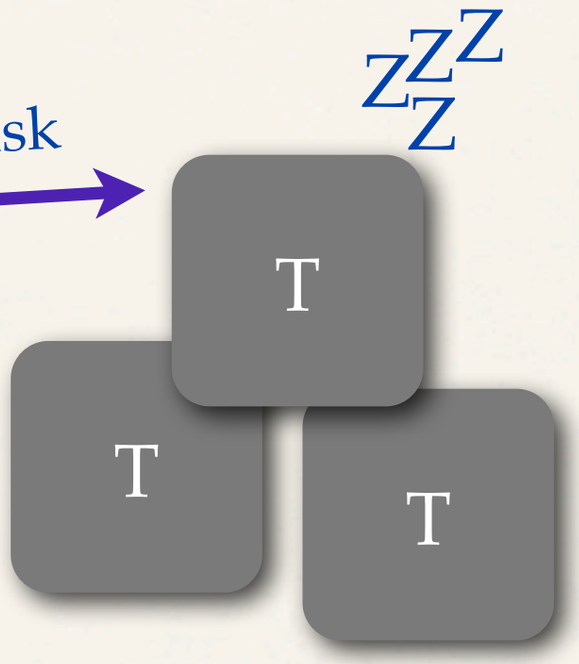
Scheduling Latency

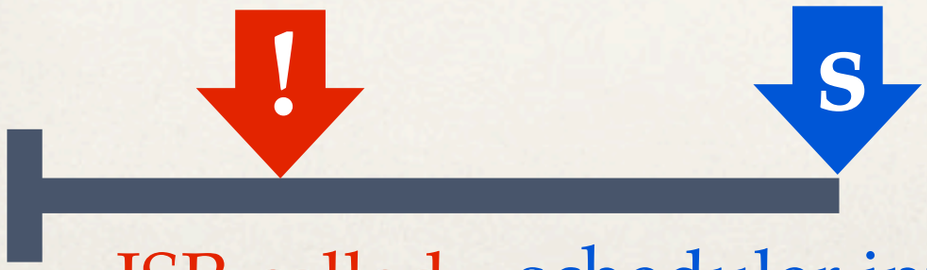
Time until the highest-priority task is scheduled



interrupt!

wake up task





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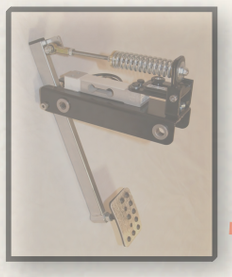

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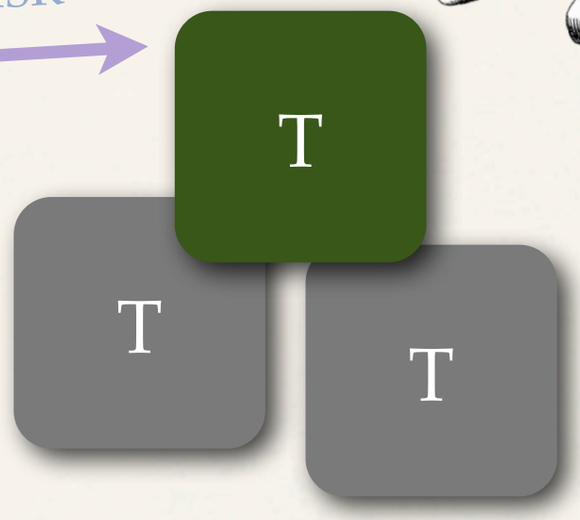

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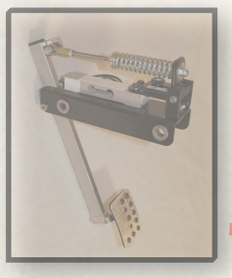

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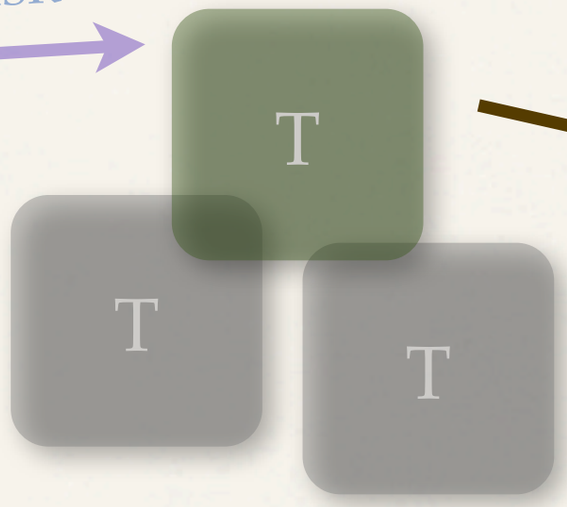
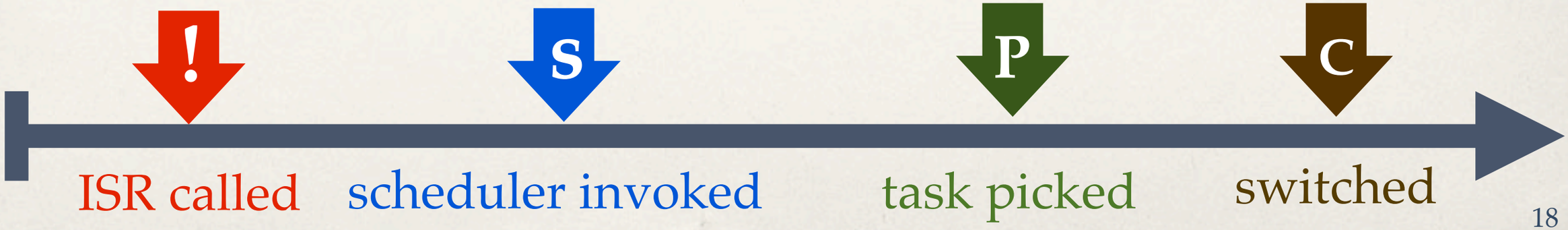
wake up task



Perform context switch



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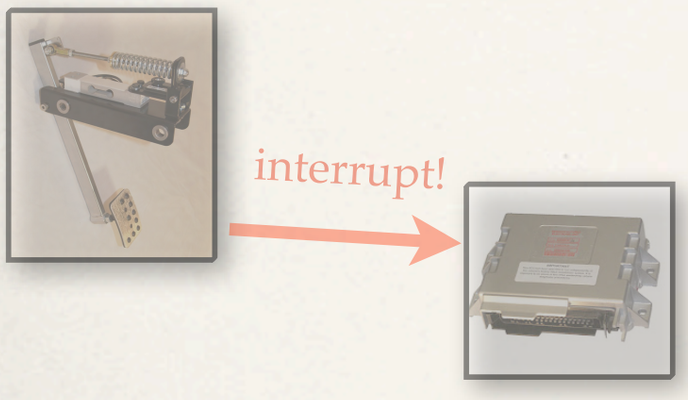

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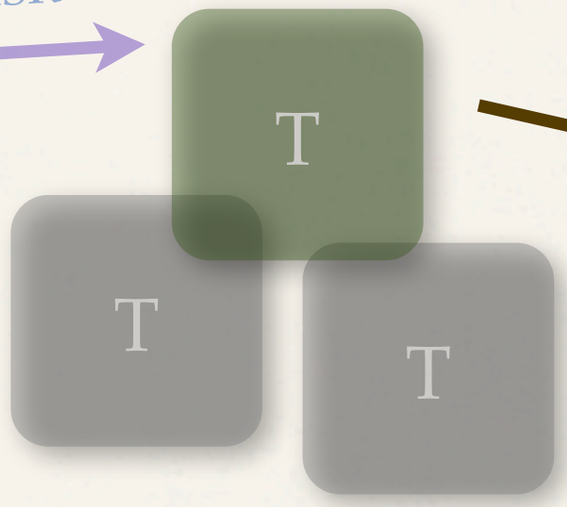

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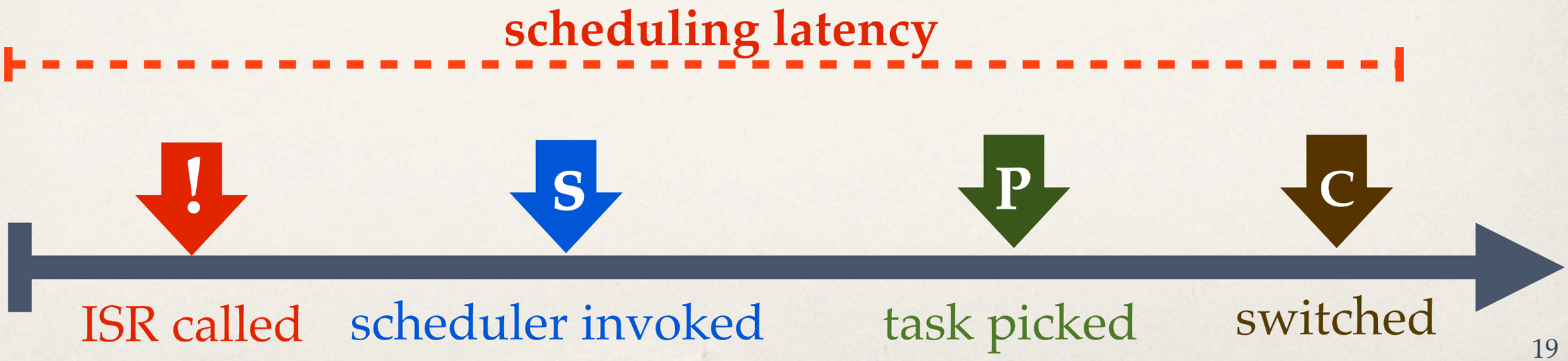
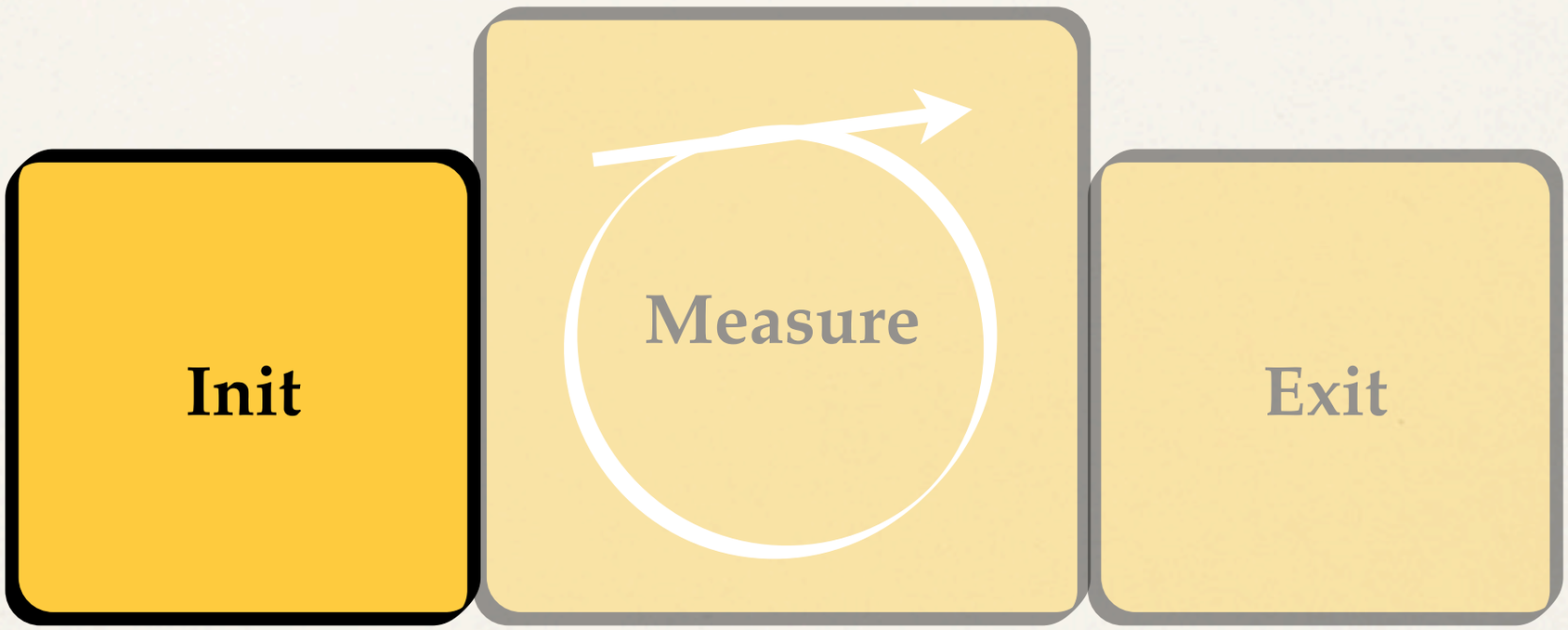


How does cyclictest measure Scheduling Latency?



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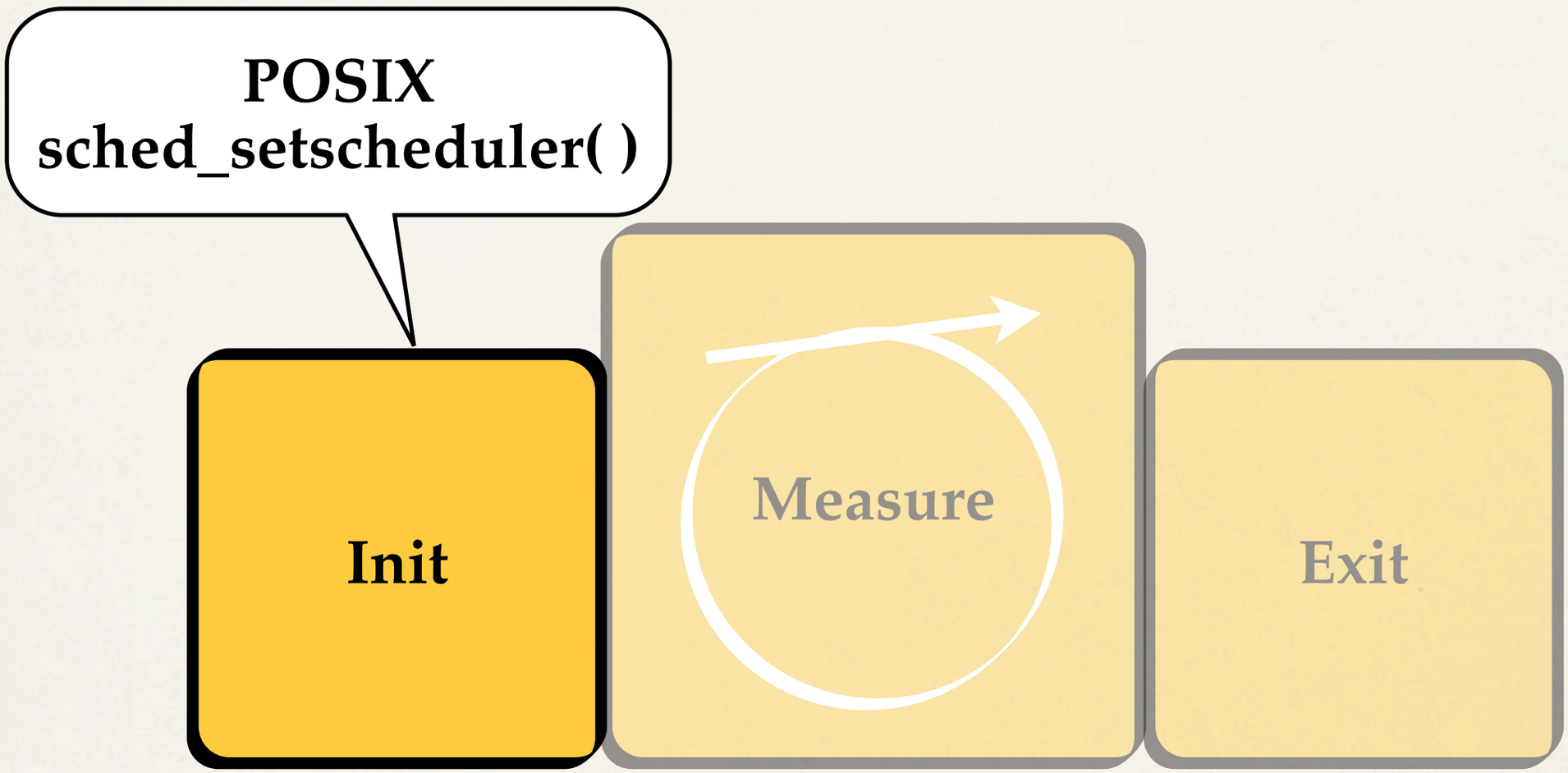

Measuring thread is granted real-time status.

How does cyclictest measure Scheduling Latency?

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Periodically setup one-shot timers with *nanosleep*.
Calculate delta between the instant the task starts executing and the instant the timer should have fired.

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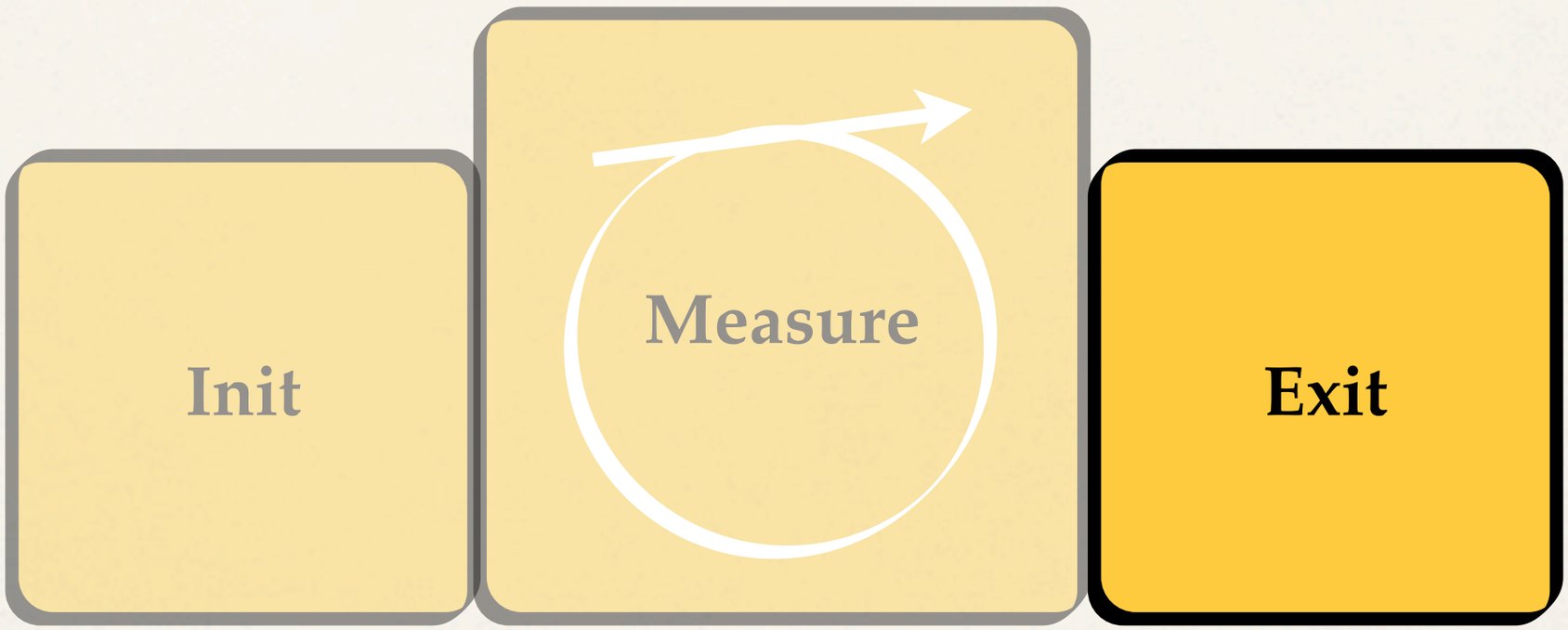

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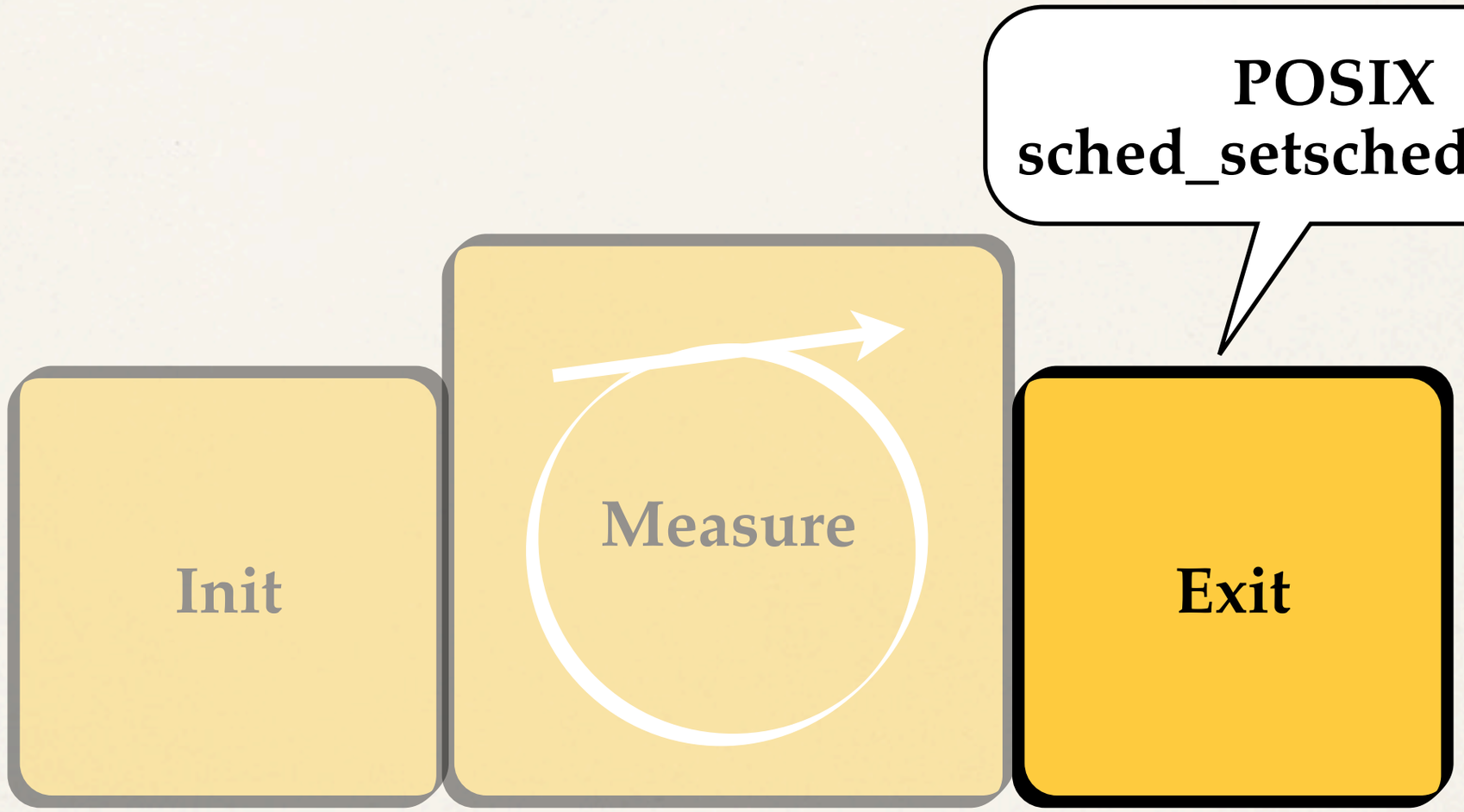
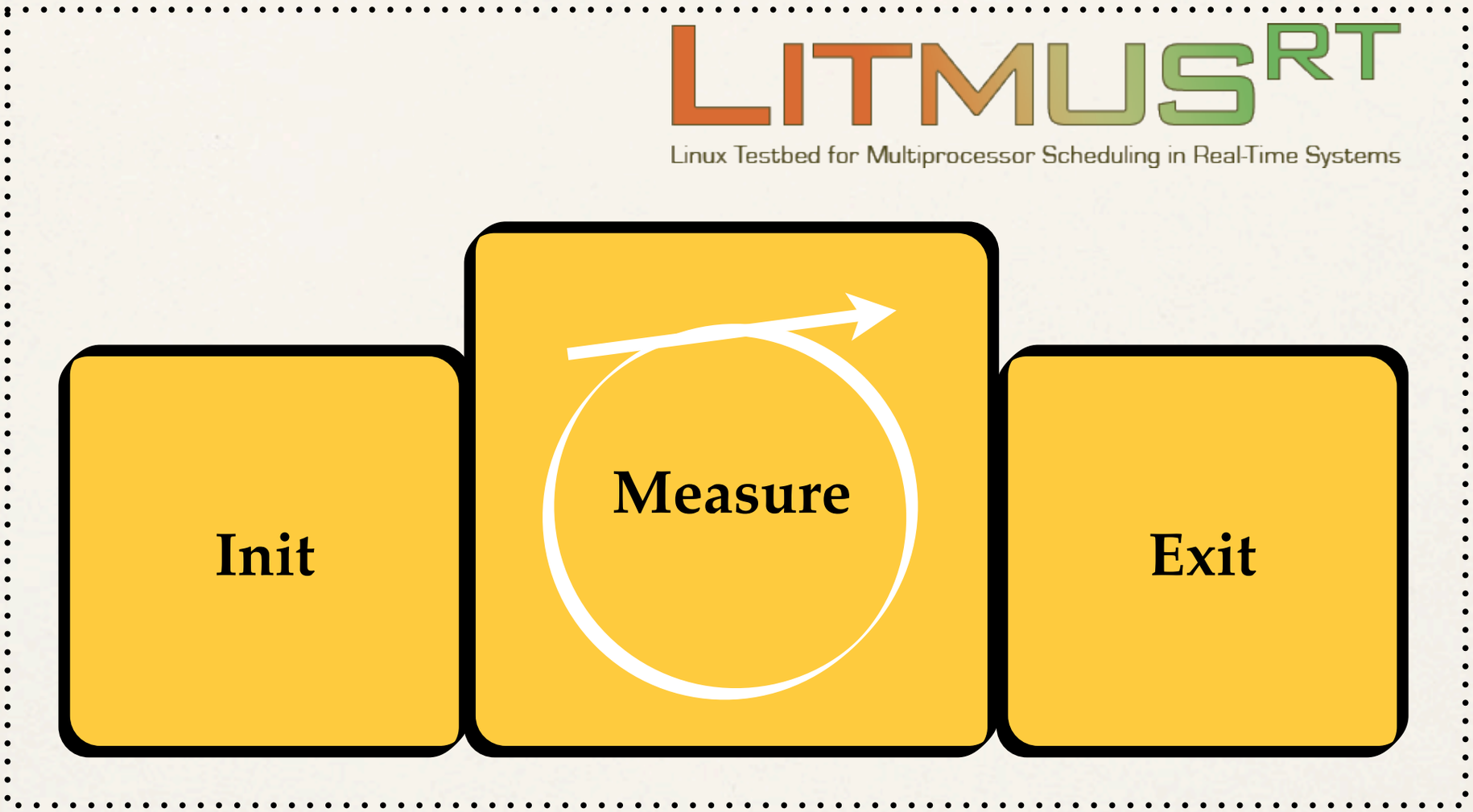


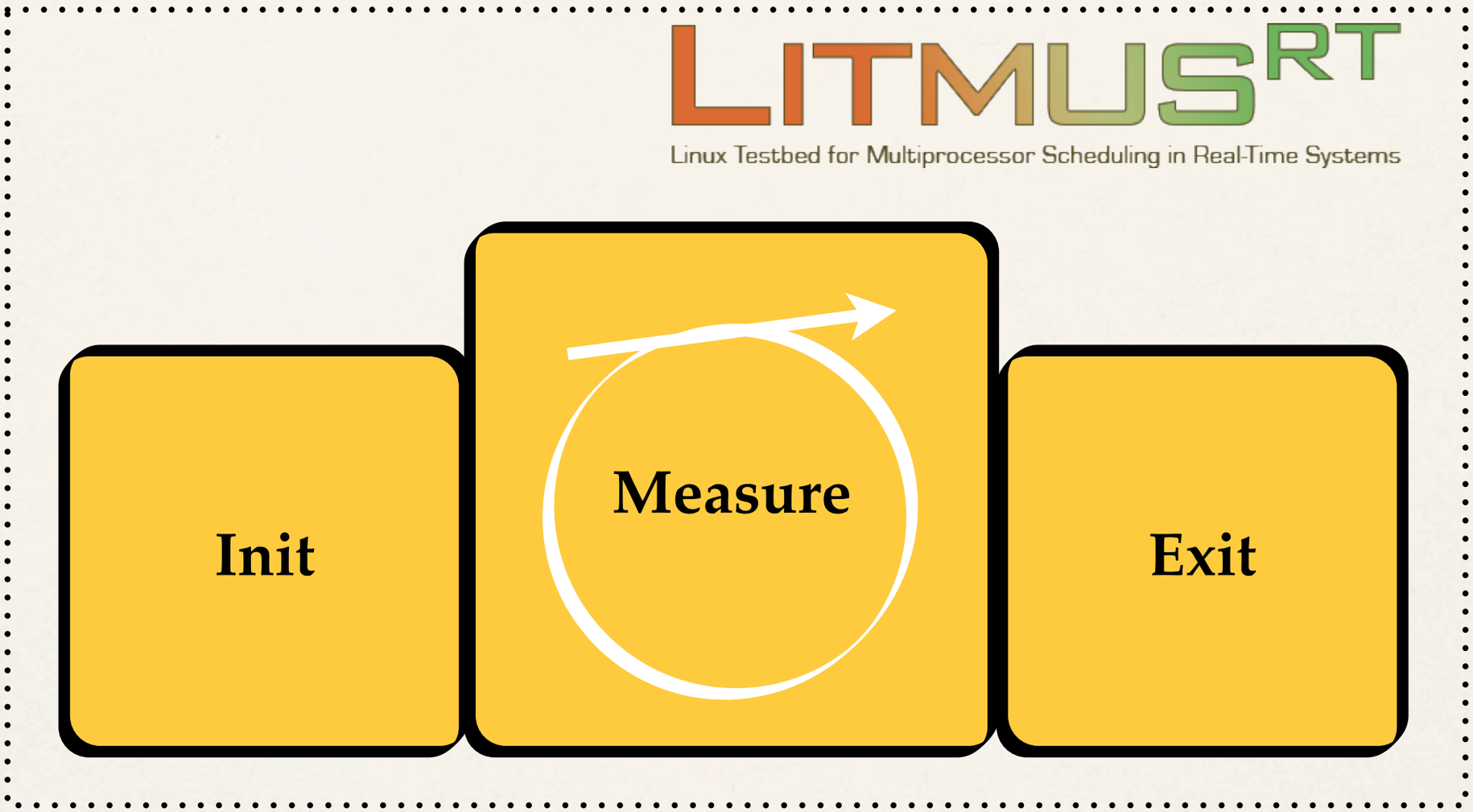
Measuring thread returns to best-effort status.

cyclictest on LITMUS^{RT}



LITMUS^{RT} does not use POSIX API to setup real-time tasks!

cyclictest on LITMUS^{RT}



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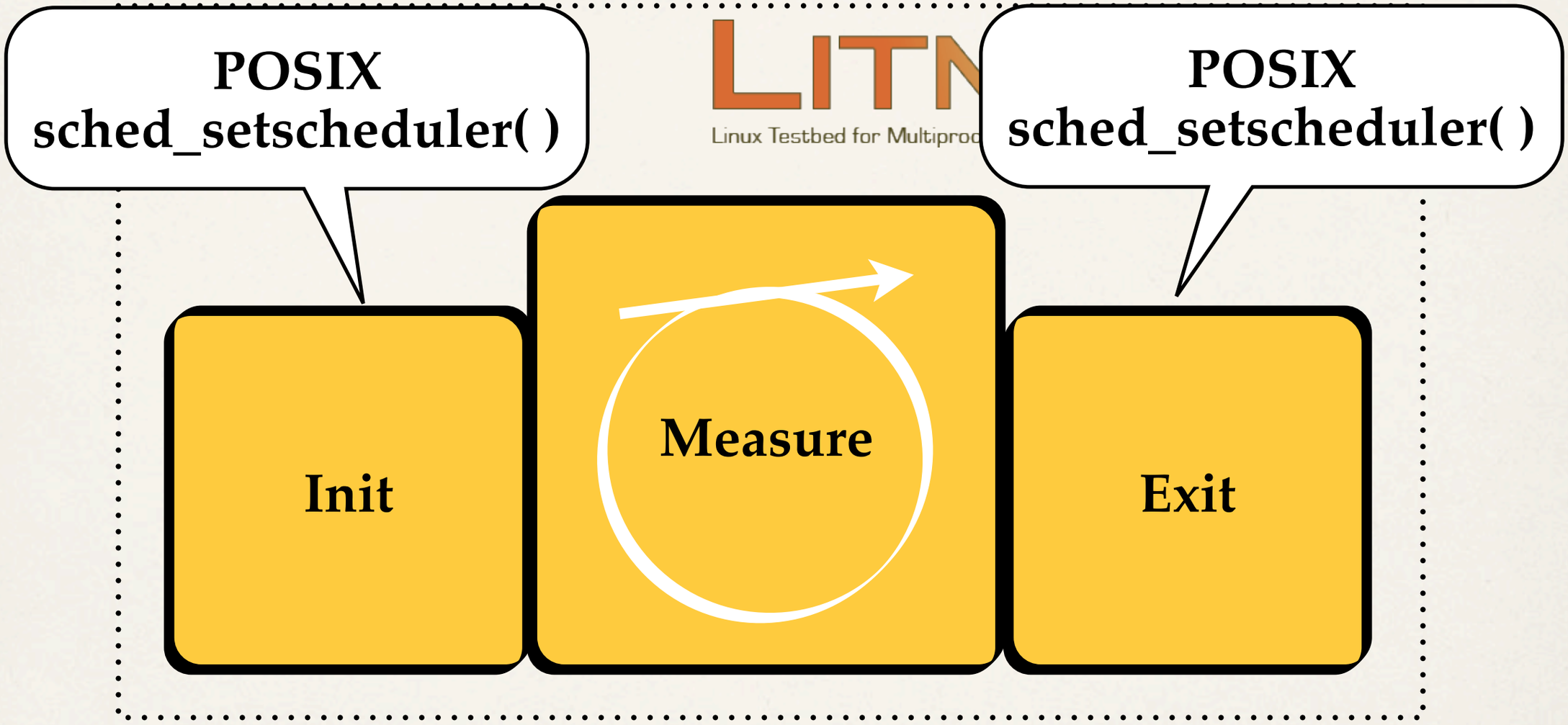
cyclictest works, but does not measure what we expect...

Porting cyclictest to LITMUS^{RT}



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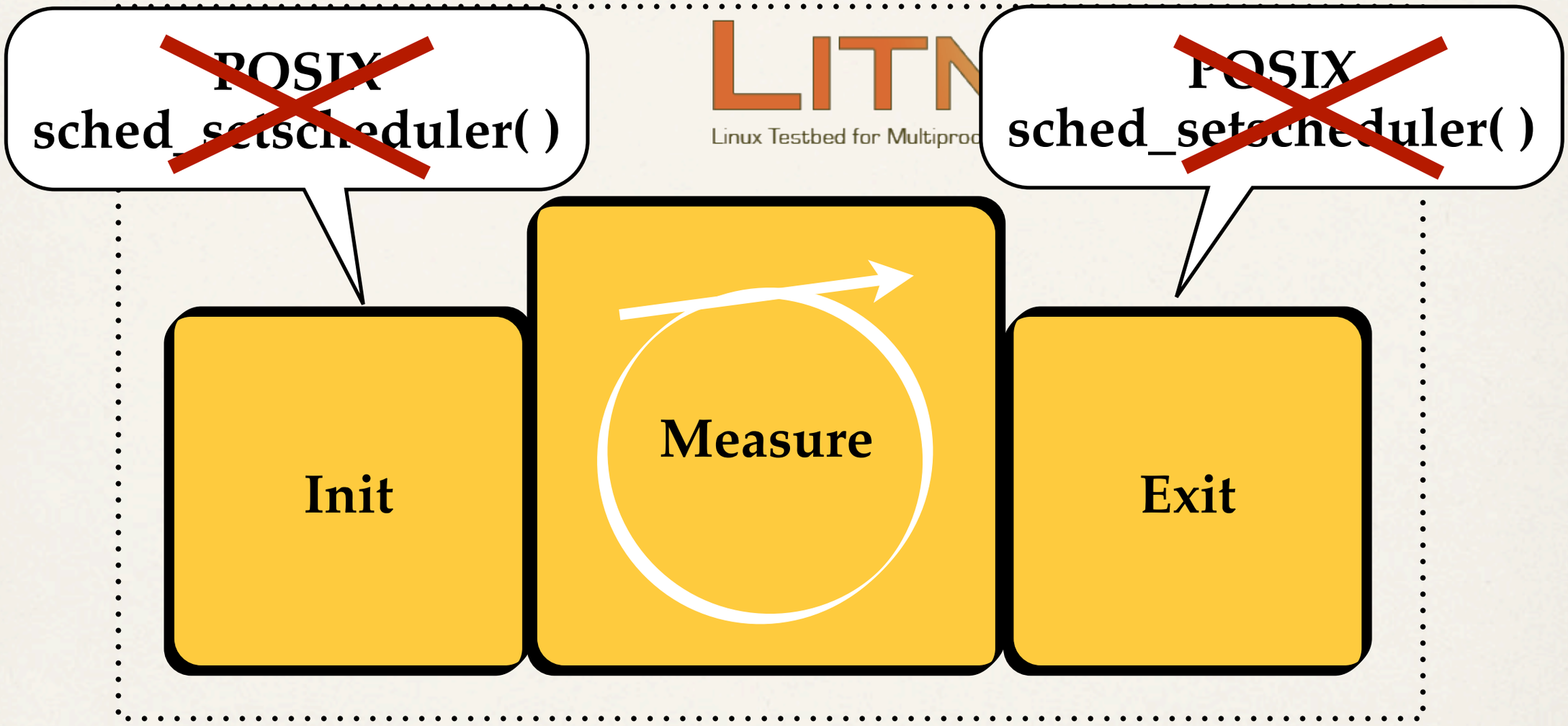

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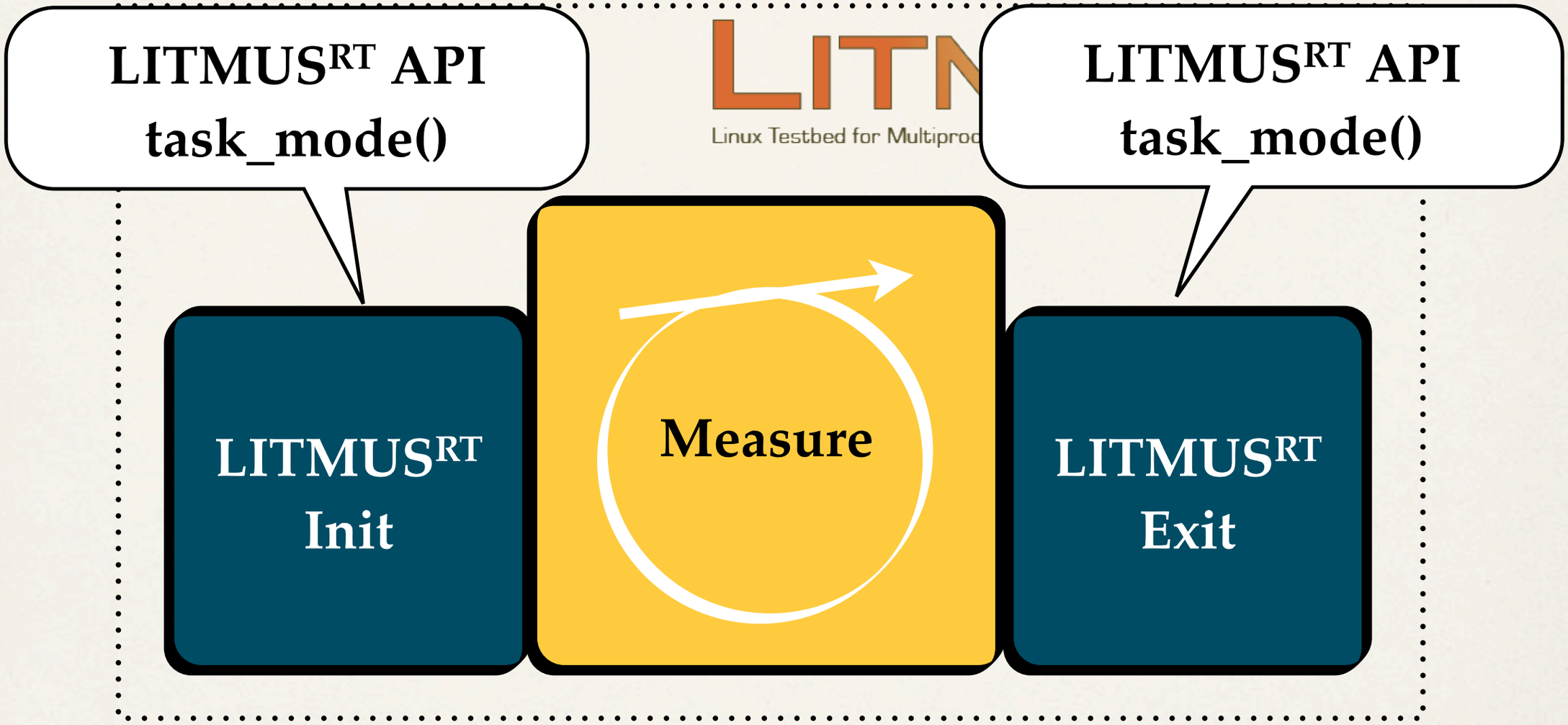
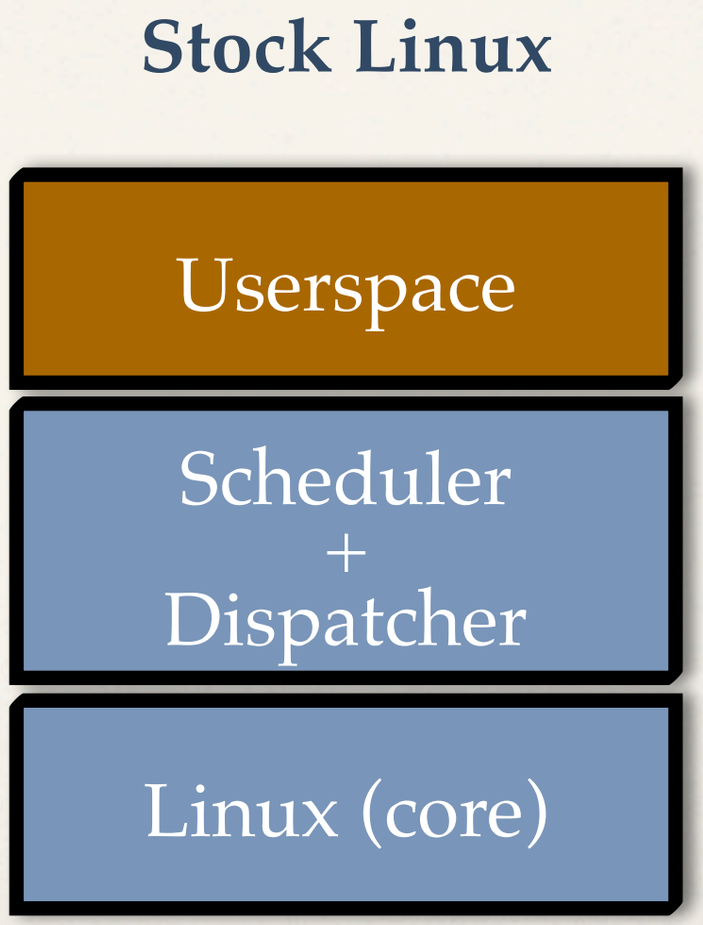


No changes in the measurement phase, no bias.

Study

Questions that We Address



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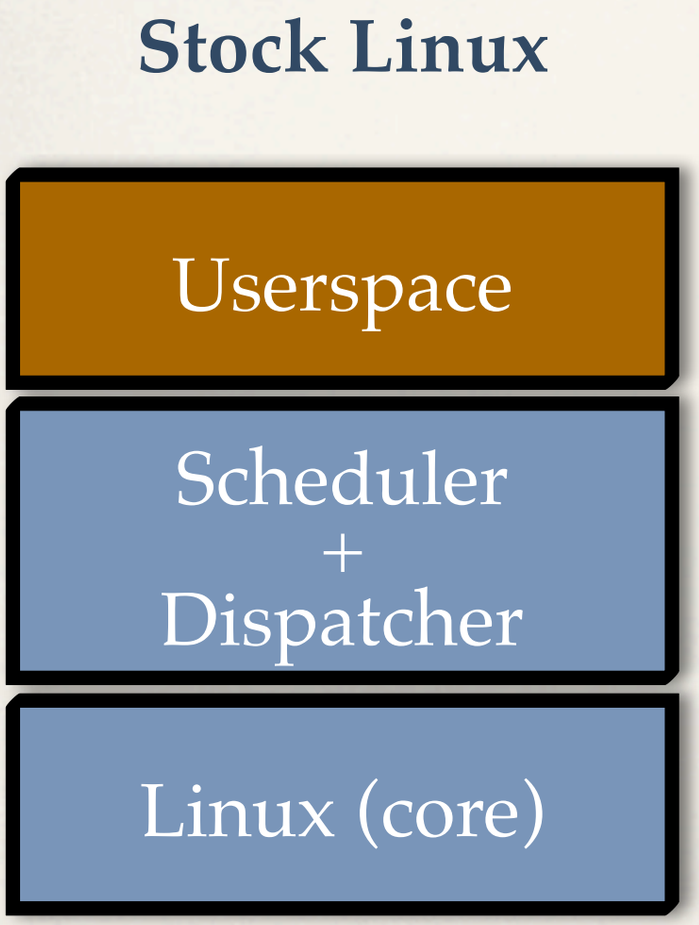
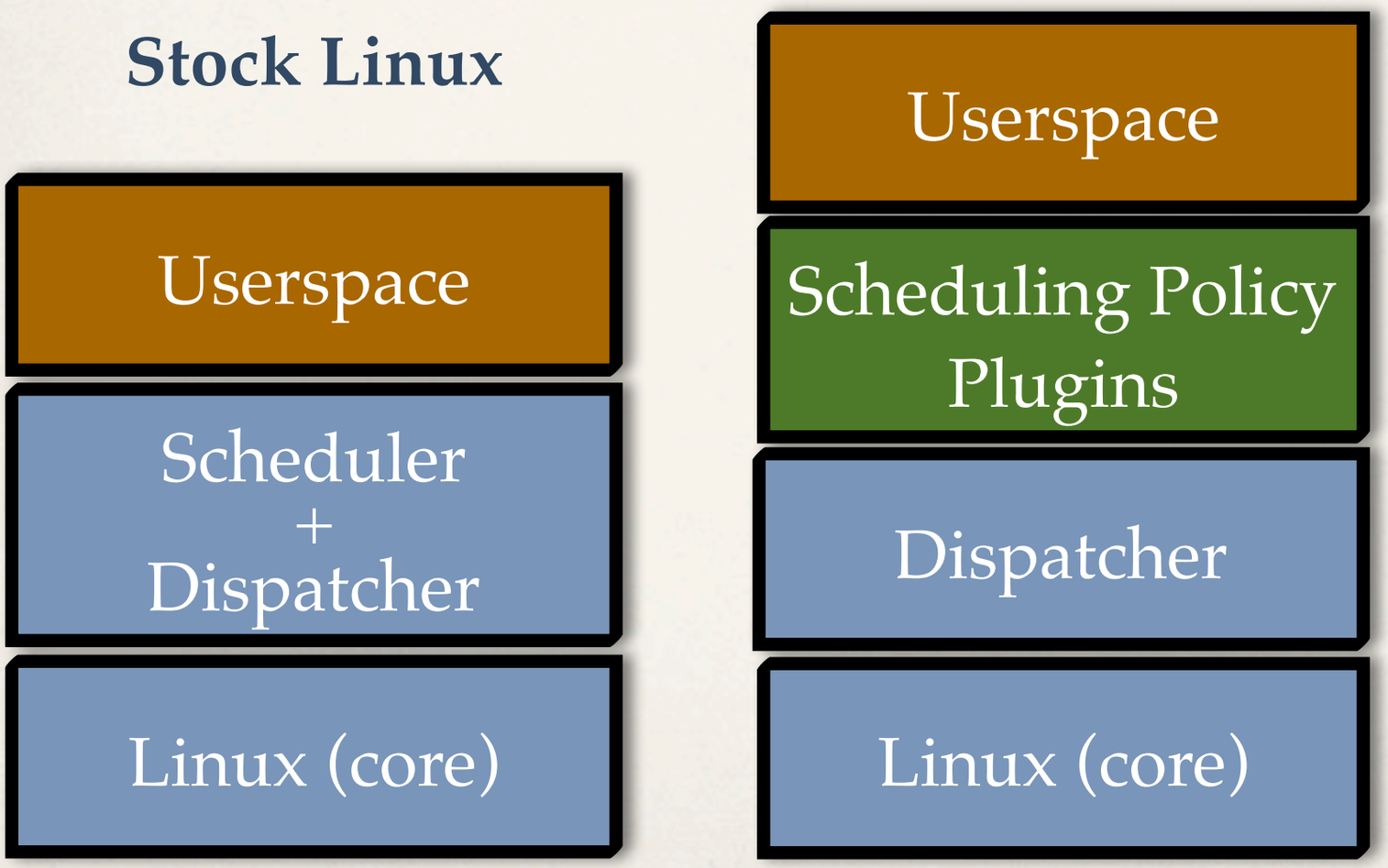
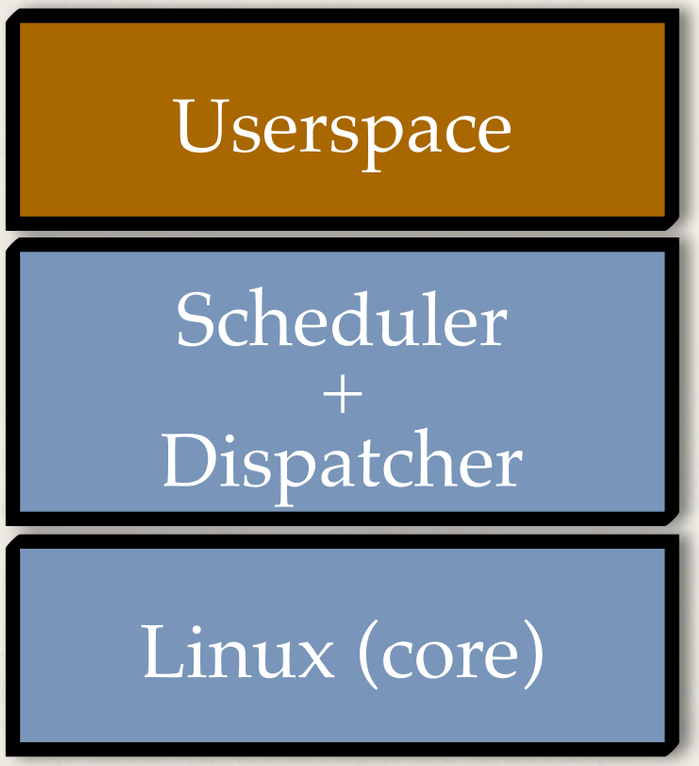


The Cost of LITMUS^{RT}

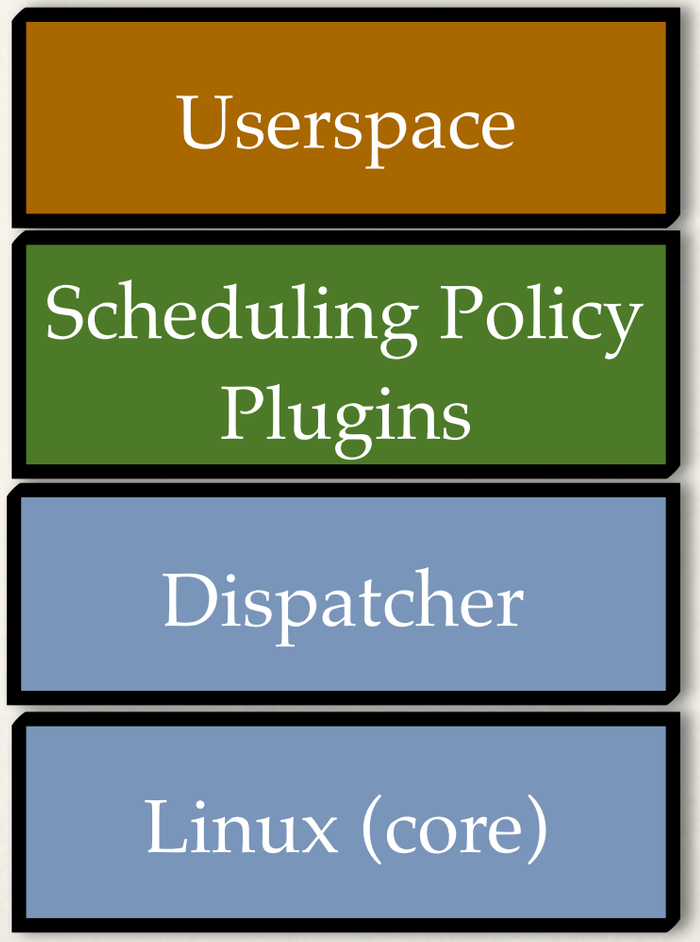


The Cost of LITMUS^{RT}

Stock Linux



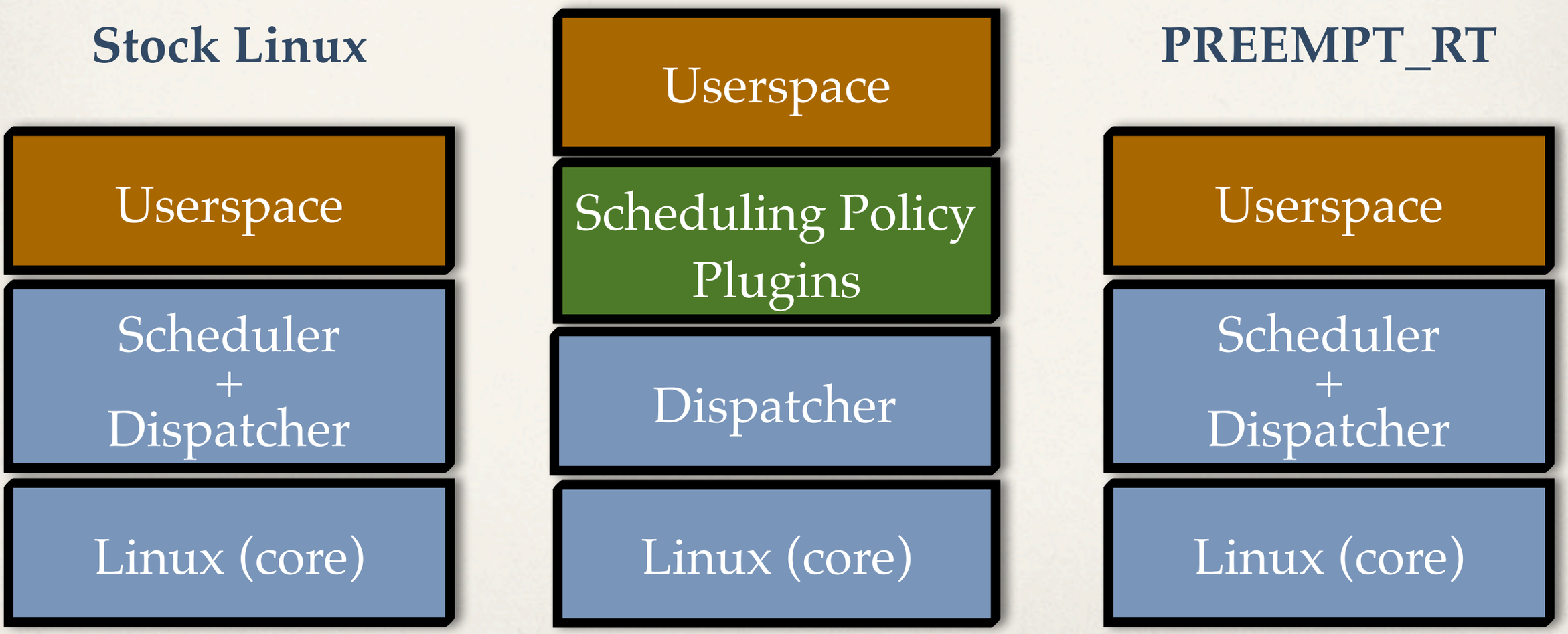
LITMUS^{RT}



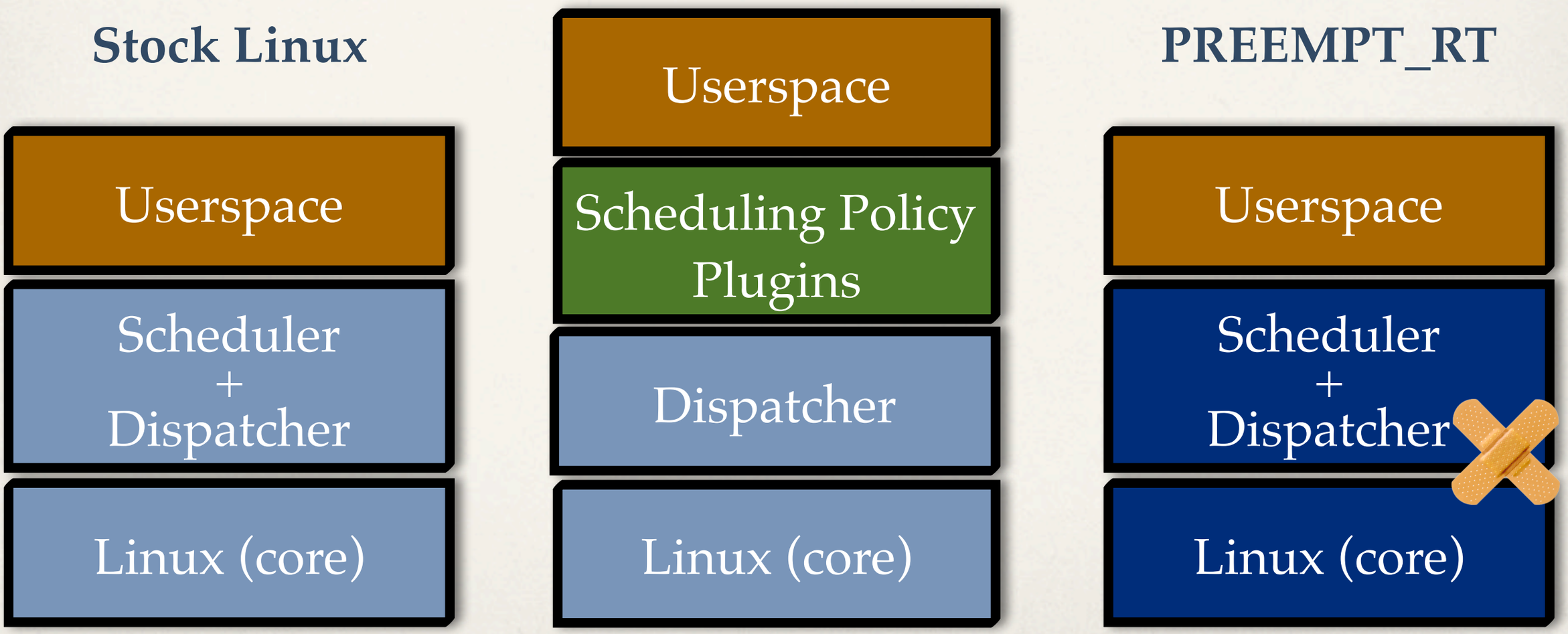
Question 1

How much latency does the scheduling policy interface add to the system?

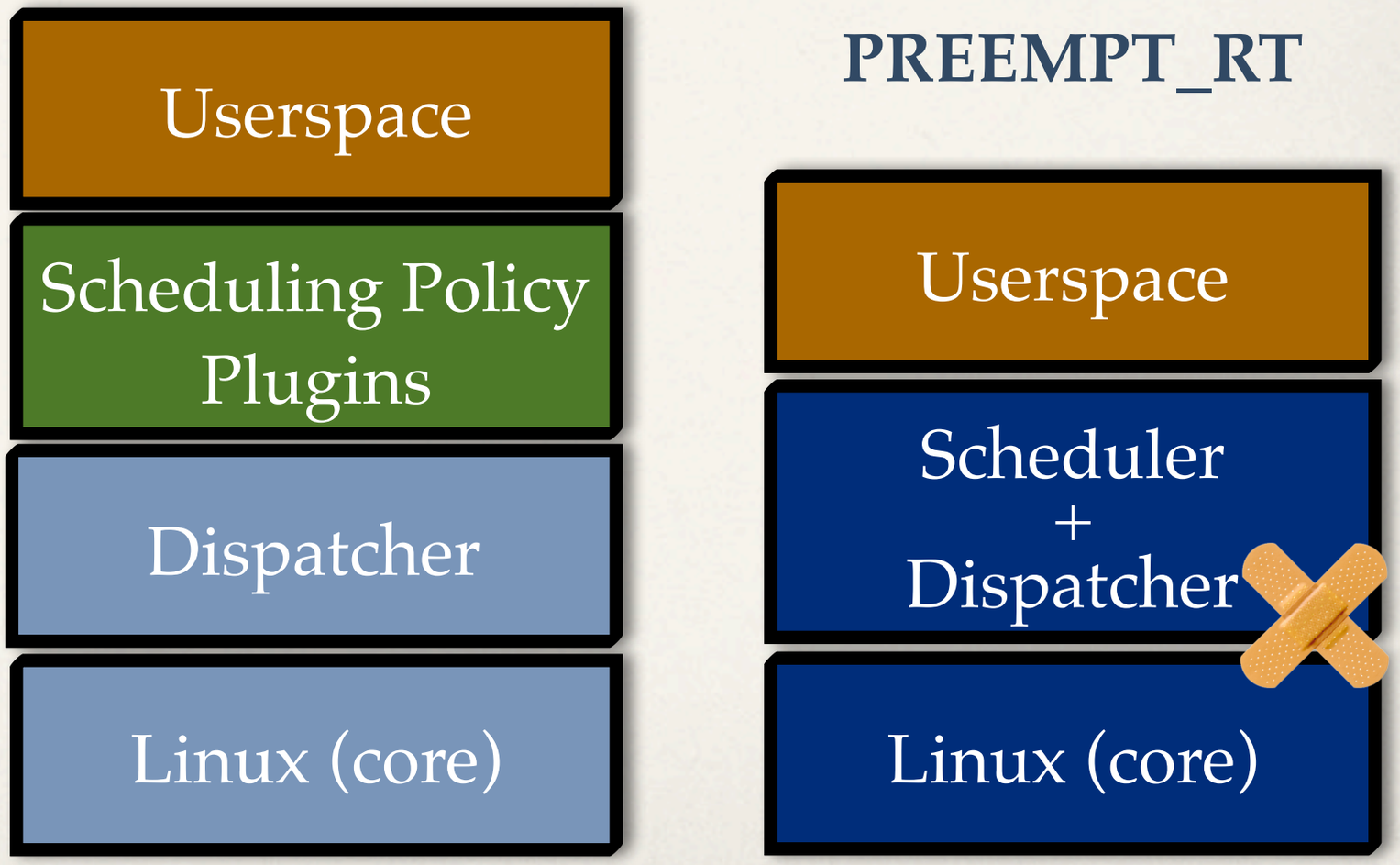
LITMUS^{RT} vs. PREEMPT_RT



LITMUS^{RT} vs. PREEMPT_RT



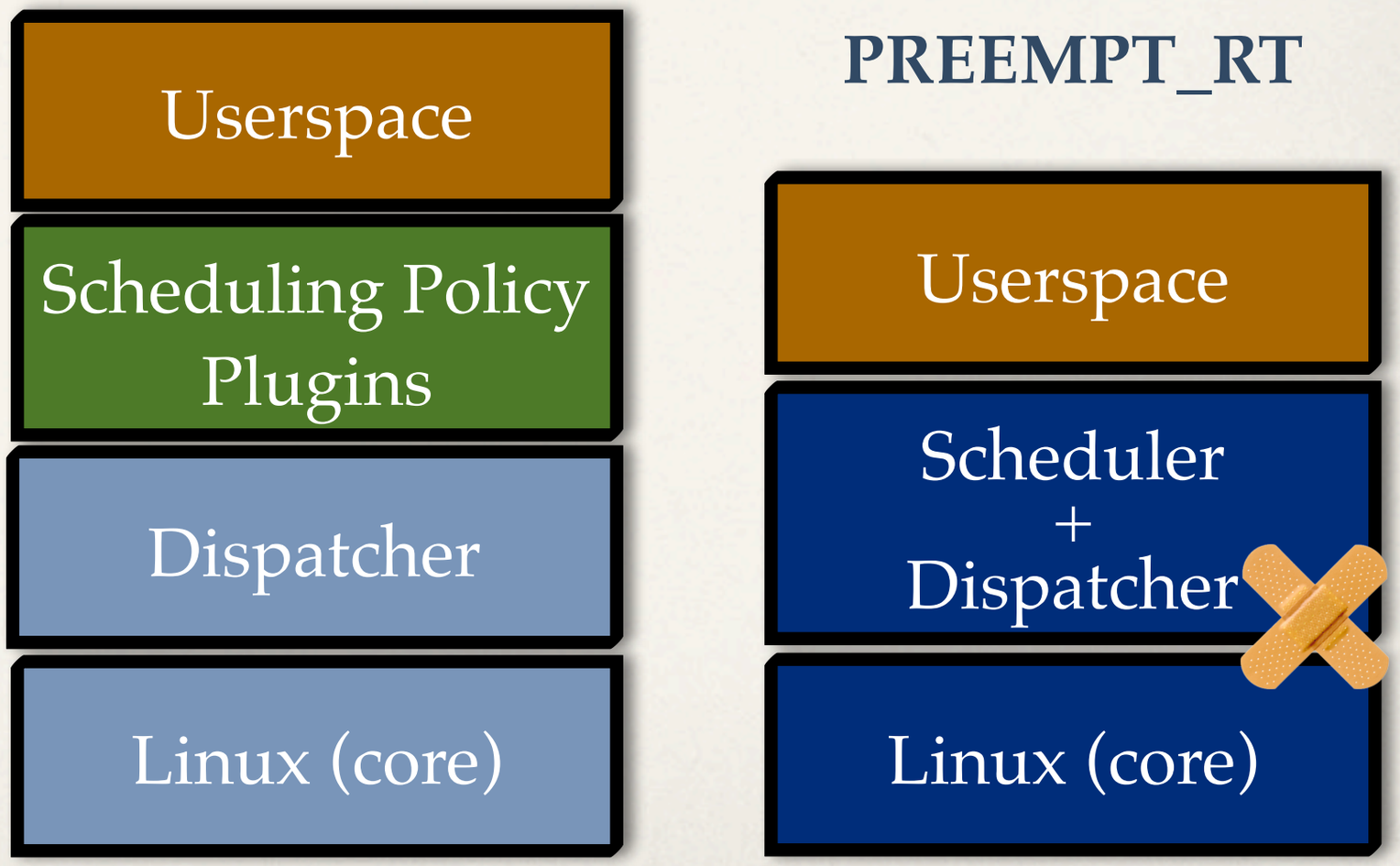
LITMUS^{RT} vs. PREEMPT_RT



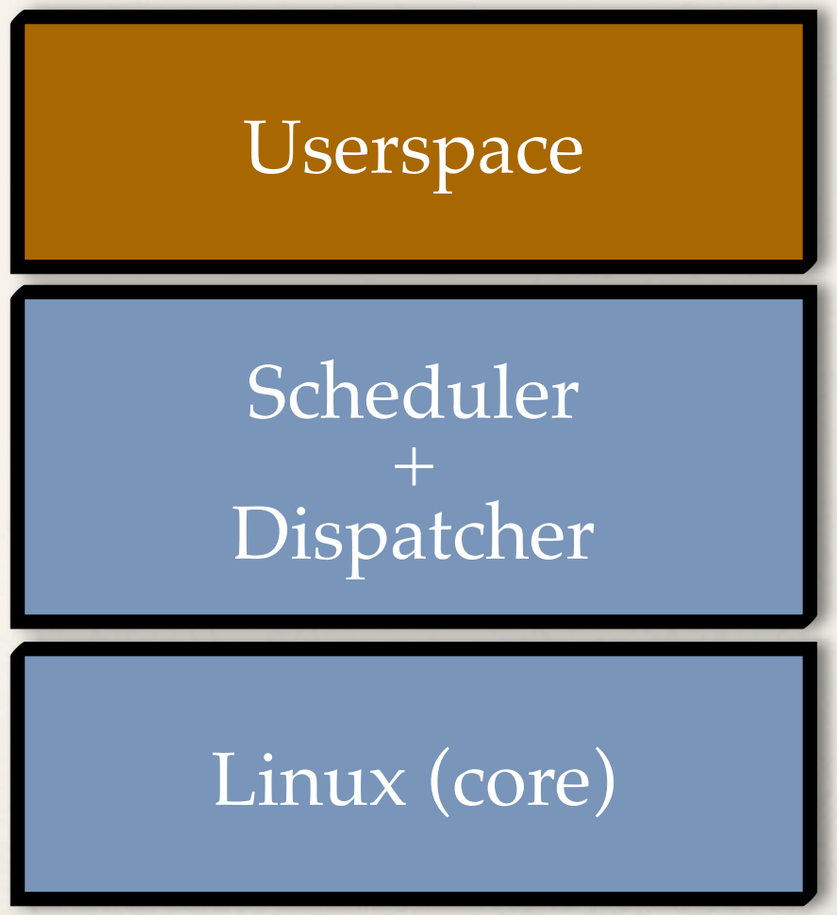
LITMUS^{RT} vs. PREEMPT_RT

Question 2

What is the penalty for LITMUS^{RT} not being based on PREEMPT_RT?



Evaluation



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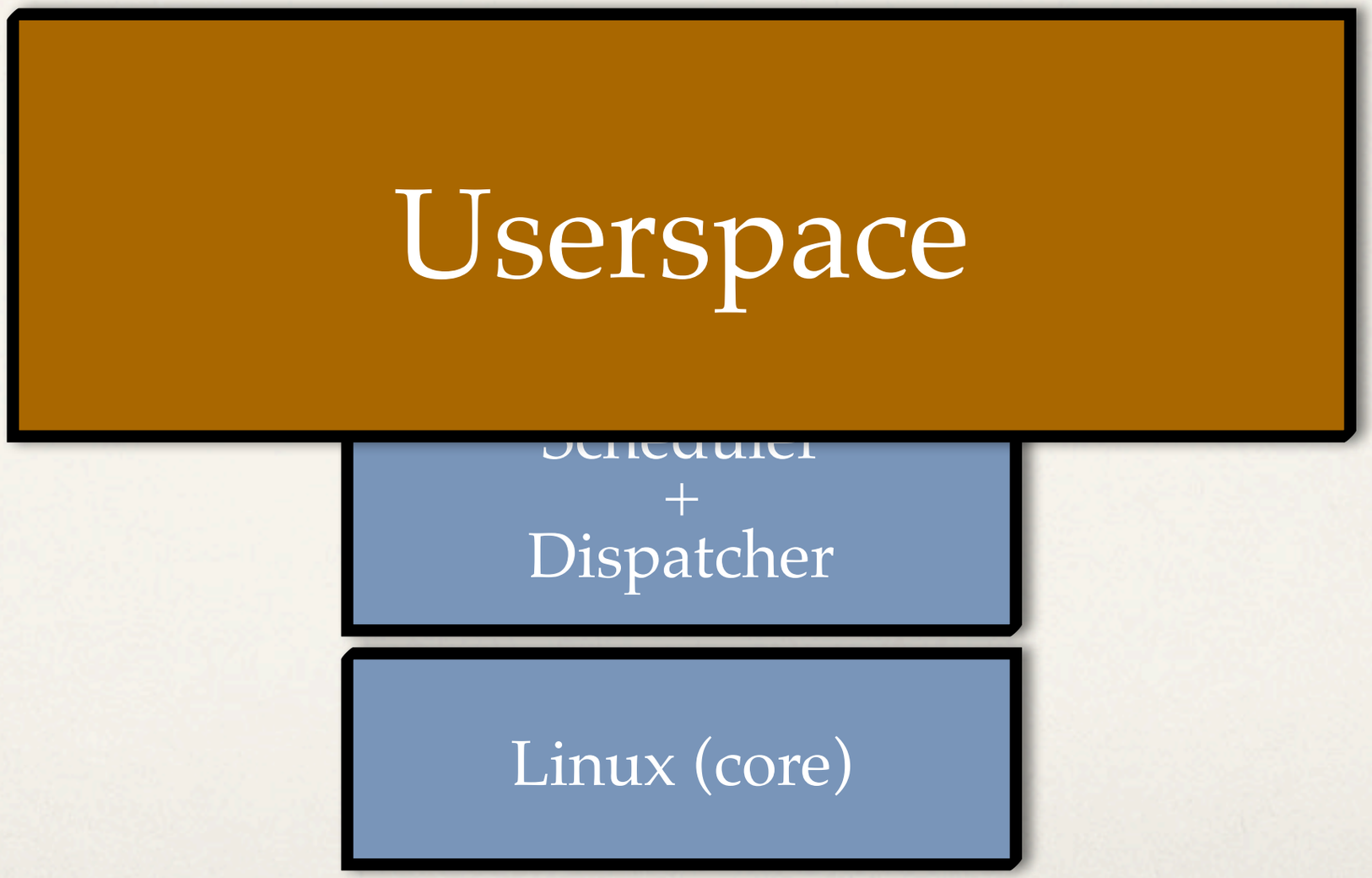

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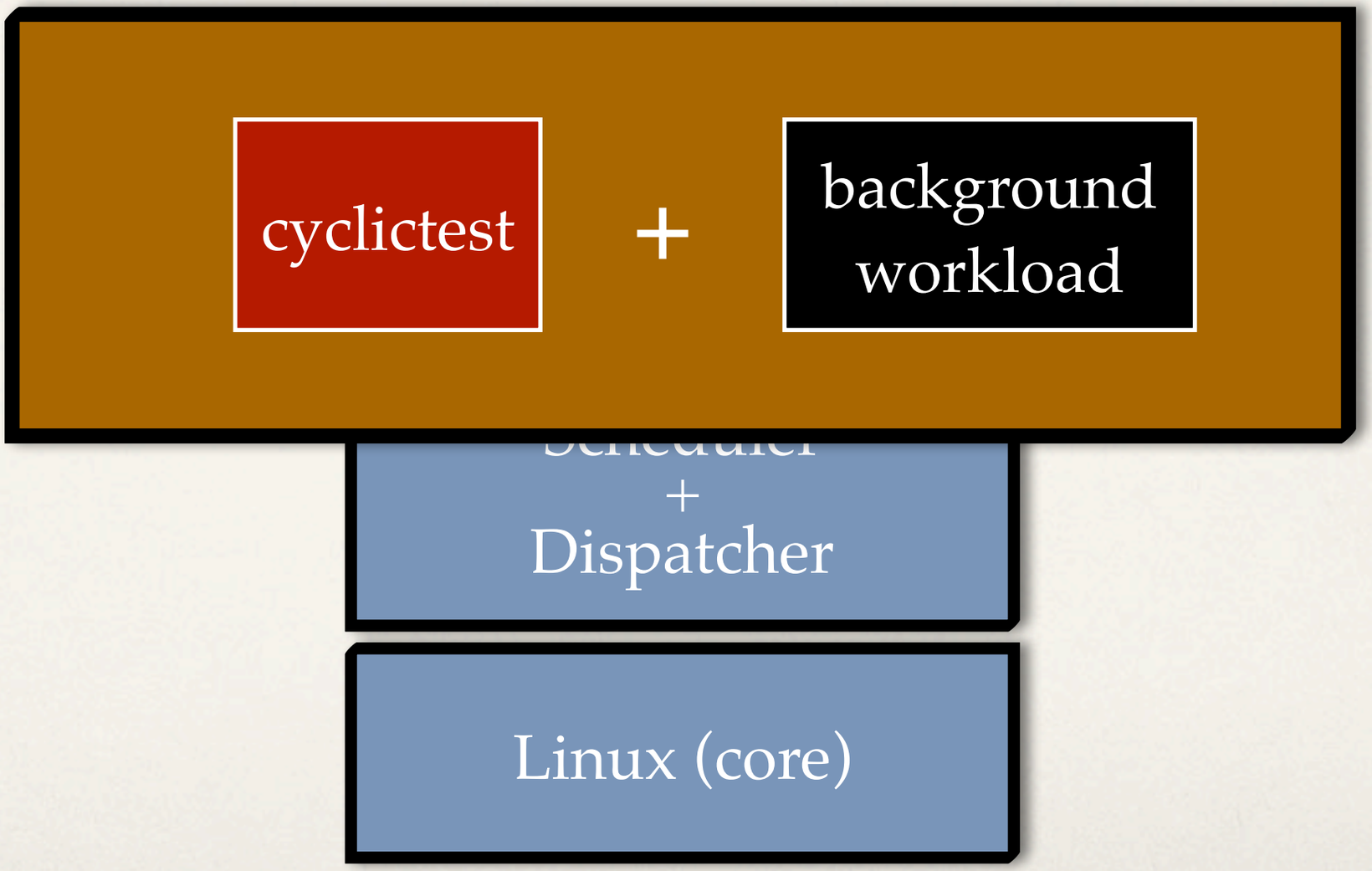

cyclictest
+
background workload
Scheduler
+
Dispatcher
Linux (core)

Background Workloads

NO

background tasks

CPU-bound background tasks

I/O-bound background tasks

Experimental Setup

Different kernels:

1. **LITMUS^{RT} (Linux 3.0)**

   Partitioned **F**ixed **P**riority (P-FP),
   Partitioned **EDF** with synchronization support (PSN-EDF),
   Global **EDF** with synchronization support (GSN-EDF)

2. **PREEMPT_RT (Linux 3.8.13)**

3. **Unpatched Linux 3.0 and Linux 3.8.13**

} SCHED_FIFO

Experimental Setup

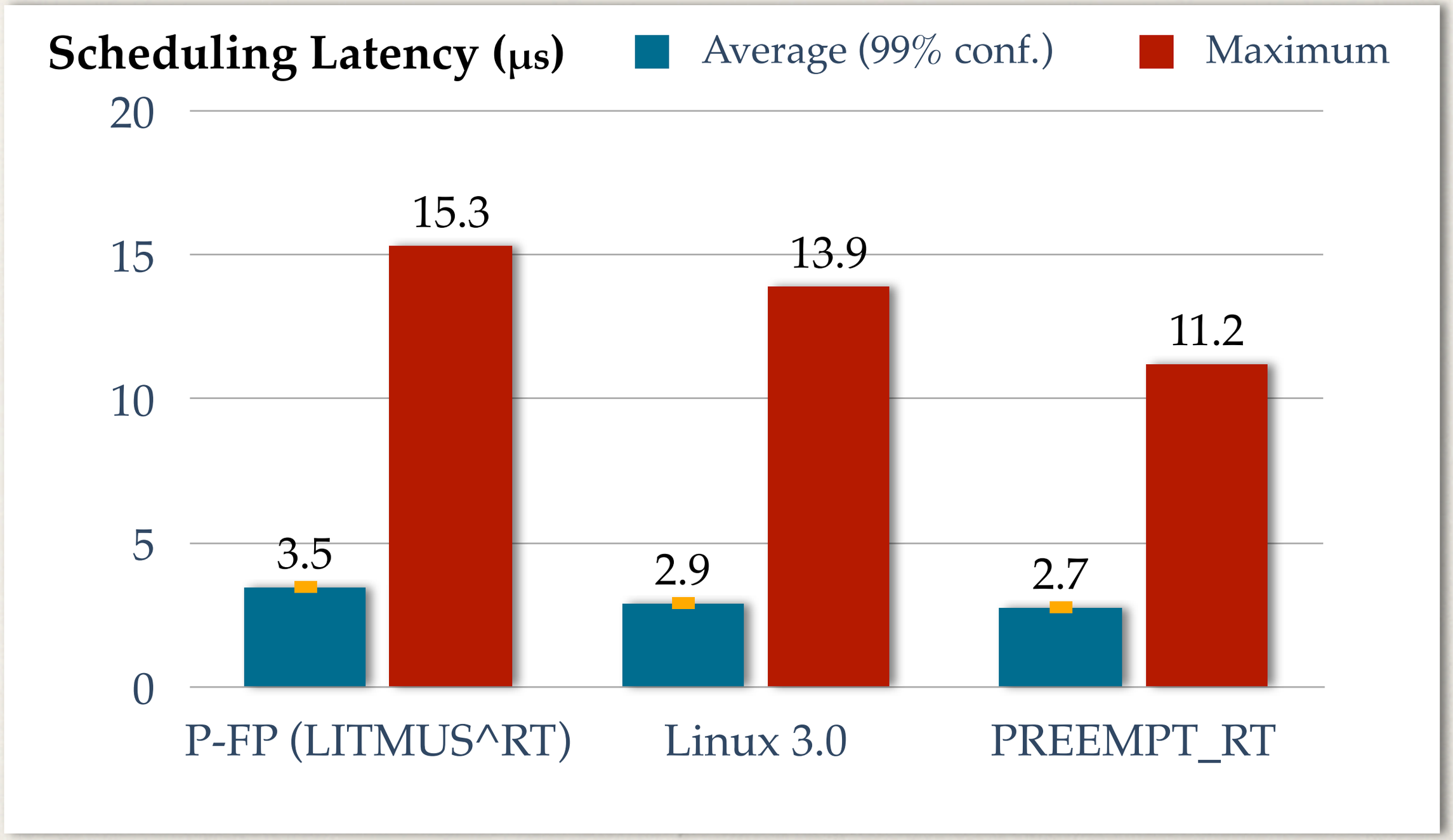
- **16-core Intel Xeon platform**
- **cyclictest's standard setup:**
  - one real-time task per processor
  - periods: {1000, 1500, 2000, ...} µs
- **Duration: 20 minutes per experiment**
  - Almost 6 million samples for each case
- **Results shown in microseconds**

First Scenario

NO

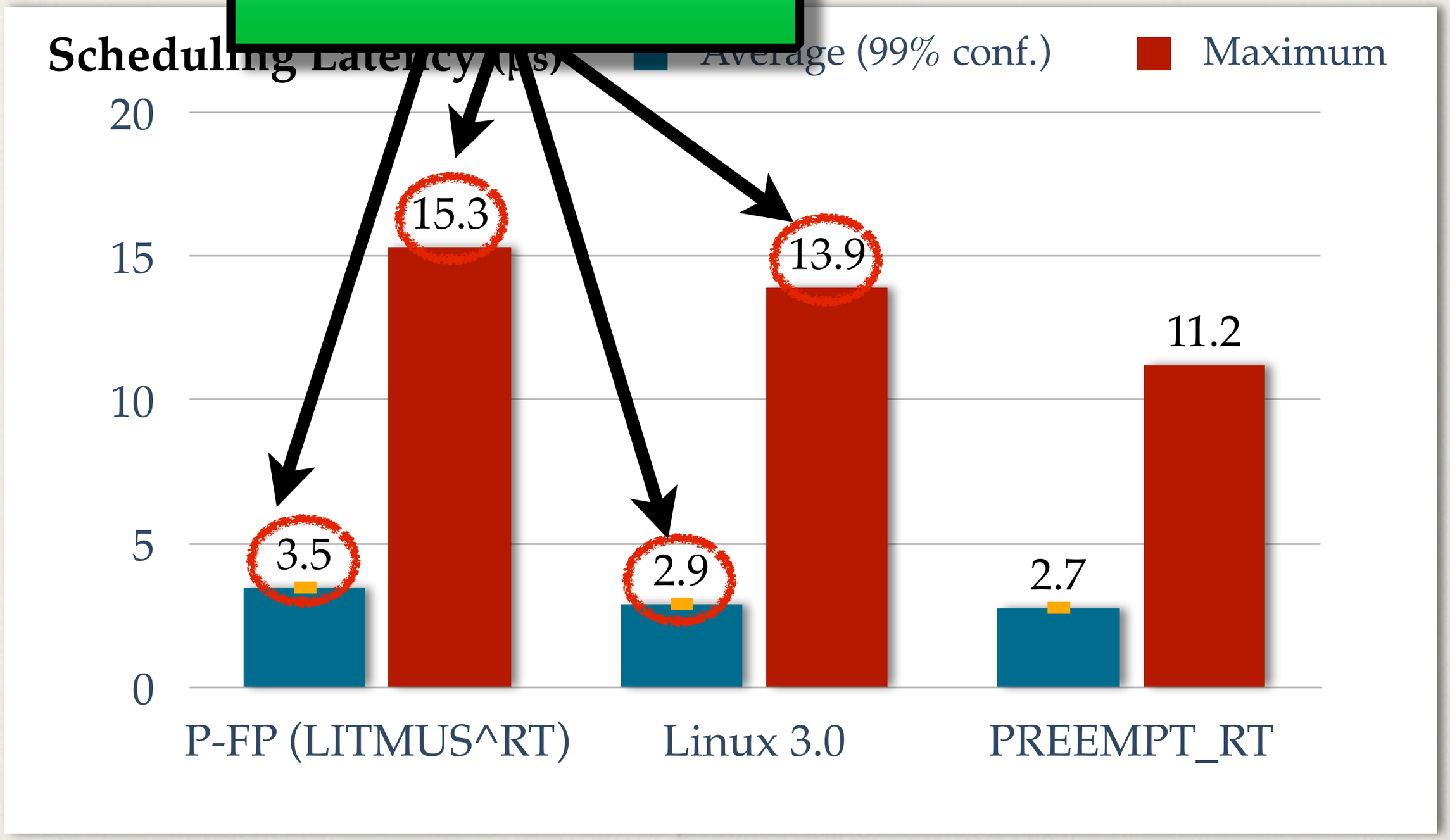
background tasks

No Background Tasks



No Ba…sks

Similar max. and avg. latency for Linux 3.0 and LITMUS^{RT}.



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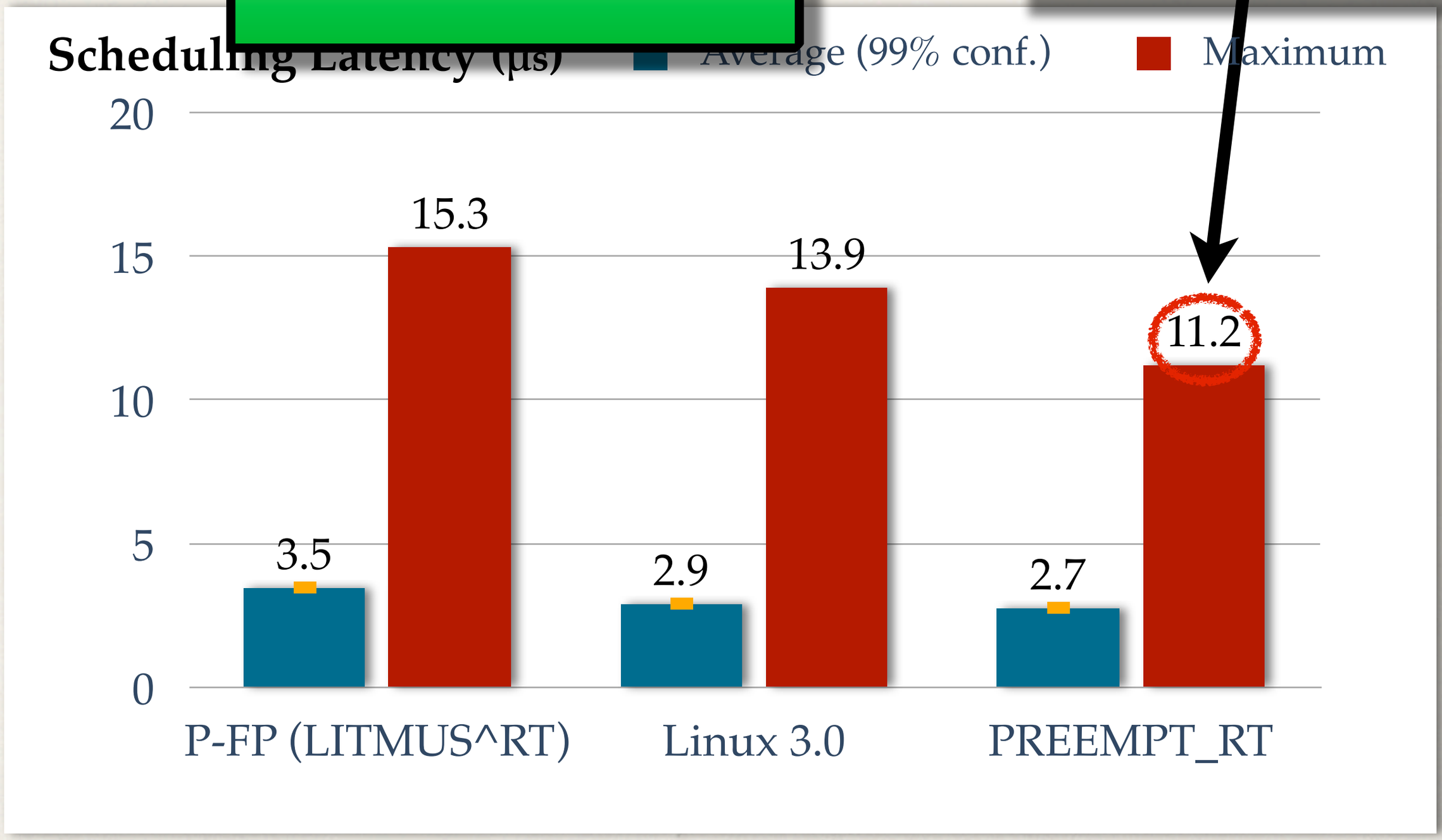
Similar max. and avg. latency for Linux 3.0 and LITMUS^{RT}.

Improved max. latency for PREEMPT_RT



Second Scenario

CPU-bound background tasks

- Tasks running an infinite loop accessing memory (read/write)
- Working set larger than L2 cache size

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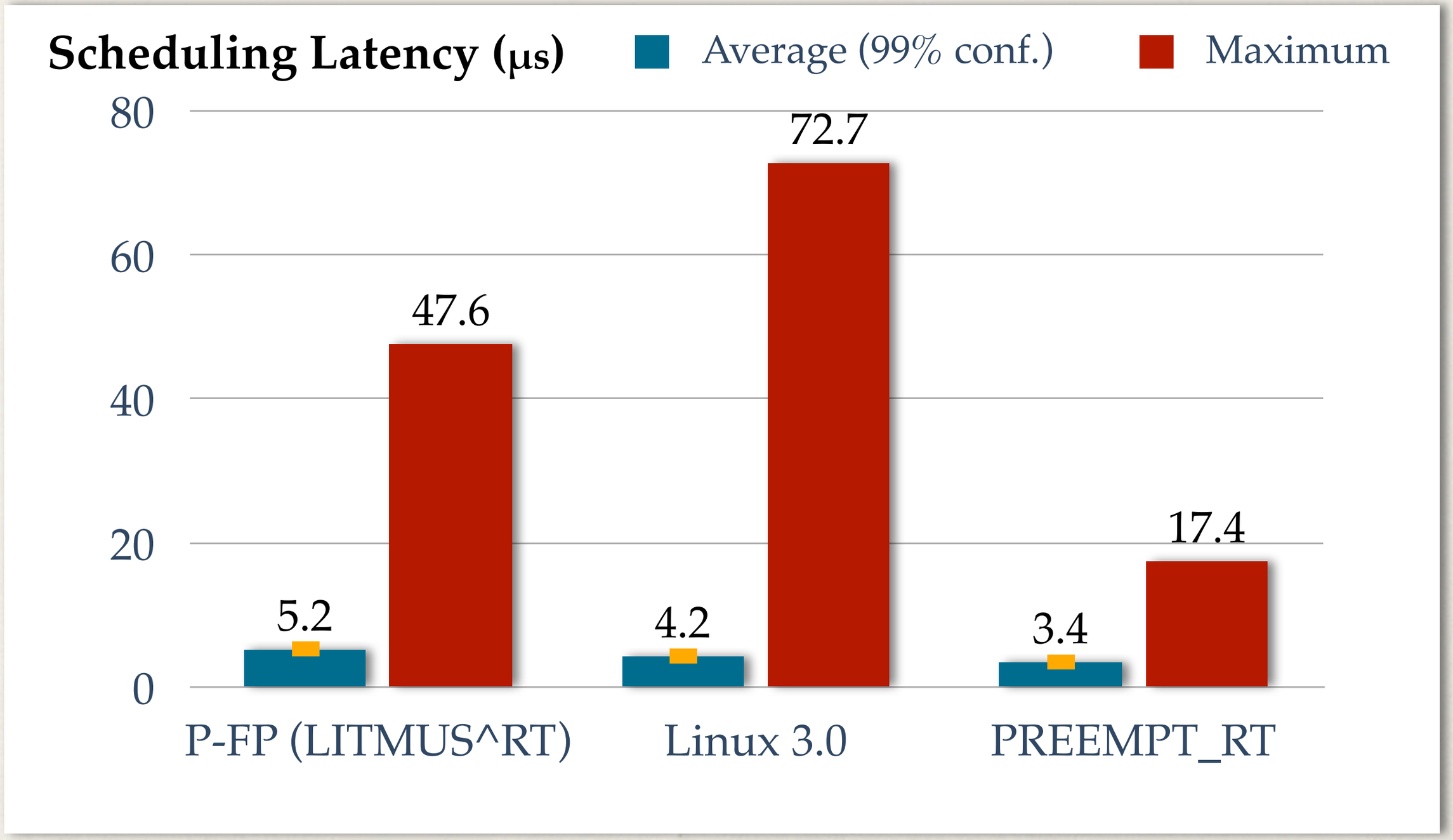
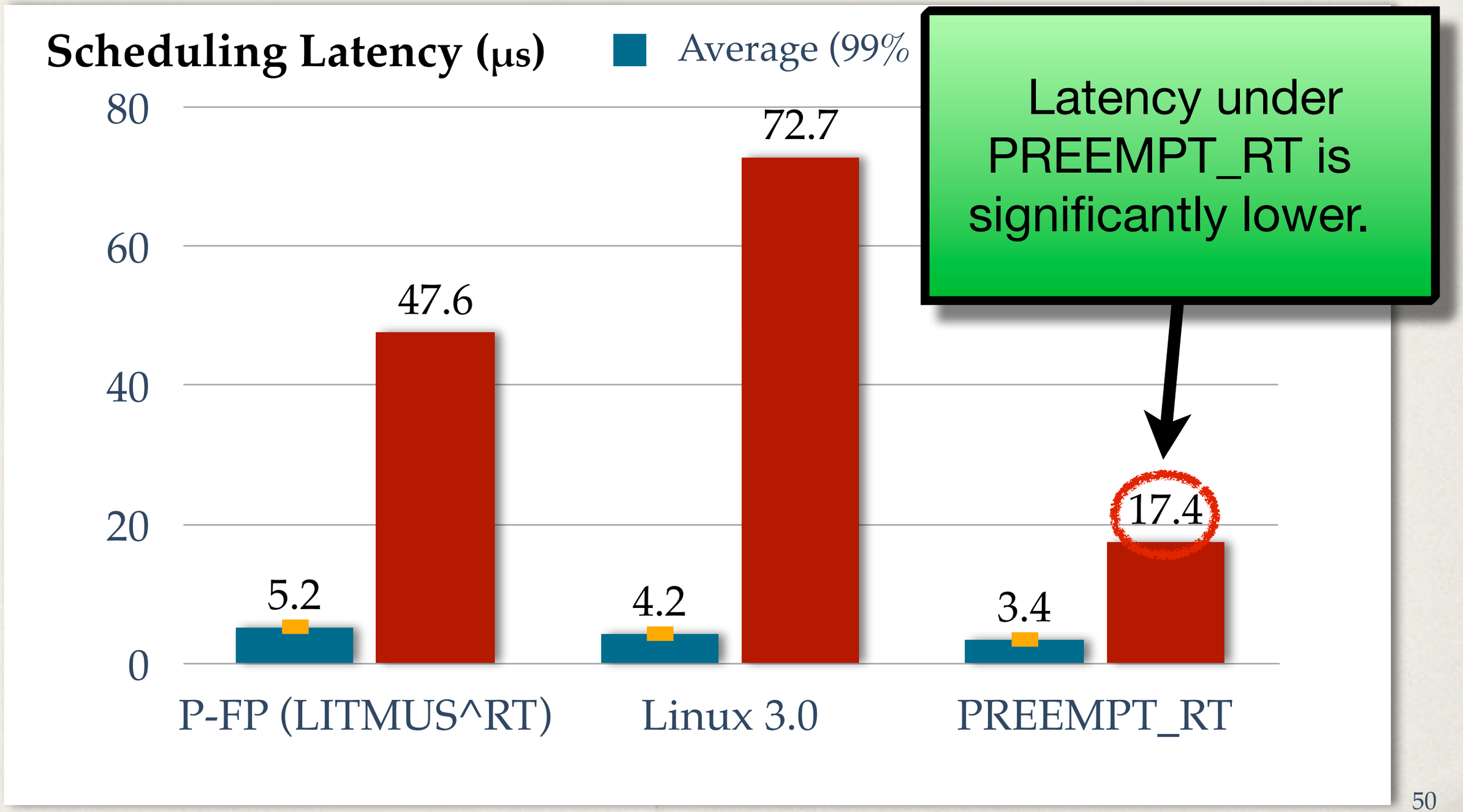
→ Generates memory traffic and cache contention!

CPU-bound Background Tasks

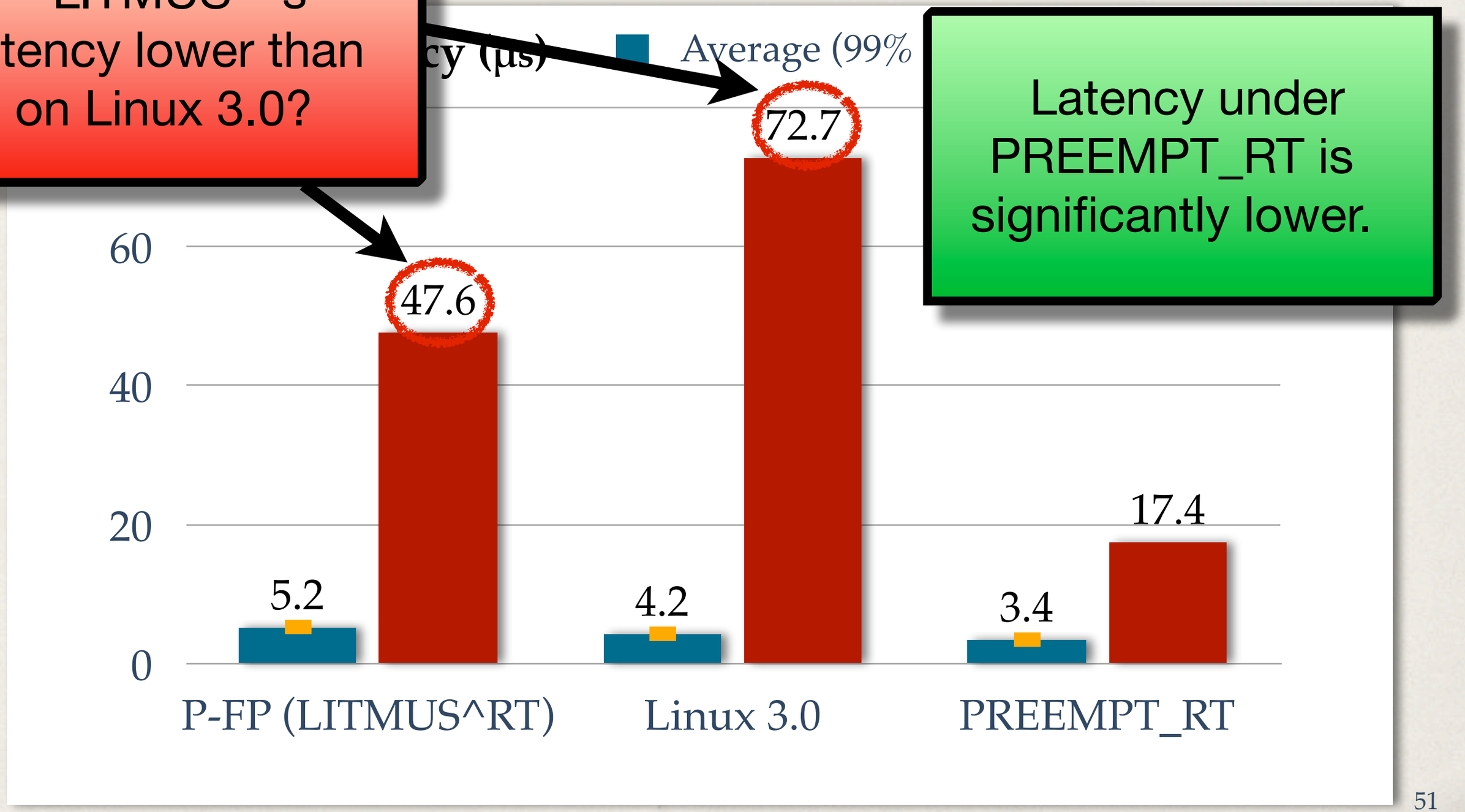


CPU-bound Background Tasks



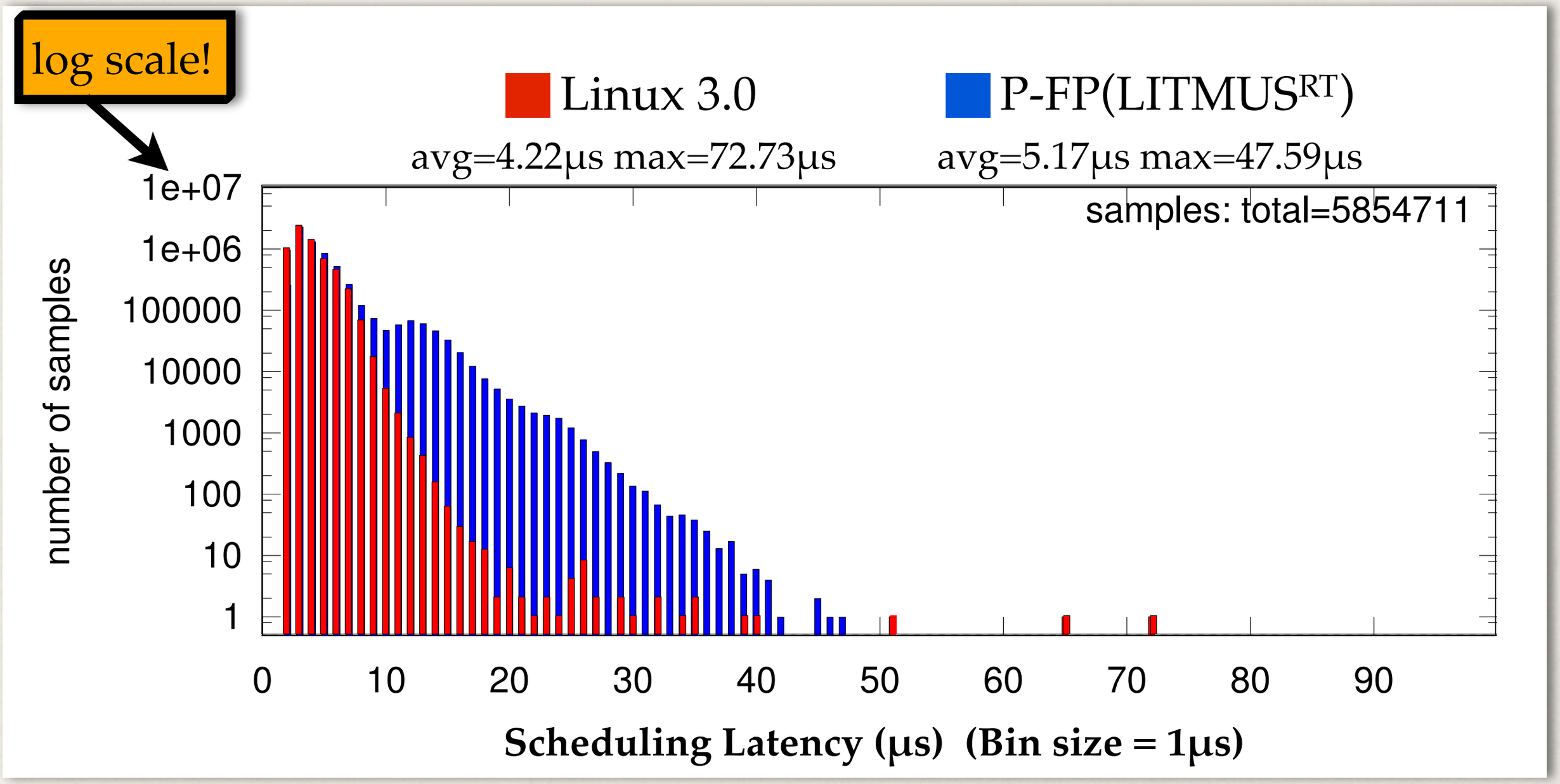
CPU-bound Background Tasks

LITMUS^{RT}'s latency lower than on Linux 3.0?



Latency under PREEMPT_RT is significantly lower.

LITMUS^{RT} vs. Linux 3.0: CPU-bound Background Tasks



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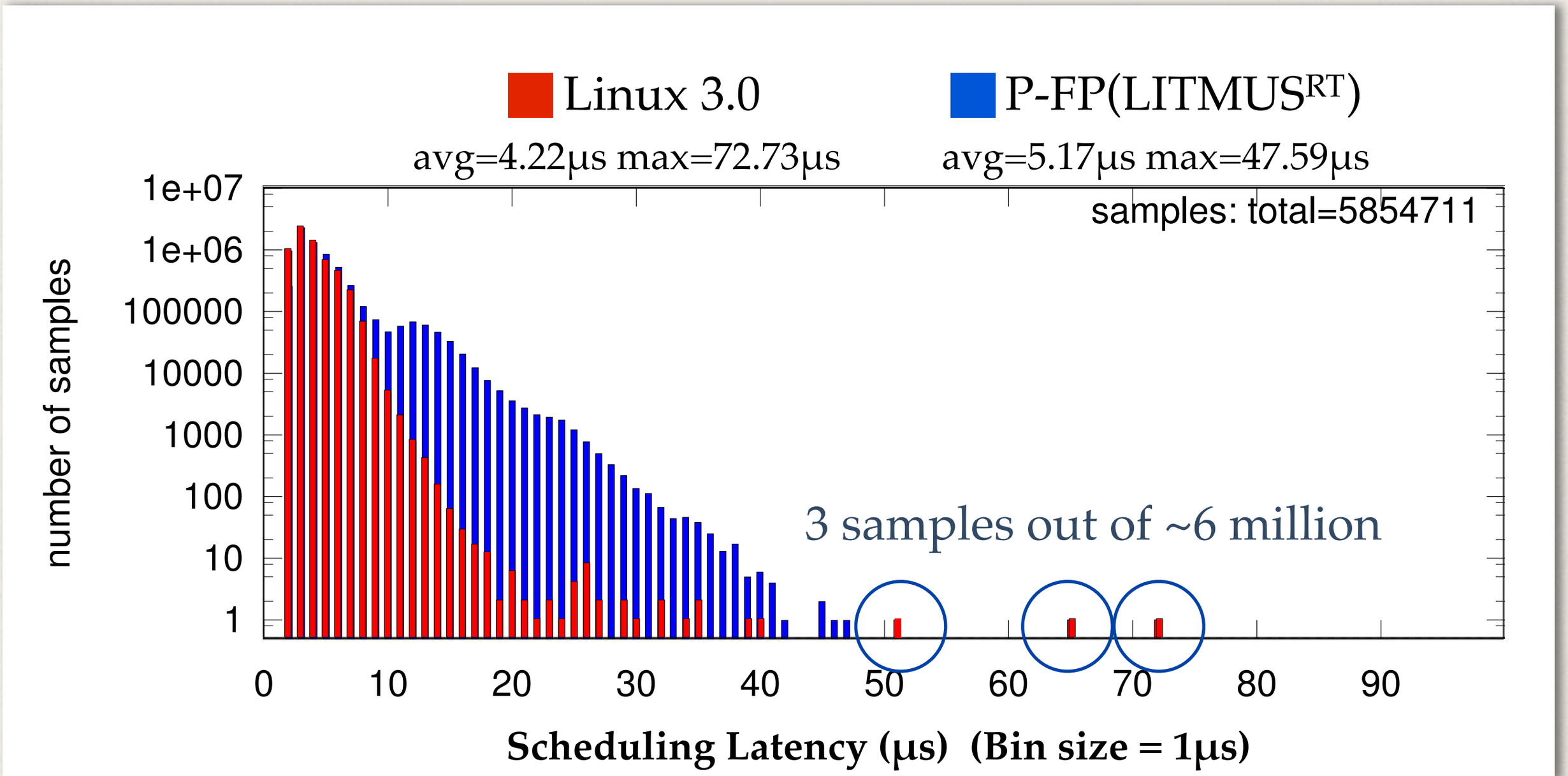
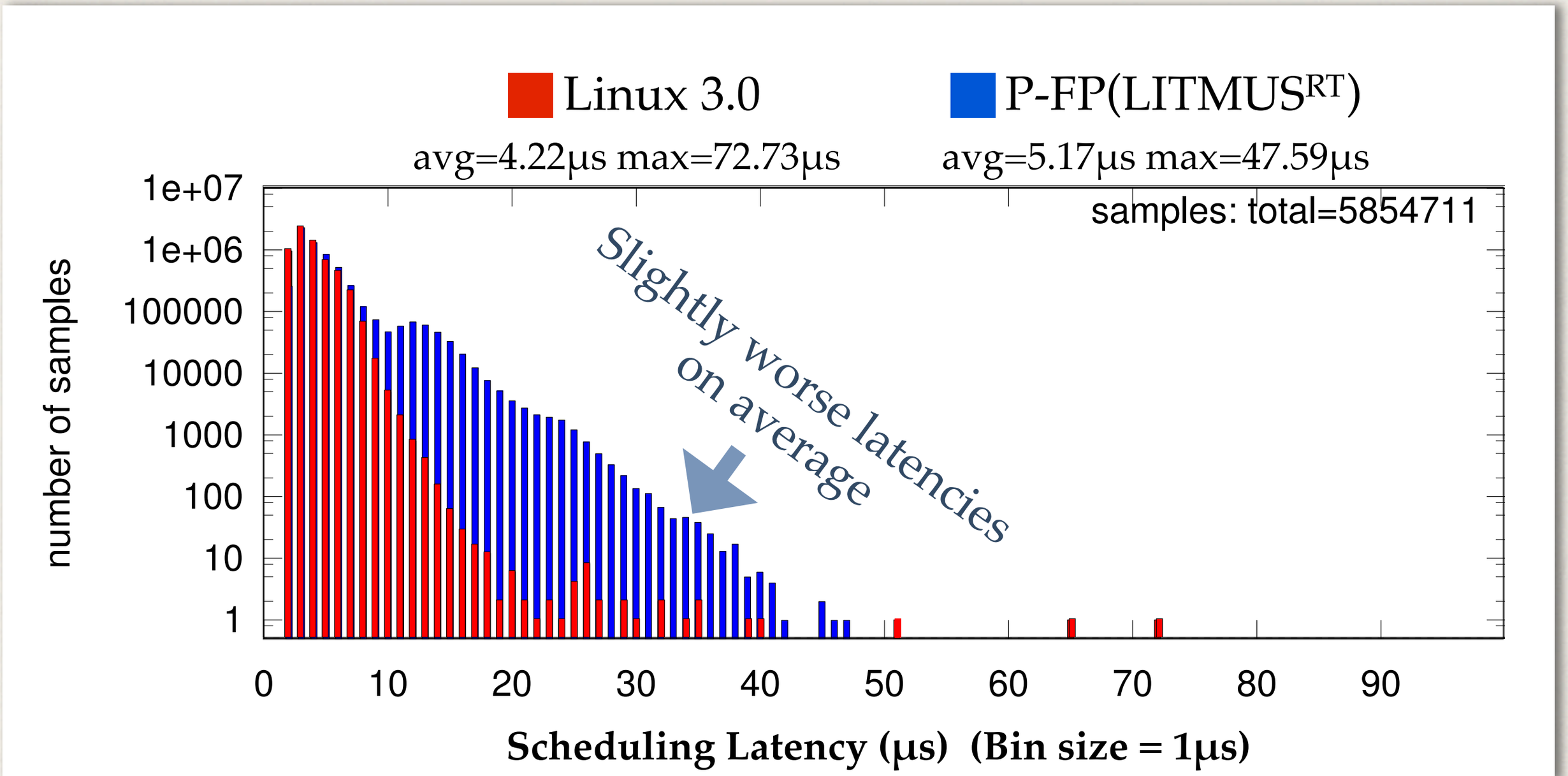
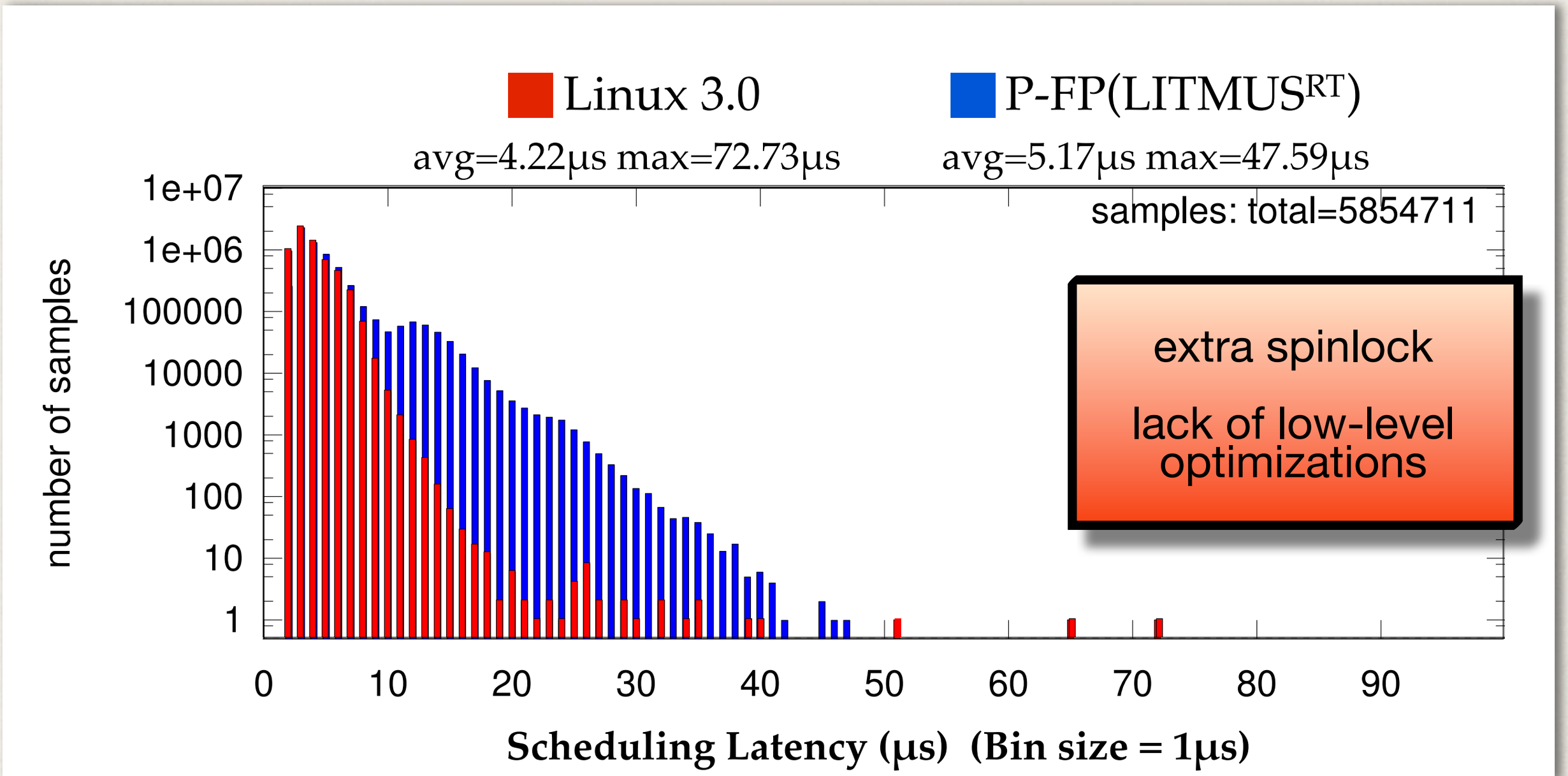


LITMUS^{RT} vs. Linux 3.0: CPU-bound Background Tasks



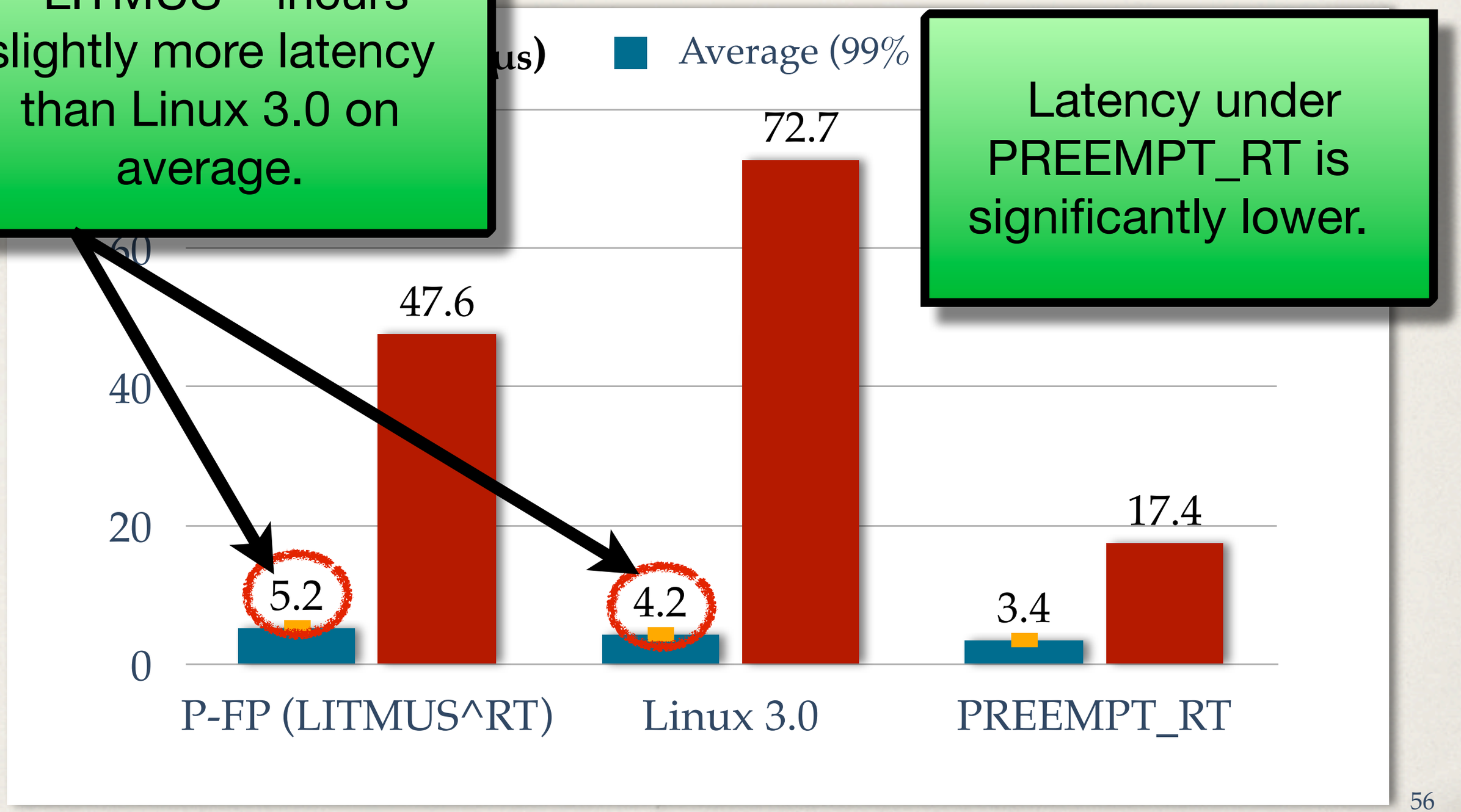
LITMUS^{RT} vs. Linux 3.0: CPU-bound Background Tasks



CPU-bound Background Tasks

LITMUS^{RT} incurs slightly more latency than Linux 3.0 on average.

Latency under PREEMPT_RT is significantly lower.



Third Scenario

I/O-bound background tasks

- **hackbench:** Linux scheduler stress tool
  bonnie++: Disk and file system benchmark
  wget: Network activity

Third Scenario

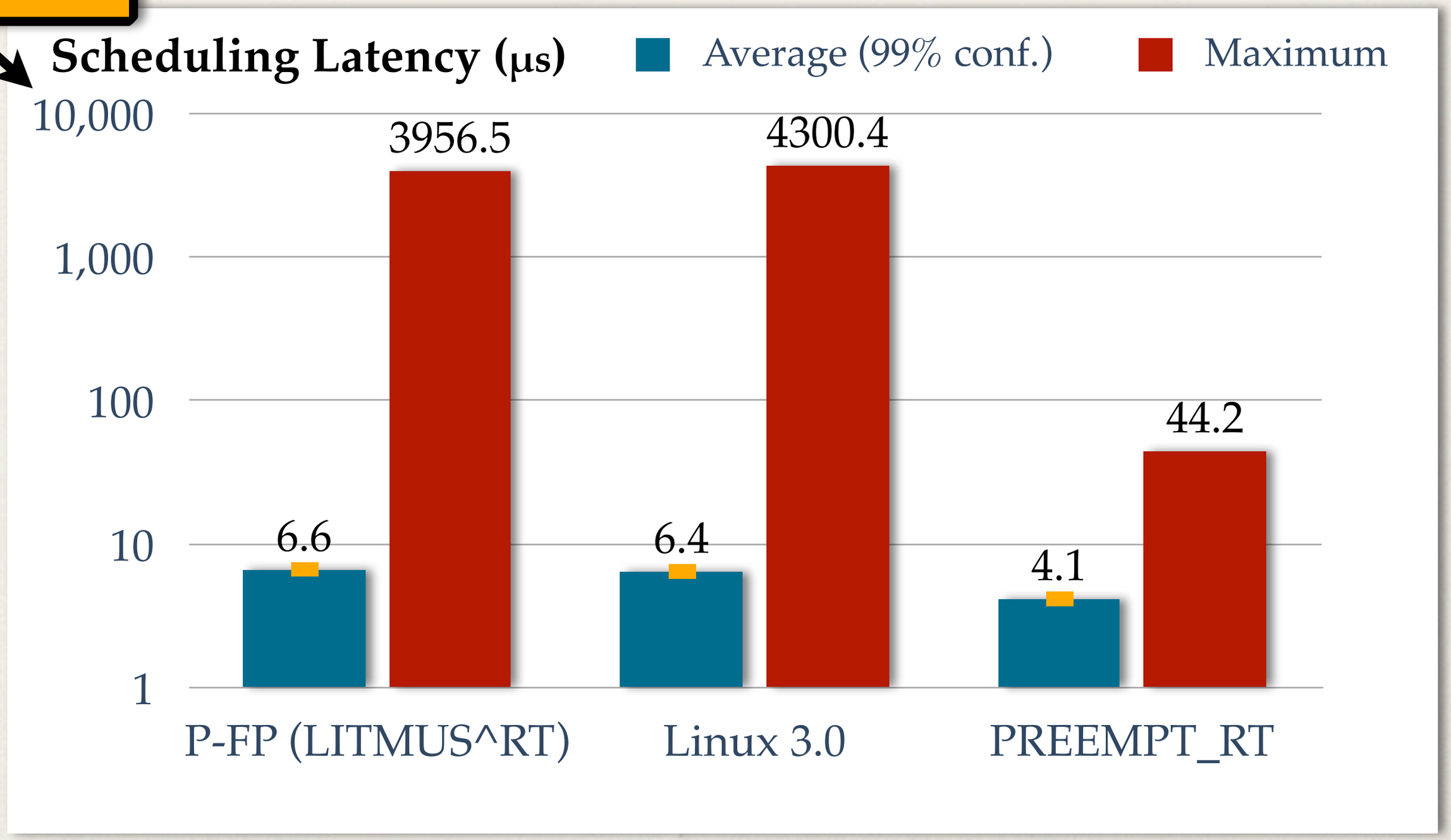
I/O-bound background tasks

→ Causes a lot of system calls and interrupts

- **hackbench:** Linux scheduler stress tool
  bonnie++: Disk and file system benchmark
  wget: Network activity

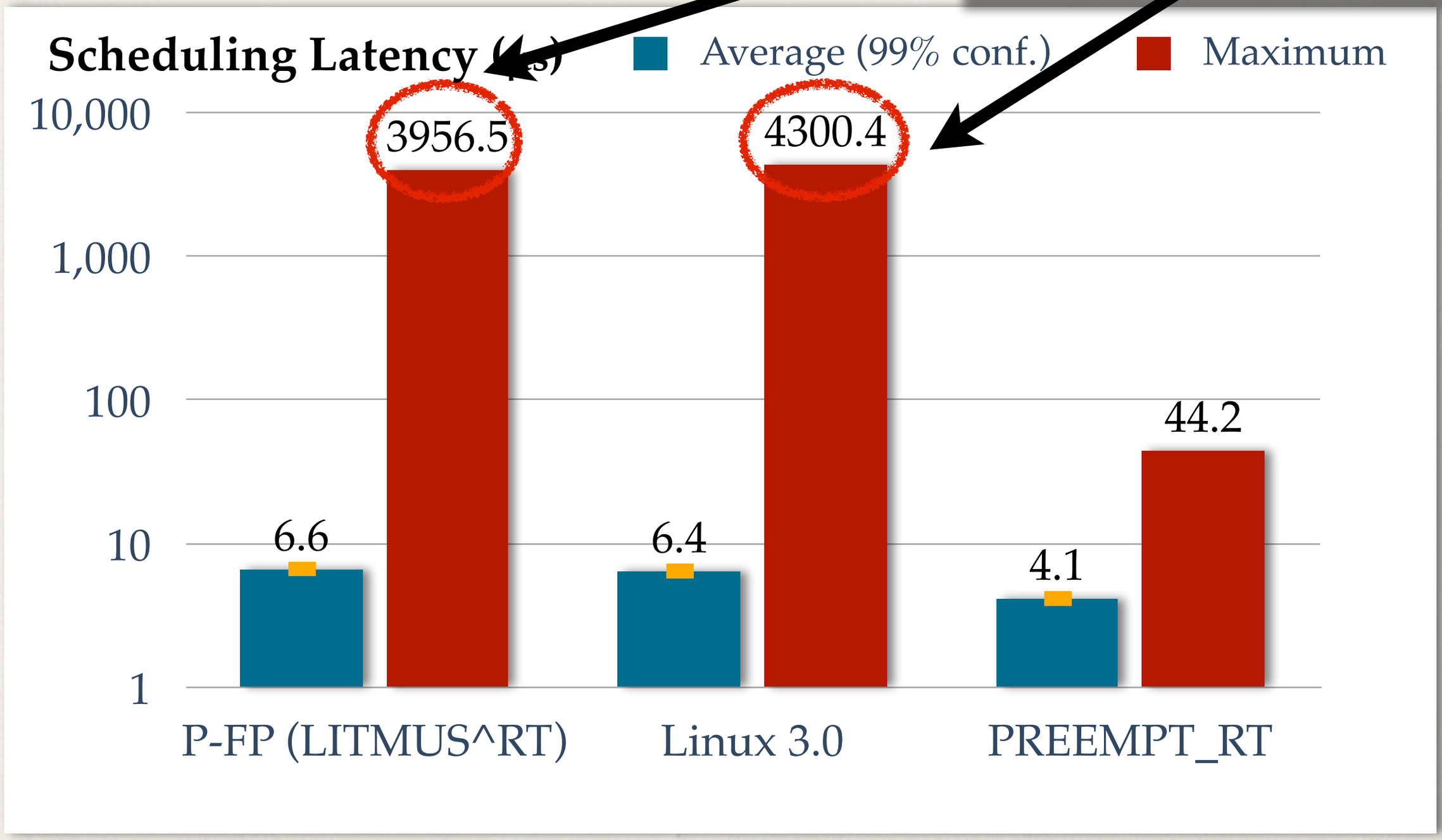
I/O-bound Background Tasks

log scale!



I/O-bound Backgrou

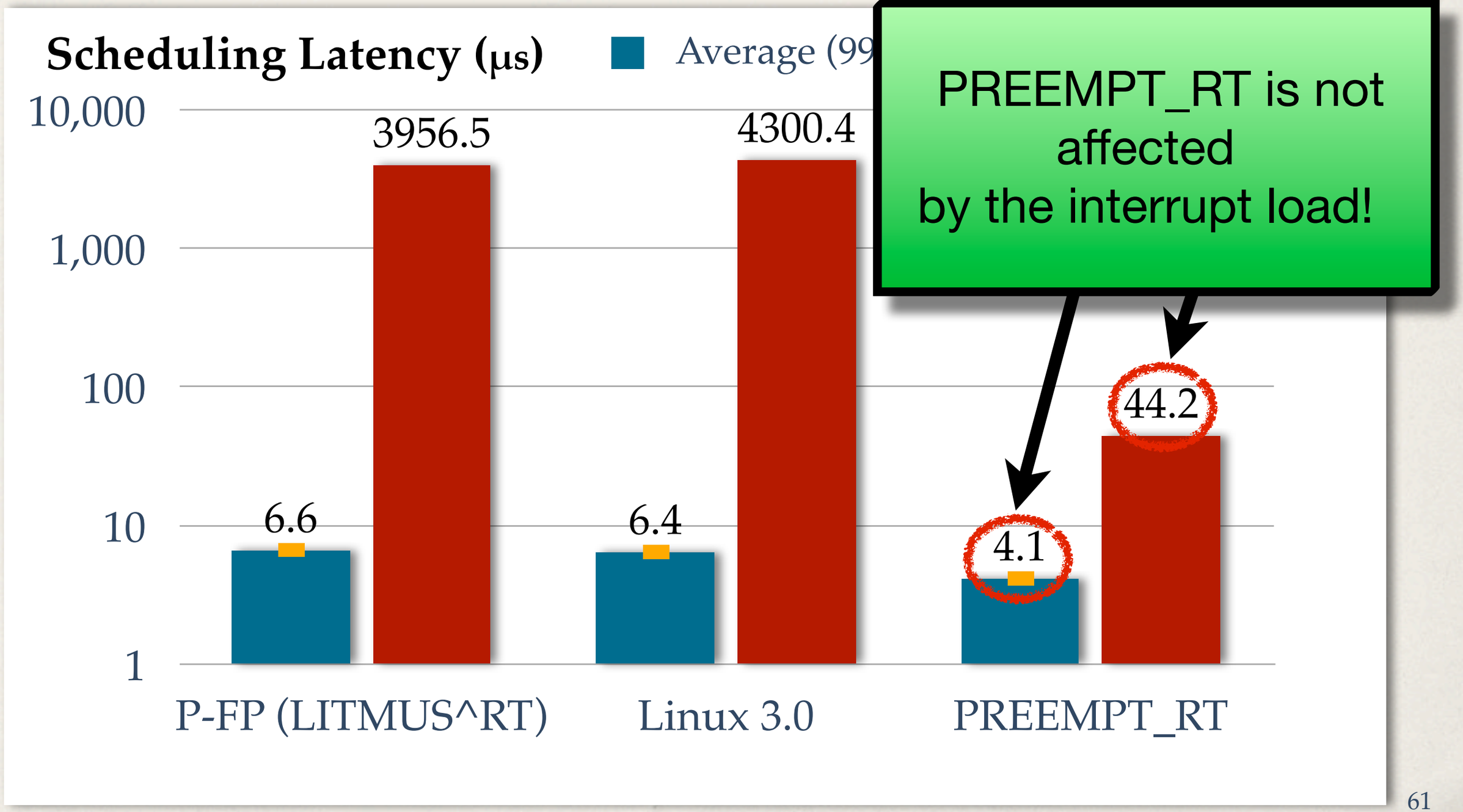
Huge impact on scheduling latency under standard Linux.



I/O-bound Backgrou

Huge impact on scheduling latency under standard Linux.

PREEMPT_RT is not affected by the interrupt load!



Summary

1. Cost of the scheduling plugin layer

2. LITMUS^{RT} vs. PREEMPT_RT

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The overhead introduced by LITMUS^{RT} is **small** ✓

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The overhead introduced by LITMUS^{RT} is **small** ✓

2. LITMUS^{RT} vs. PREEMPT_RT

PREEMPT_RT **significantly** decreases scheduling latency. ✓

Importance of Feather-Trace

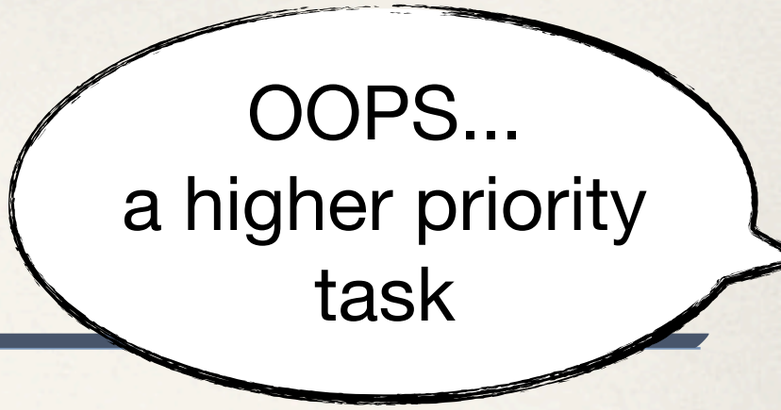
- cyclictest was ported to LITMUS^{RT}.
- Should it become the standard tool for evaluating LITMUS^{RT}?

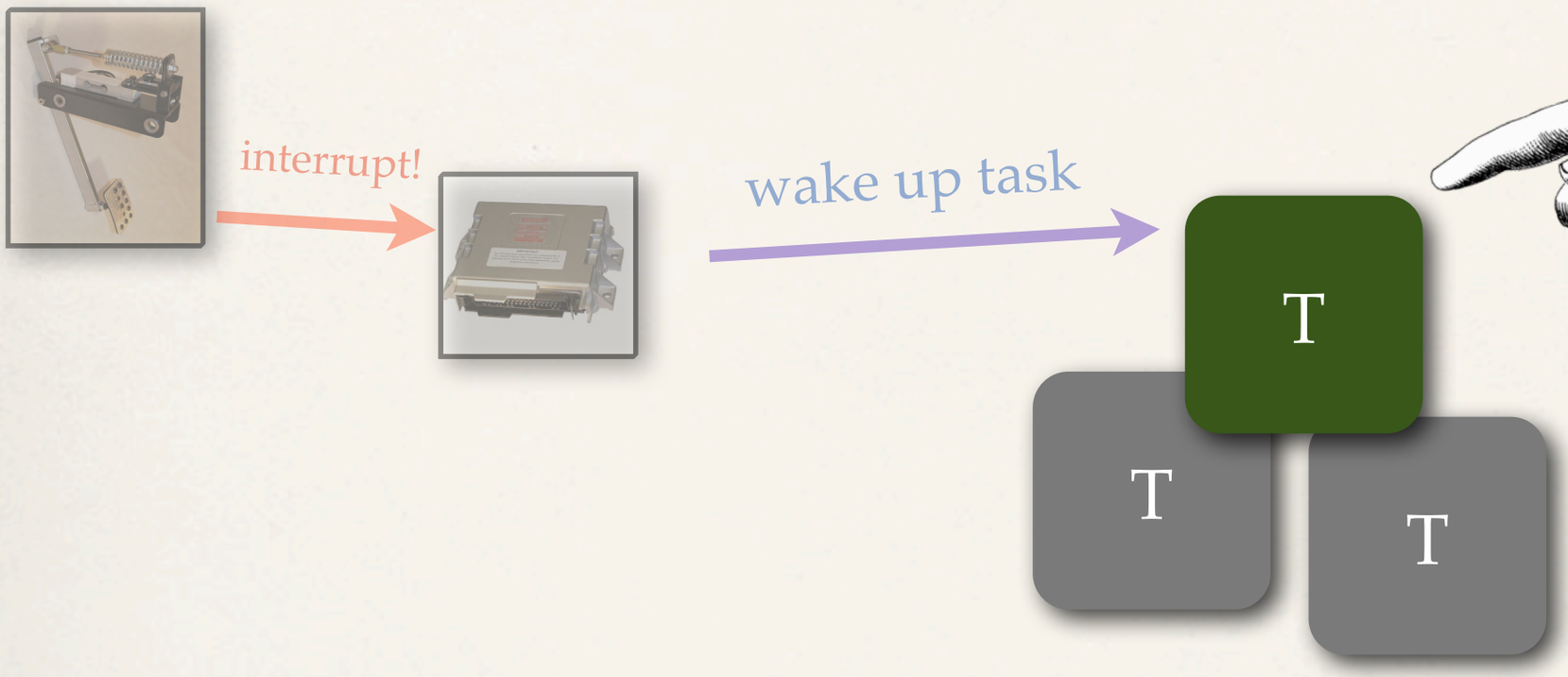
Importance of Feather-Trace

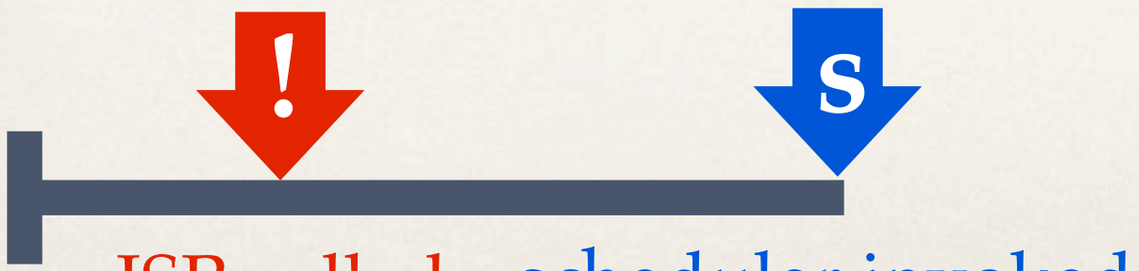
- cyclictest was ported to LITMUS^{RT}.
- Should it become the standard tool for evaluating LITMUS^{RT}?

NO!

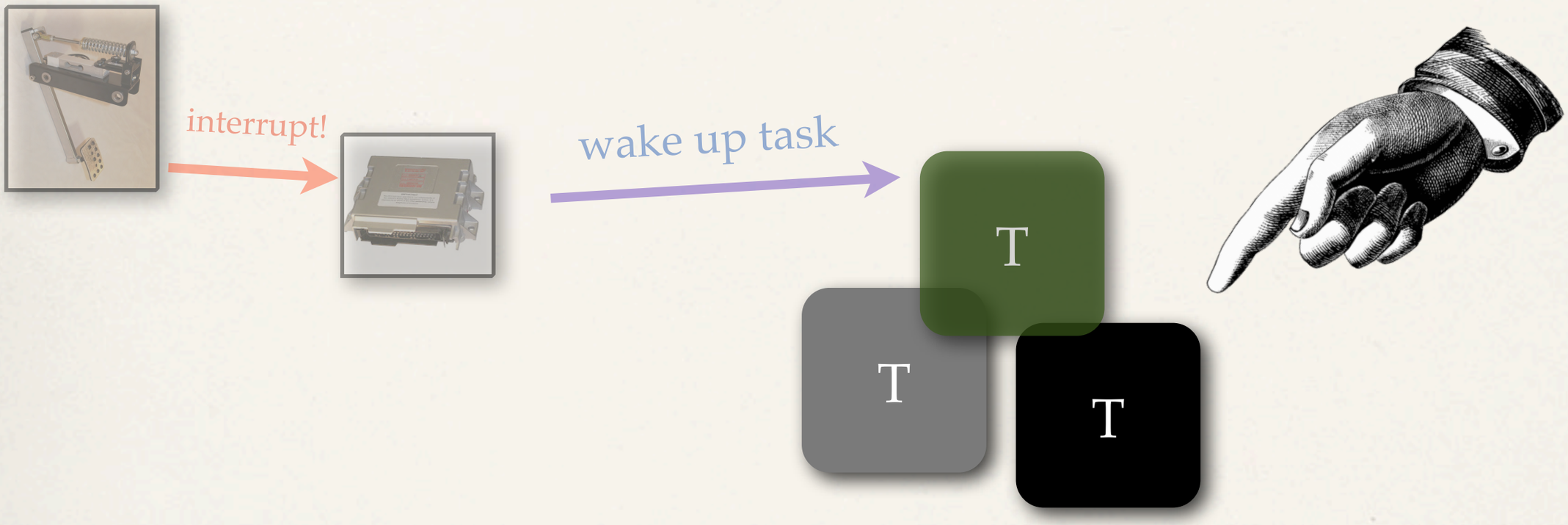
Interference?



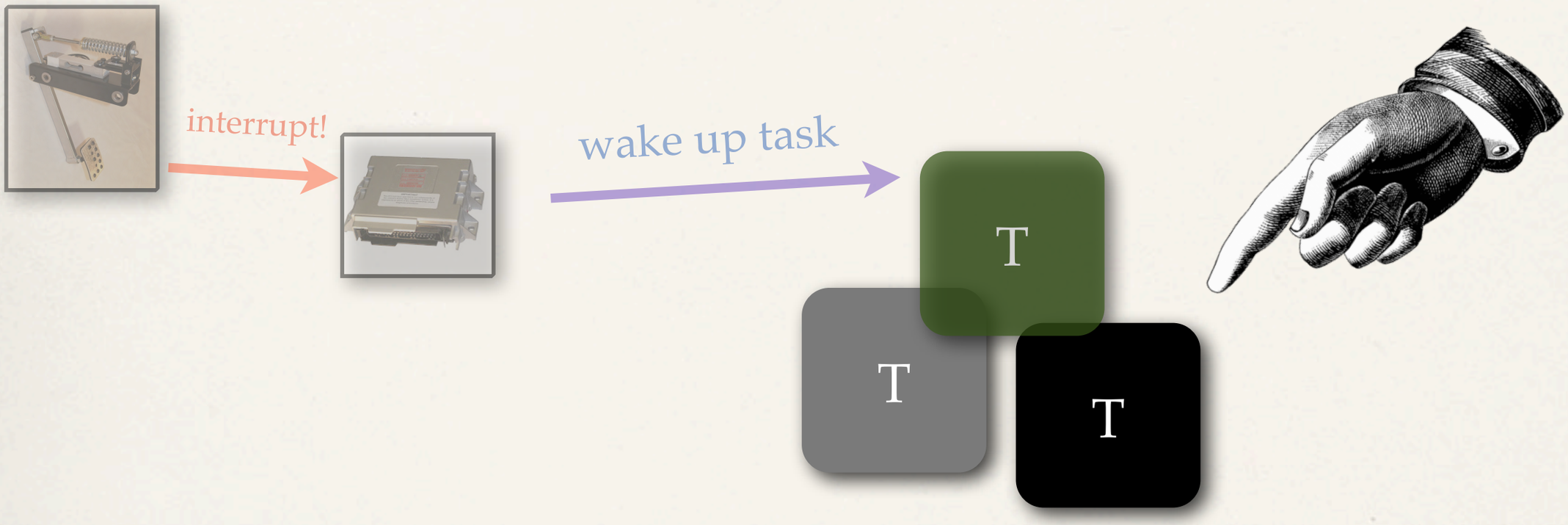


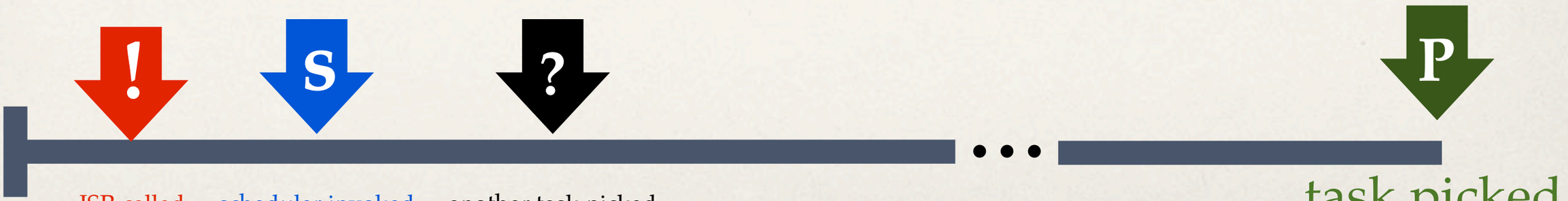


Interference?

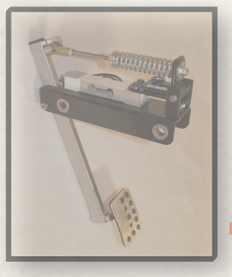


Interference?





Interference?



interrupt!

wake up task

T

T

This length of this interval depends on the execution of other tasks...

!

S

?

P

ISR called

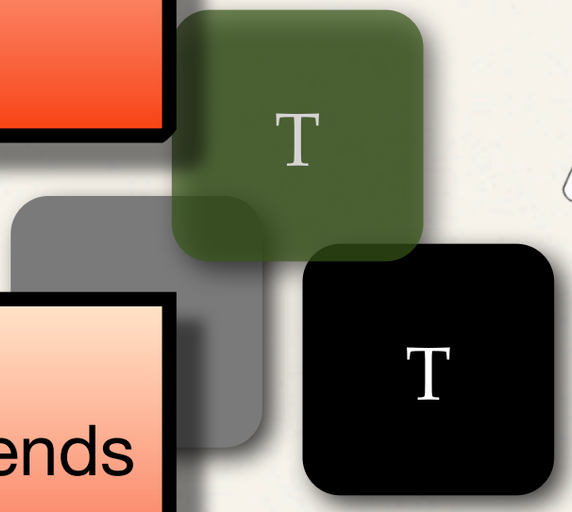
scheduler invoked

another task picked

task picked

Interference?

..., which depends on other kinds of overhead, preemptions, context switches, etc.



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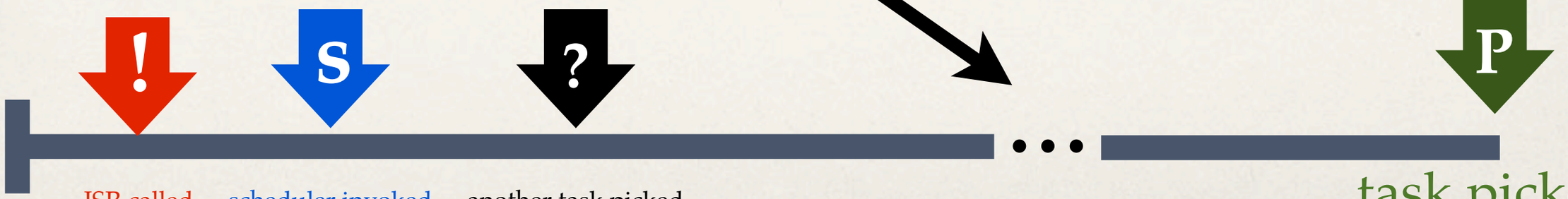


Interference?

..., which depends on other kinds of overhead, preemptions, context switches, etc.

This length of this interval depends on the execution of other tasks...

Overhead-aware schedulability analysis is required!

cyclictest or Feather-Trace?

BOTH!

cyclictest

Practical, easy-to-understand measure

Can easily compare responsiveness between kernels.

LITMUS^{RT}/Feather-Trace

For tasks other than the highest-priority ones, schedulability analysis is necessary.

Only with Feather-Trace we obtain the data required for the analysis.

Conclusion

LITMUS^{RT}: small overheads in comparison with stock Linux

PREEMPT_RT is highly necessary for Linux as a RTOS

LITMUS^{RT} will be ported to PREEMPT_RT soon

Scheduling latency should not be used as the sole metric for quantifying real-time guarantees

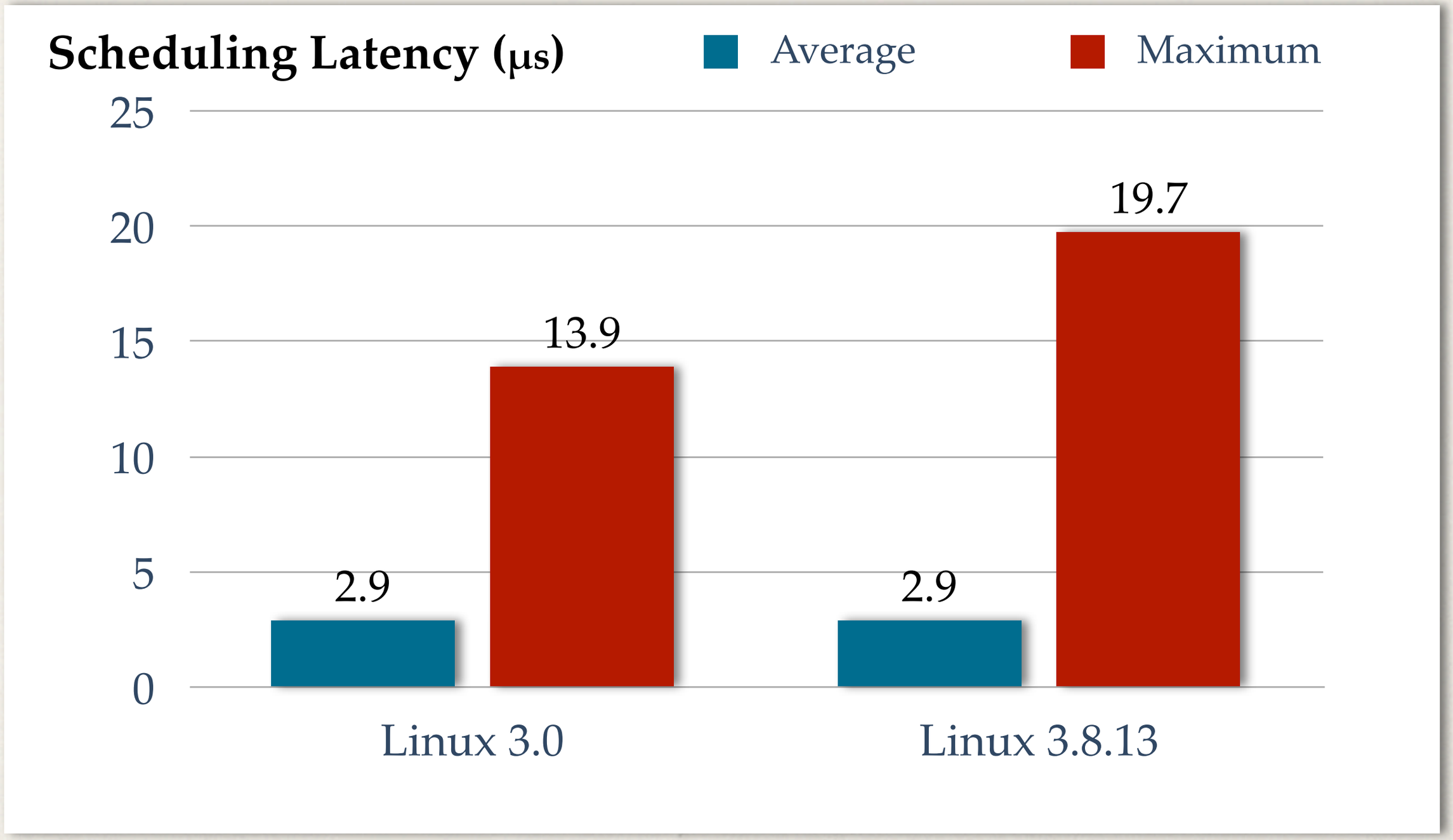
Thank You!

We also have a patch that implements Feather-Trace on top of standard Linux, enabling fine-grained measurements.

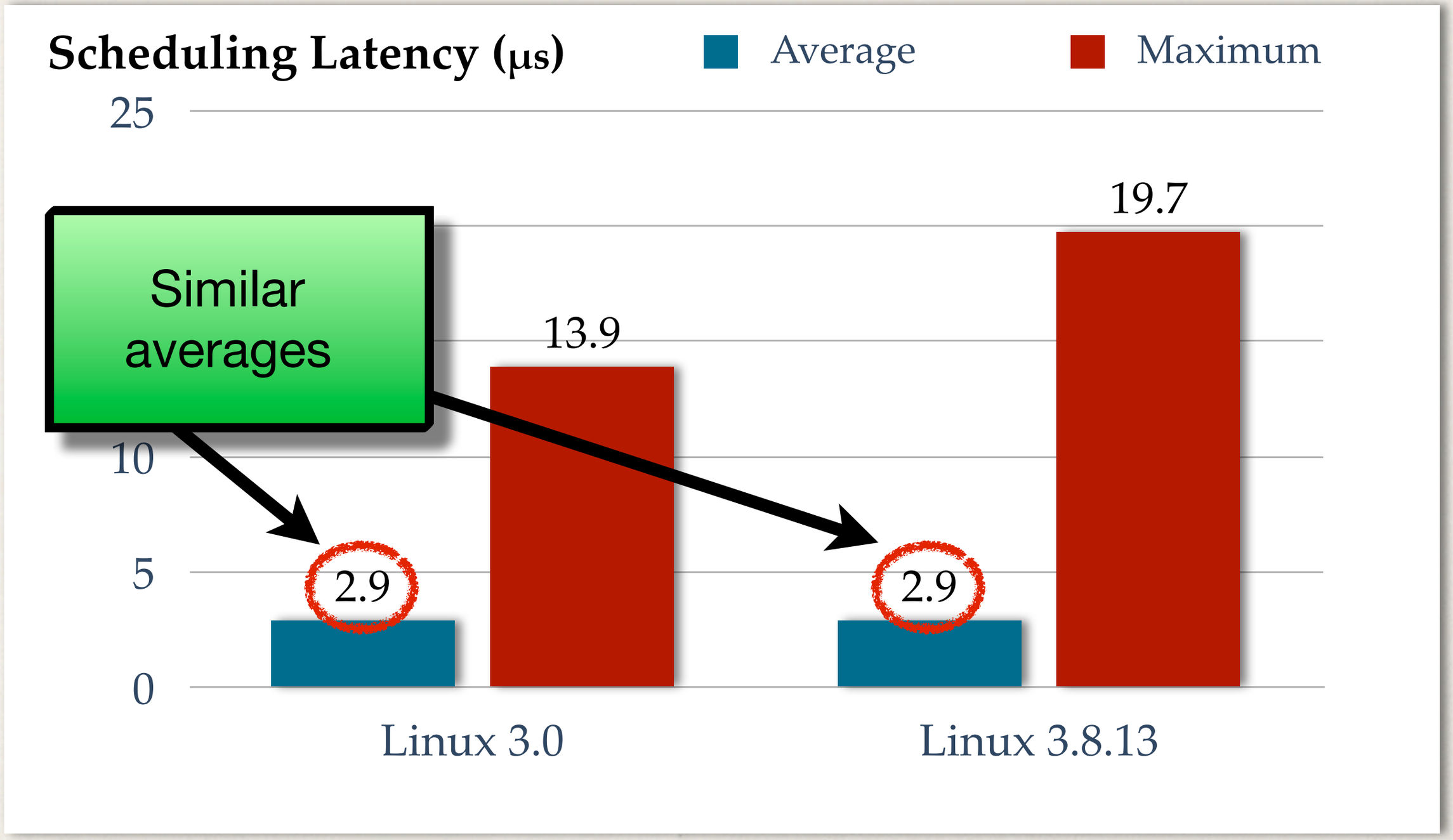
Appendix

Linux 3.0 vs. Linux 3.8.13

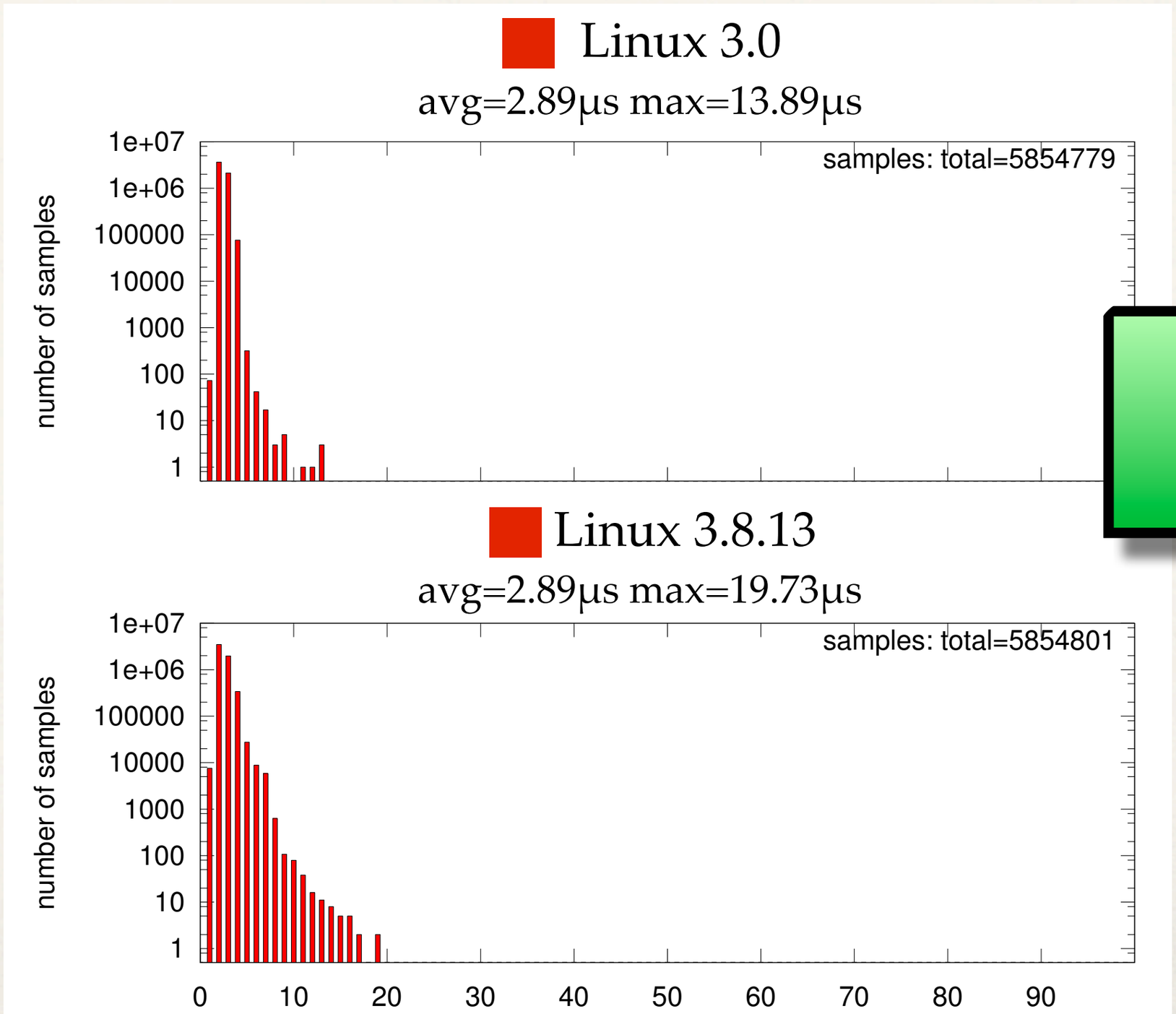
No Background Tasks



No Background Tasks

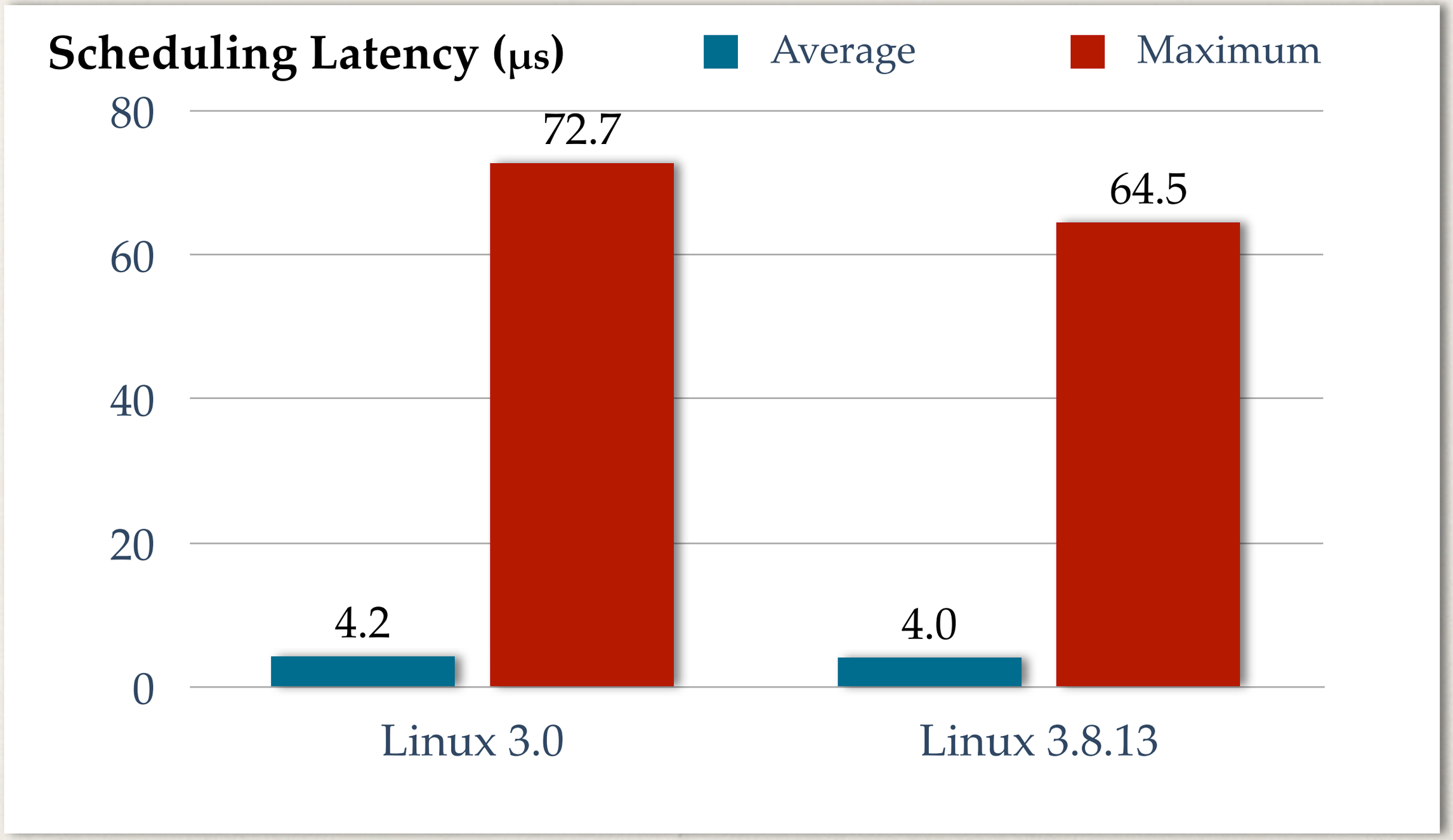


No Background Tasks

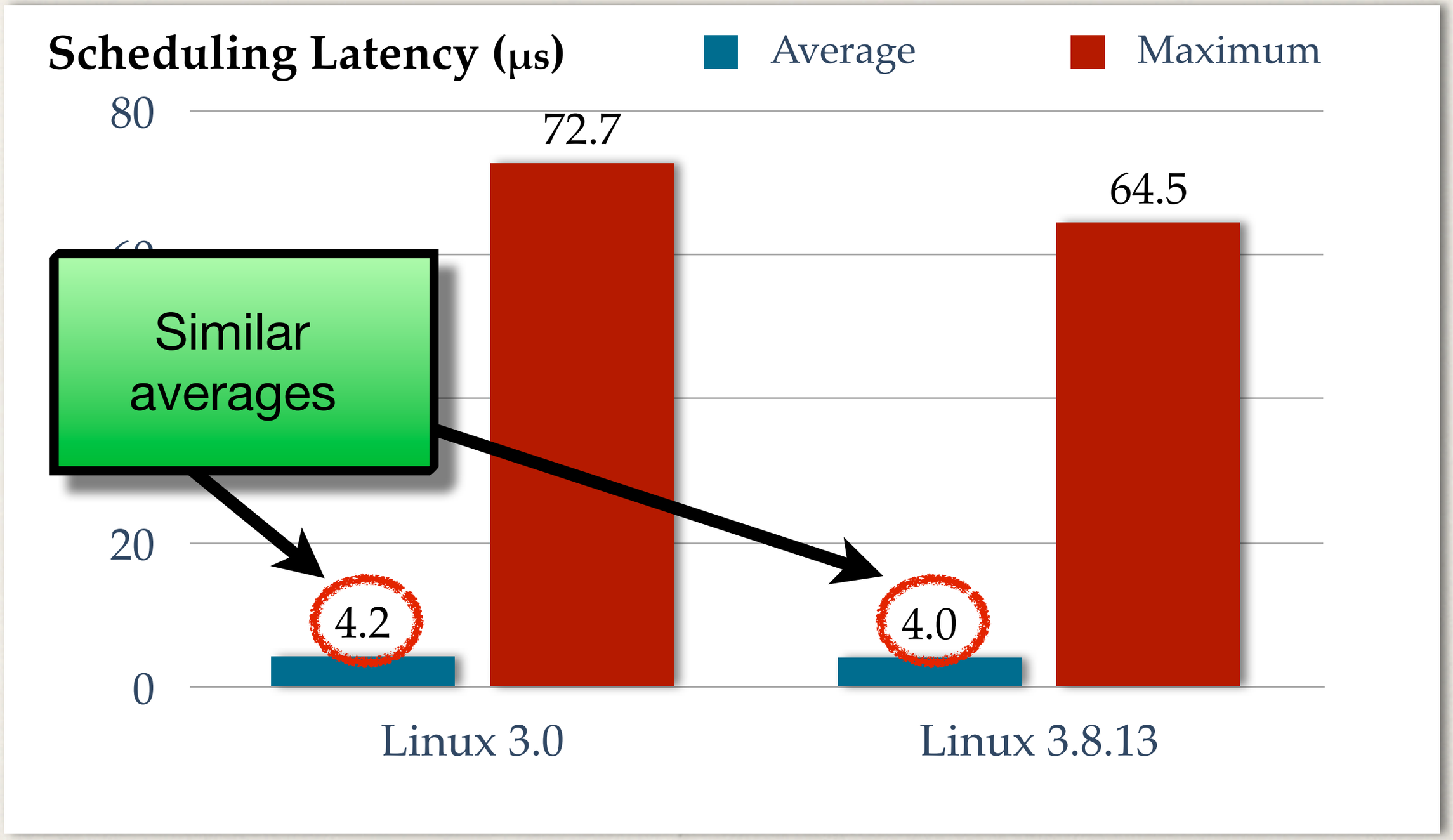


Similar shapes

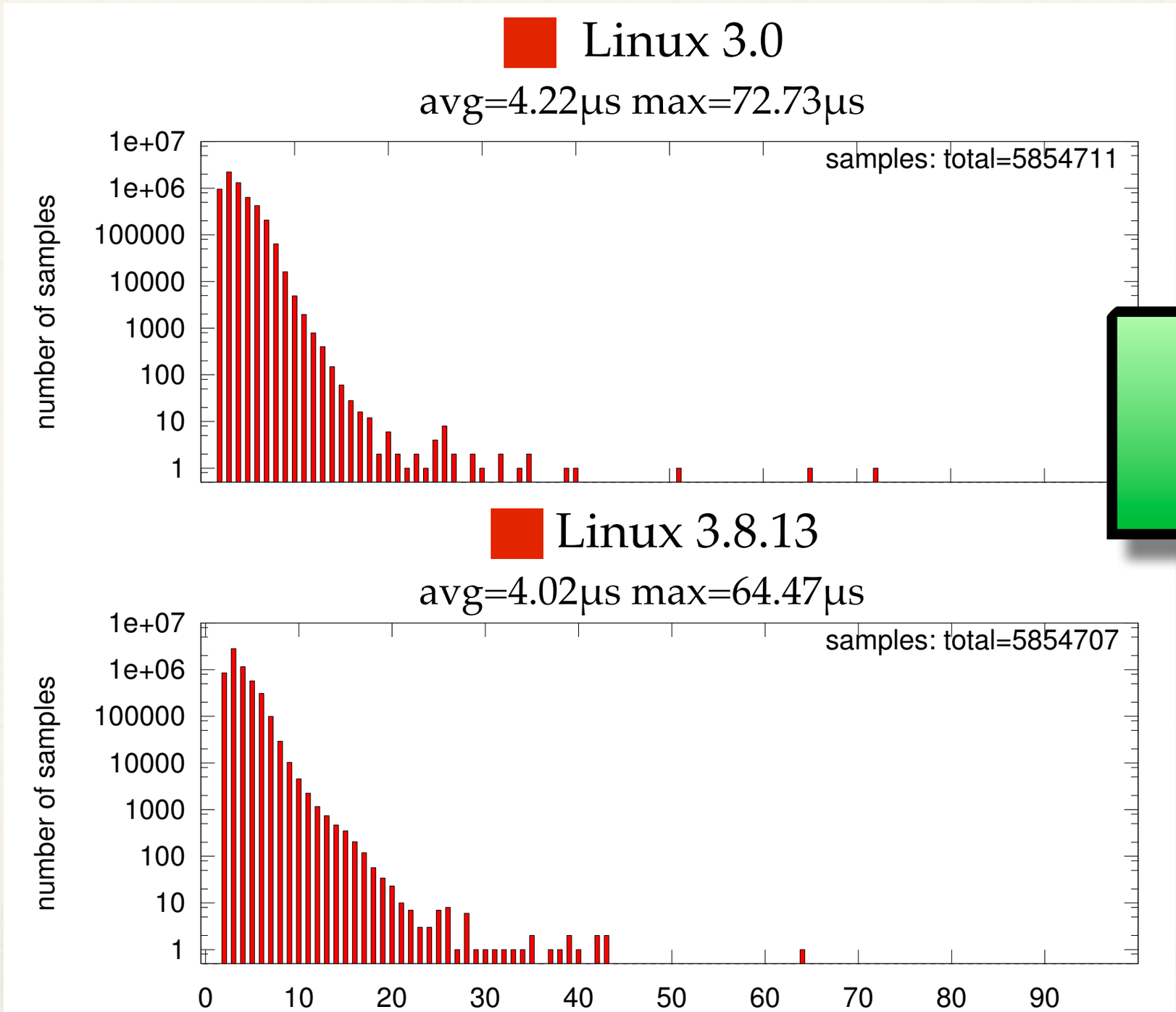
CPU-bound Background Tasks



CPU-bound Background Tasks



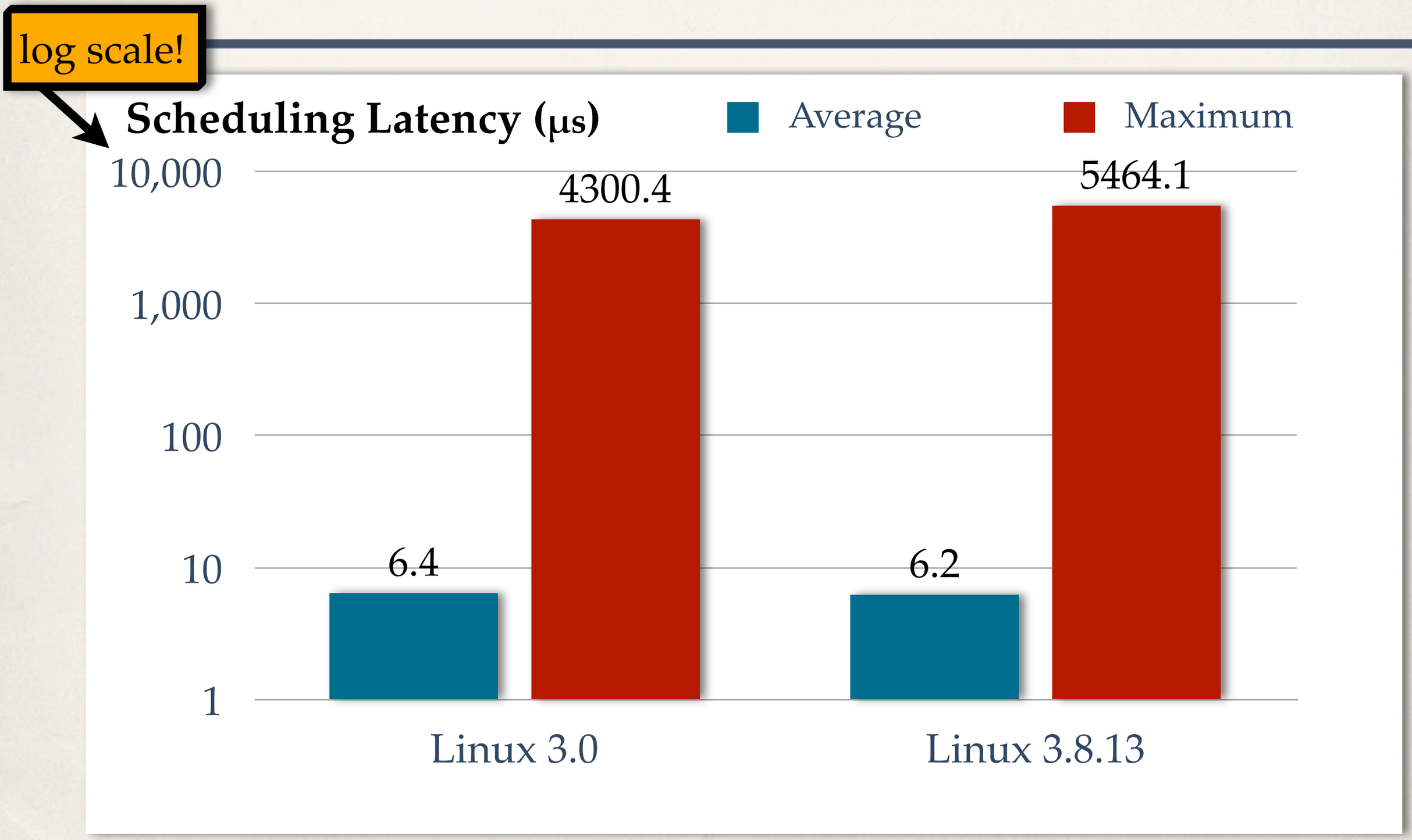
CPU-bound Background Tasks



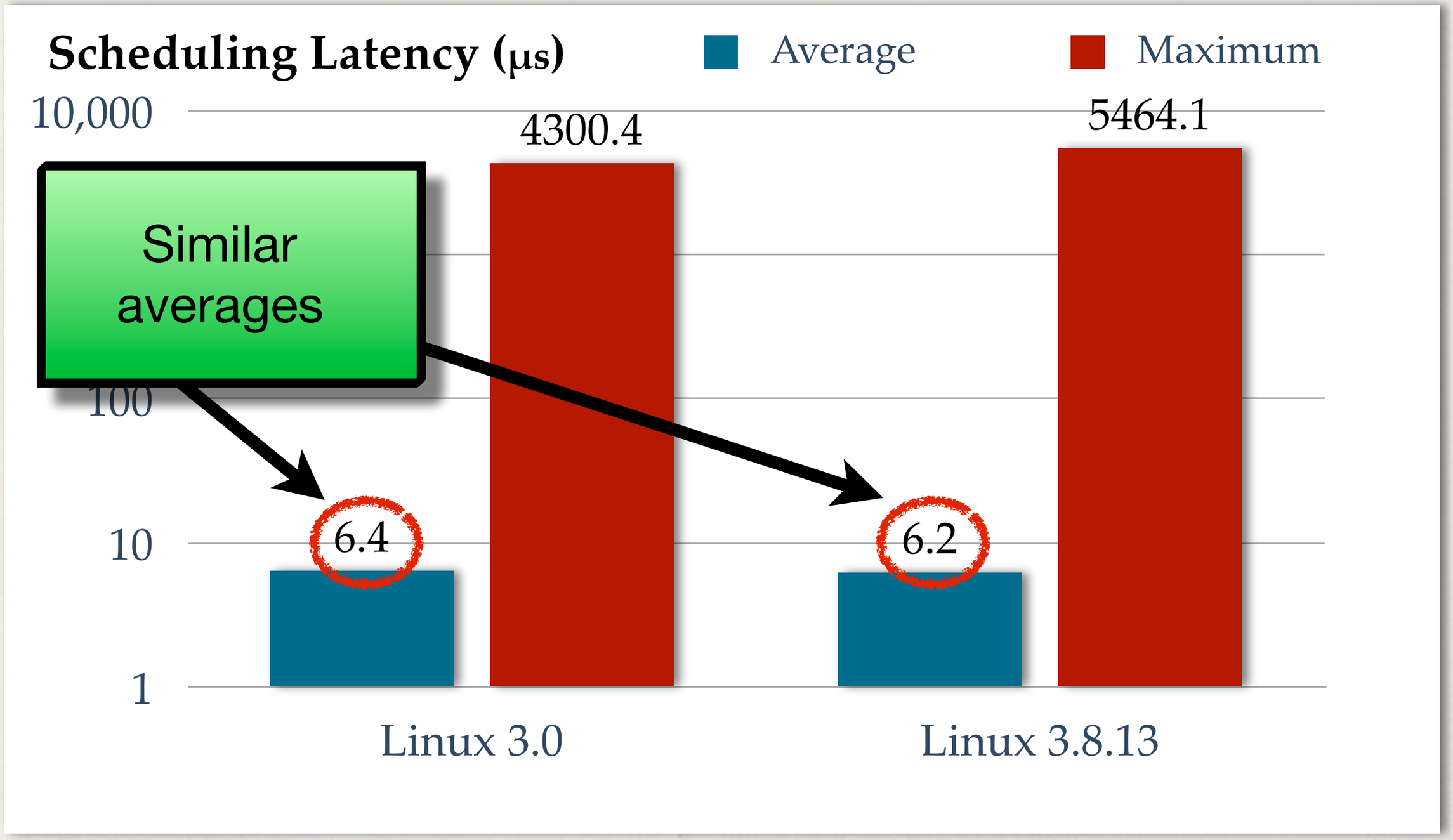
Similar shapes

I/O-bound Background Tasks

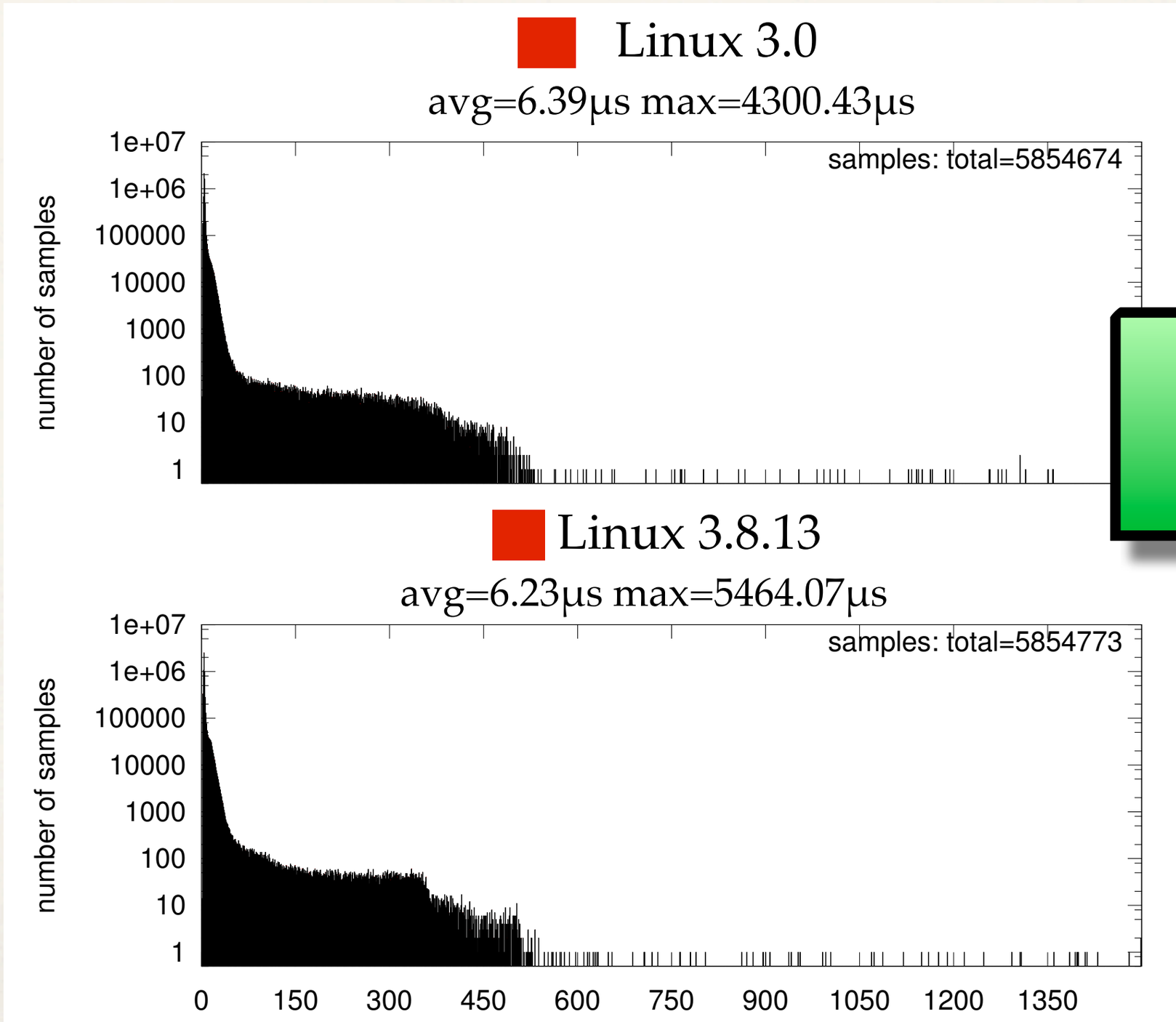
log scale!



I/O-bound Background Tasks



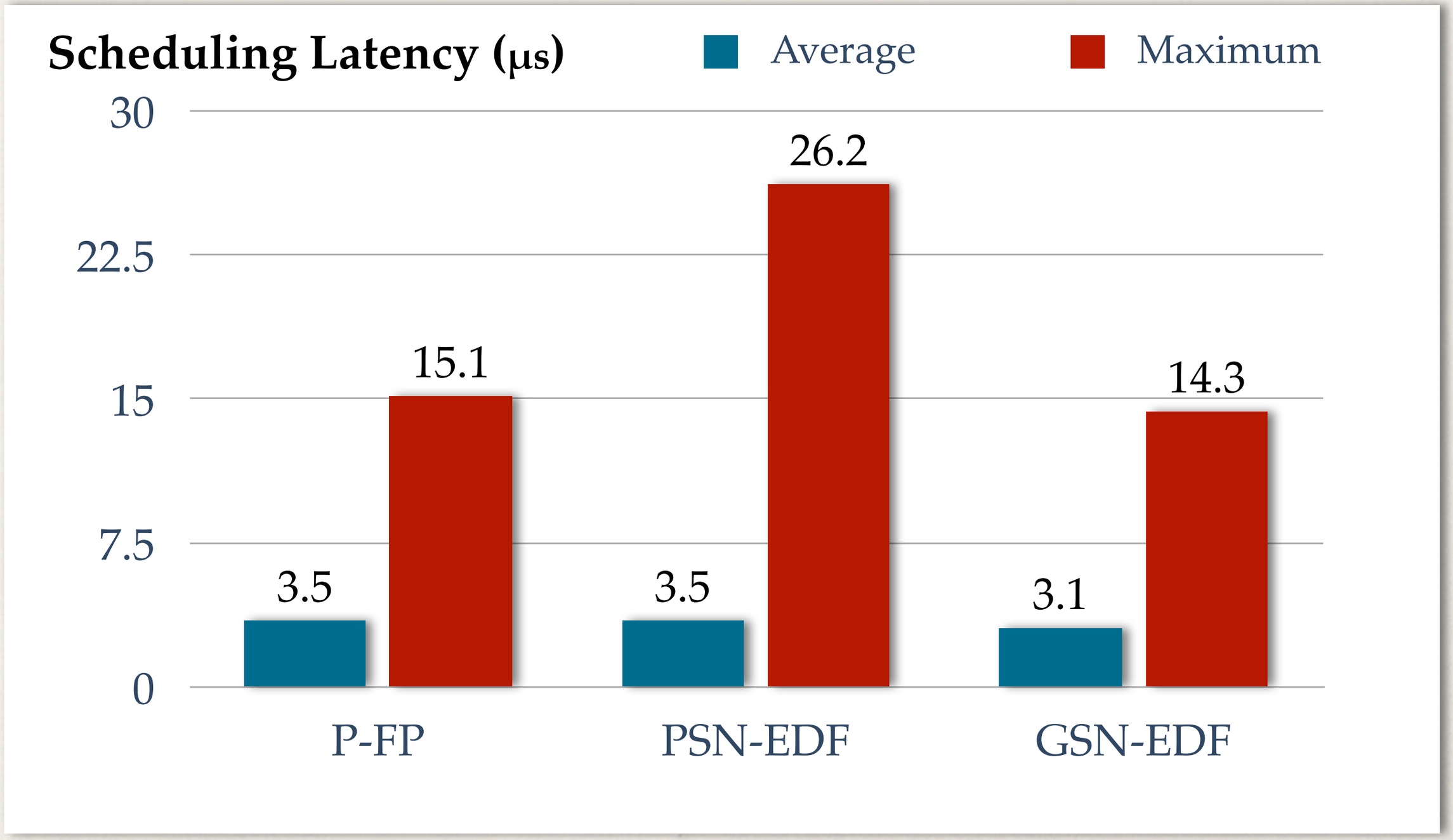
I/O-bound Background Tasks



Similar shapes

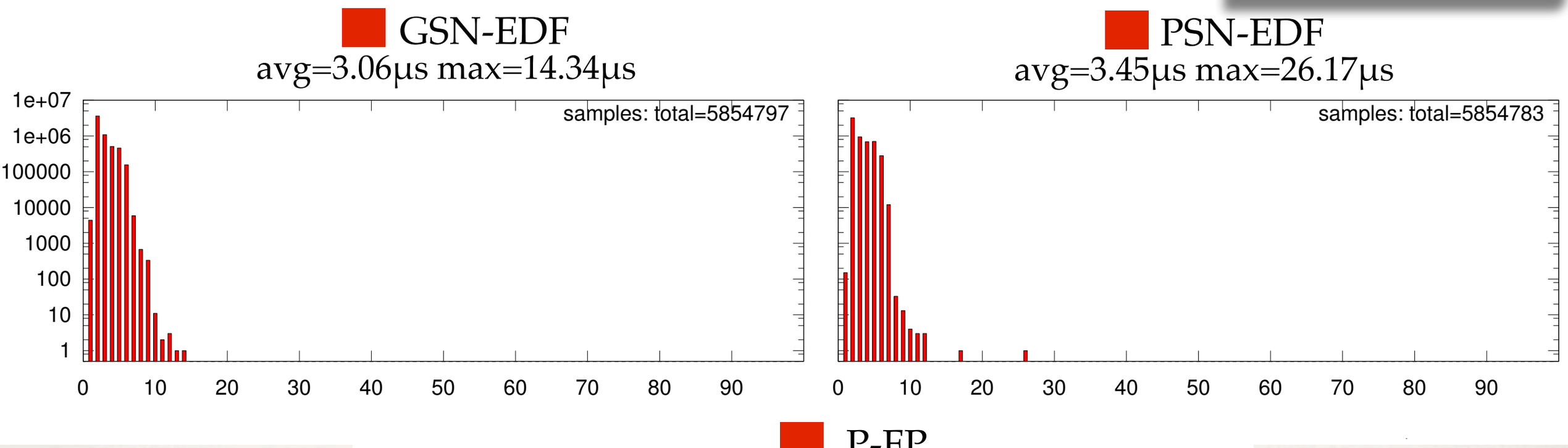
LITMUS^{RT}'s plugins

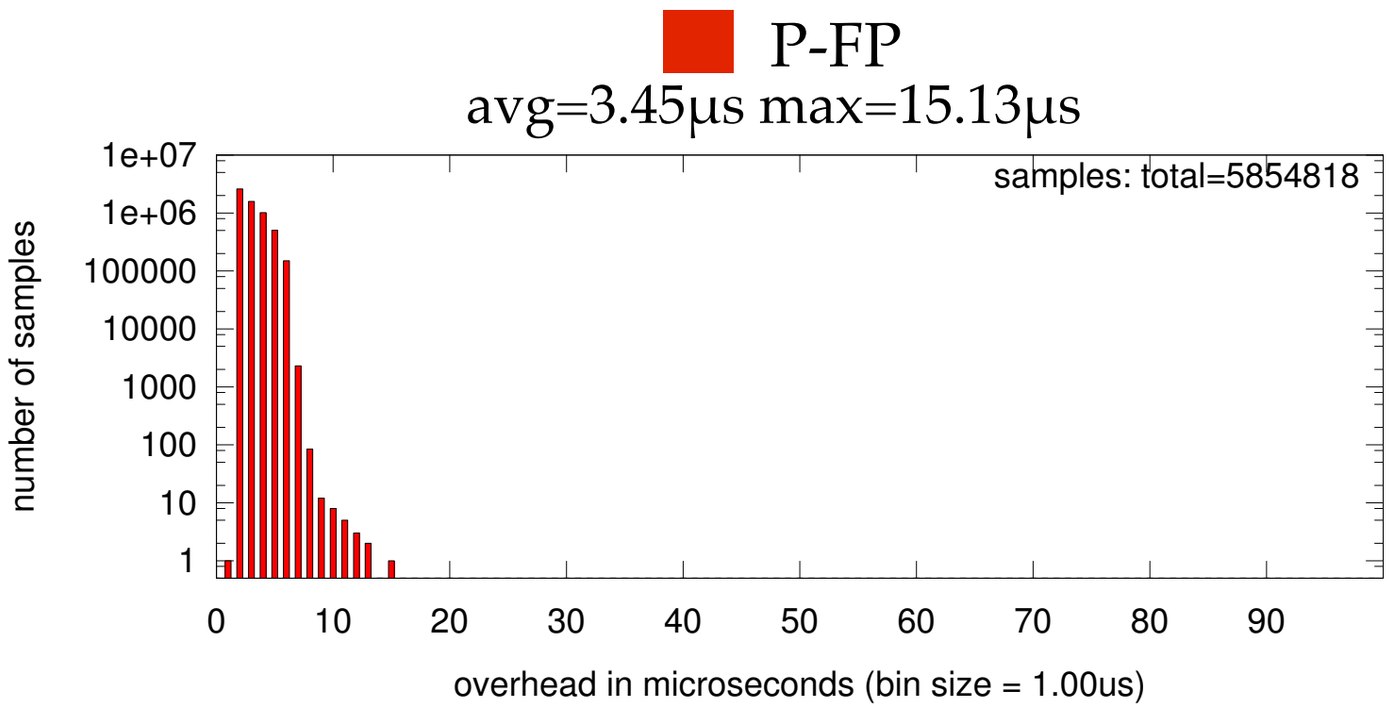
No Background Tasks



No Background Tasks

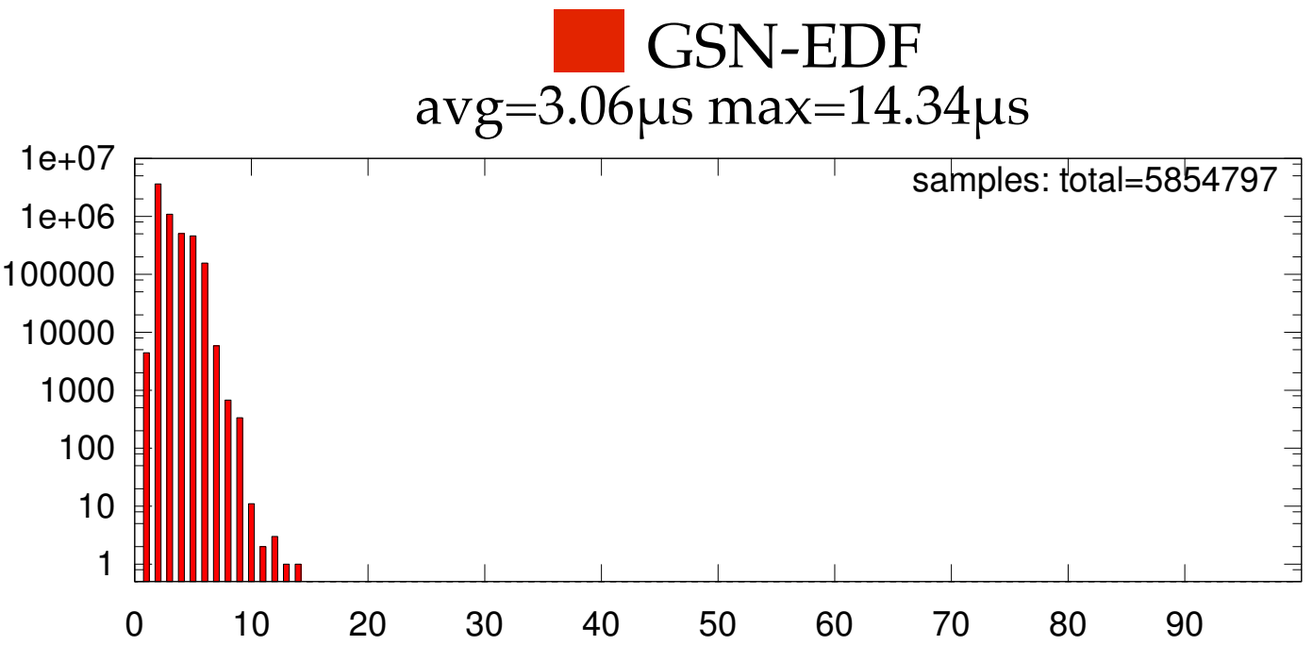
Similar shapes

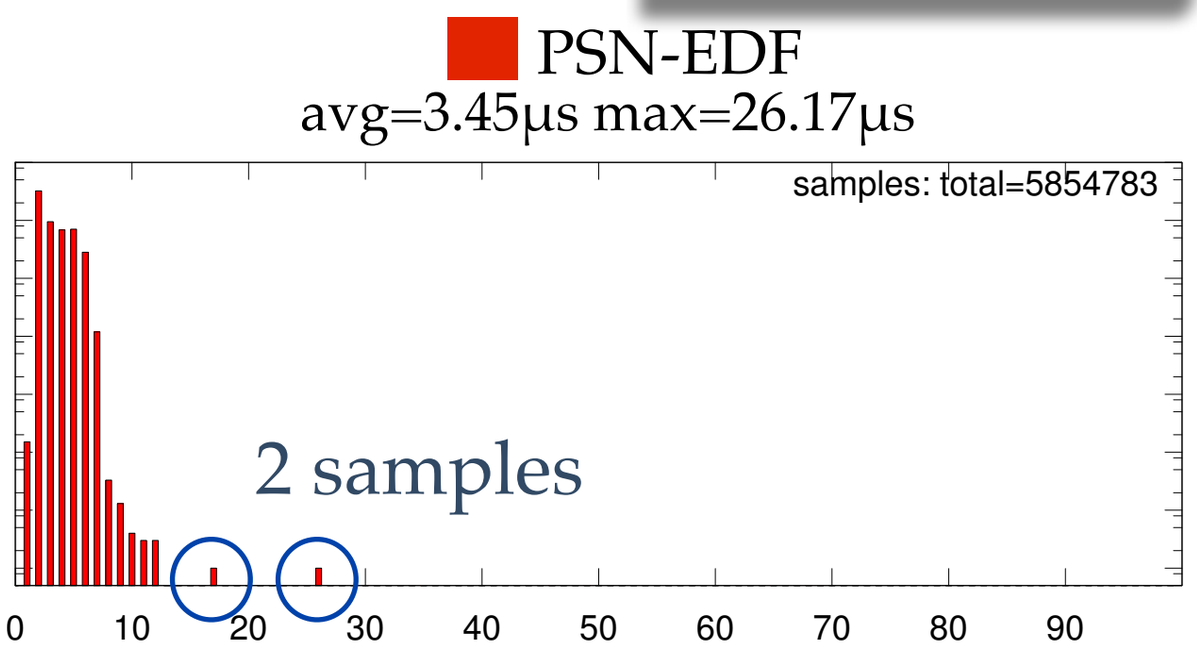


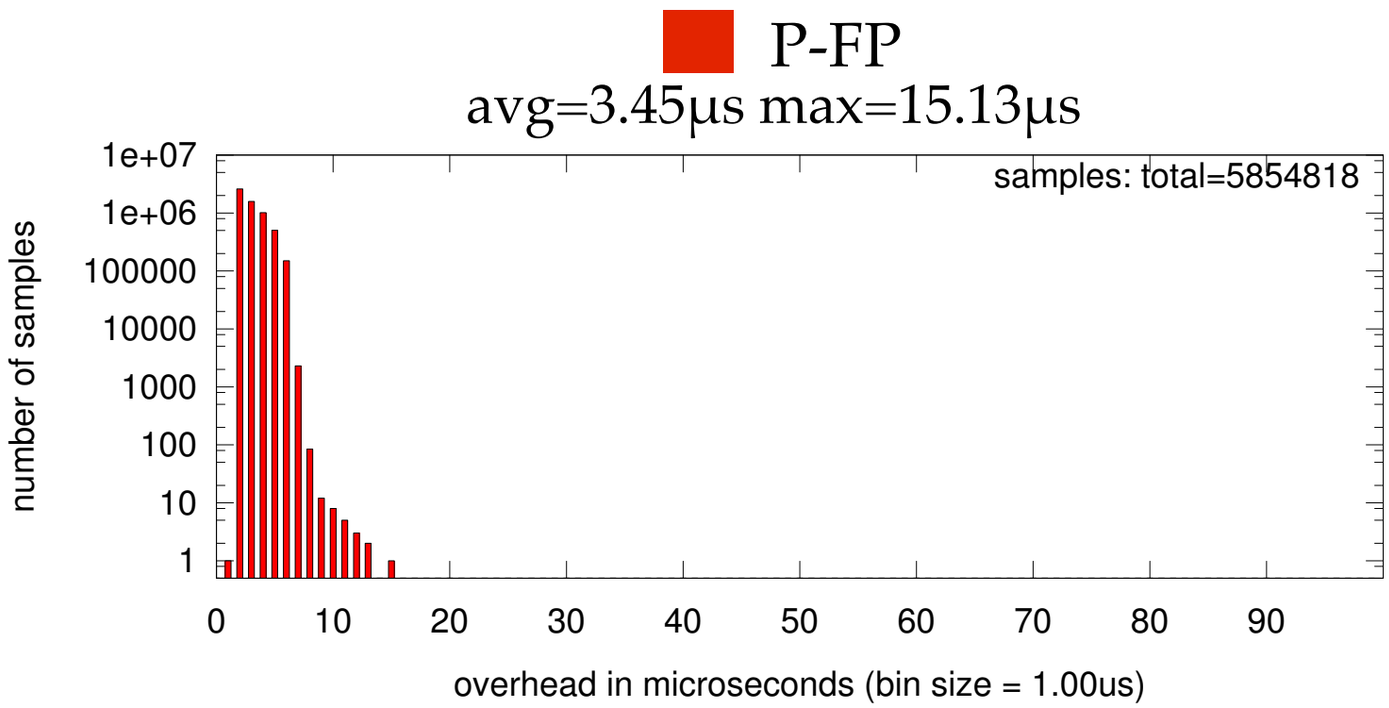


No Background Tasks

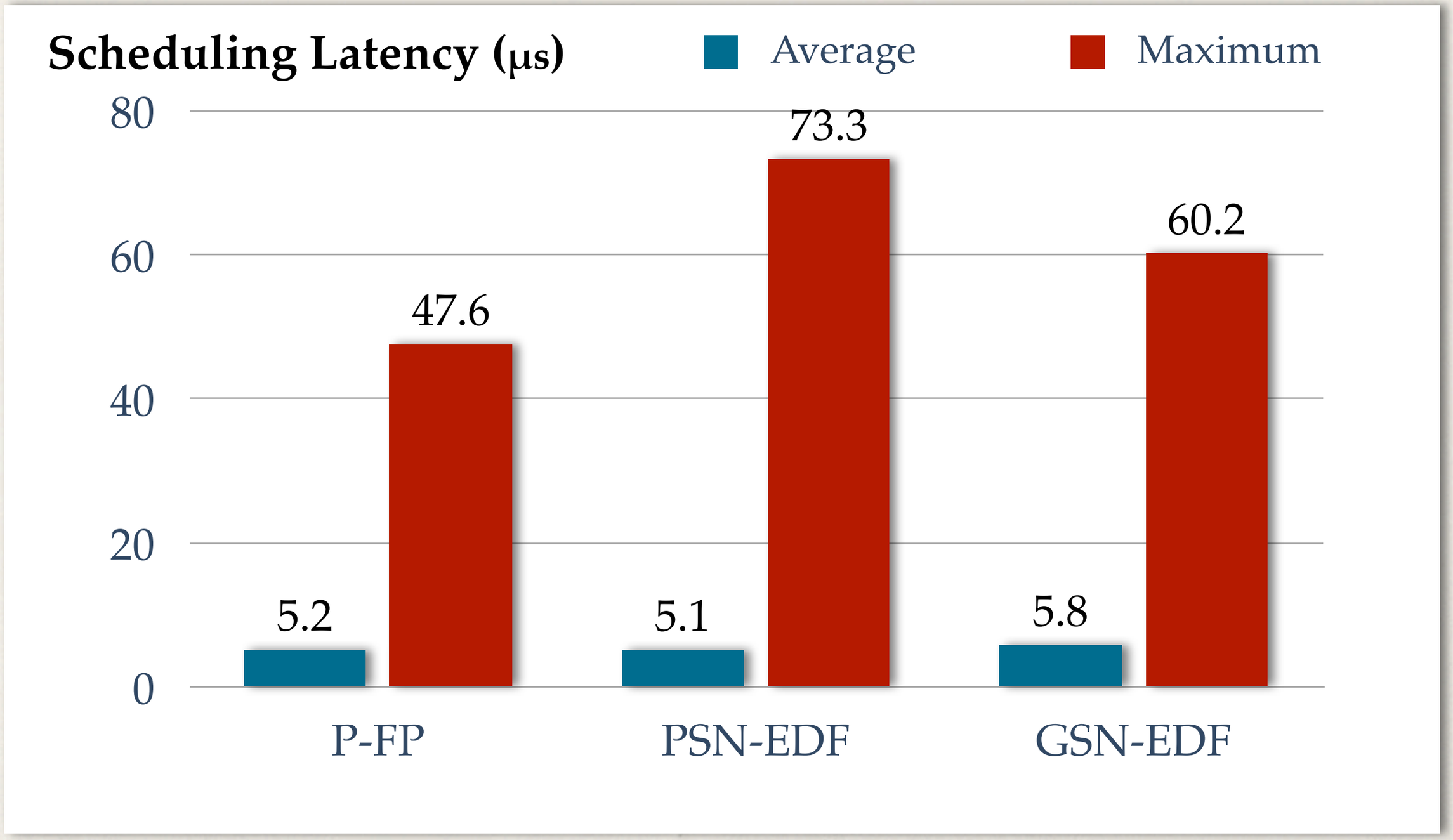
Similar shapes







CPU-bound Background Tasks



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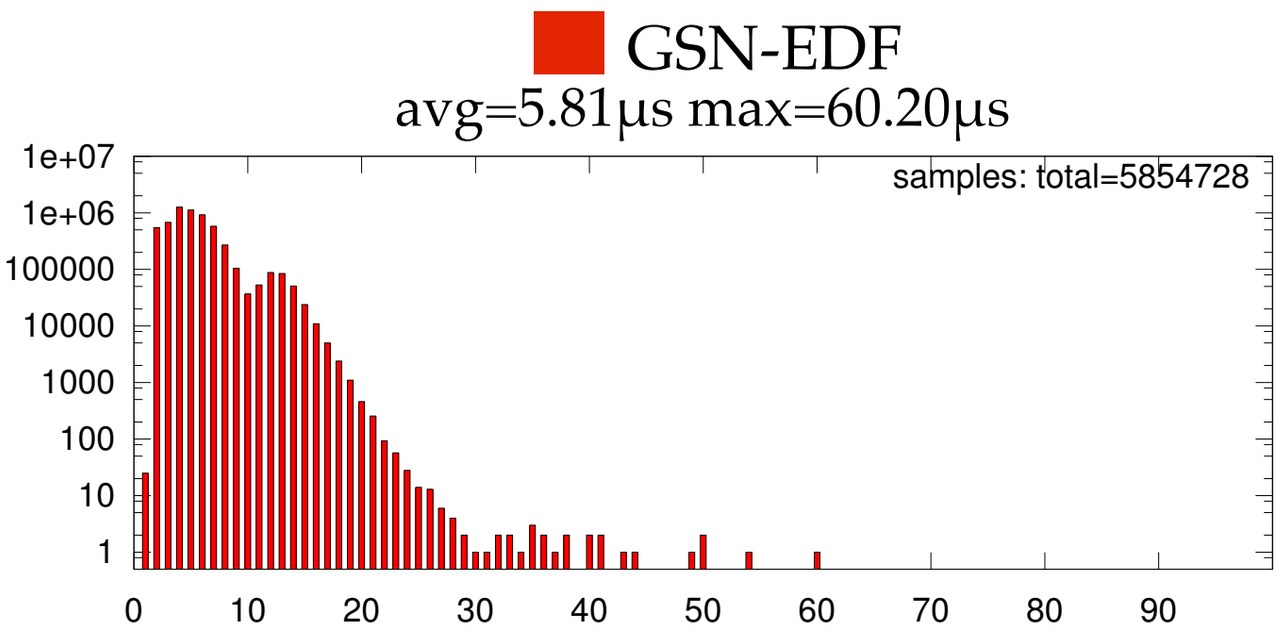

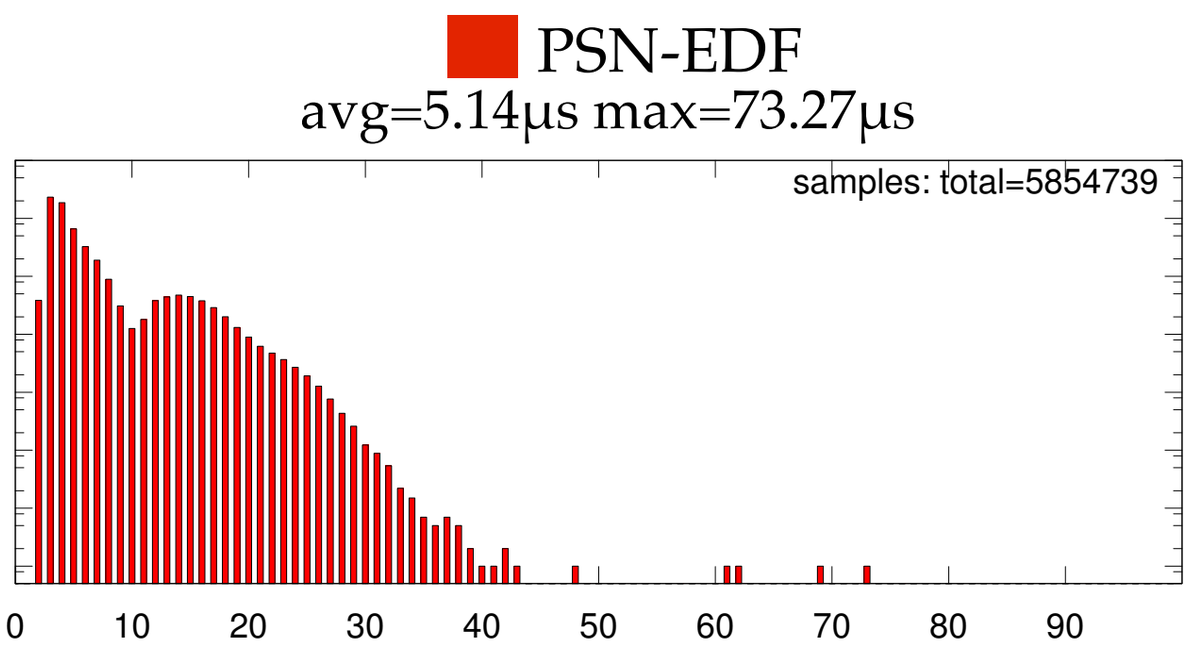

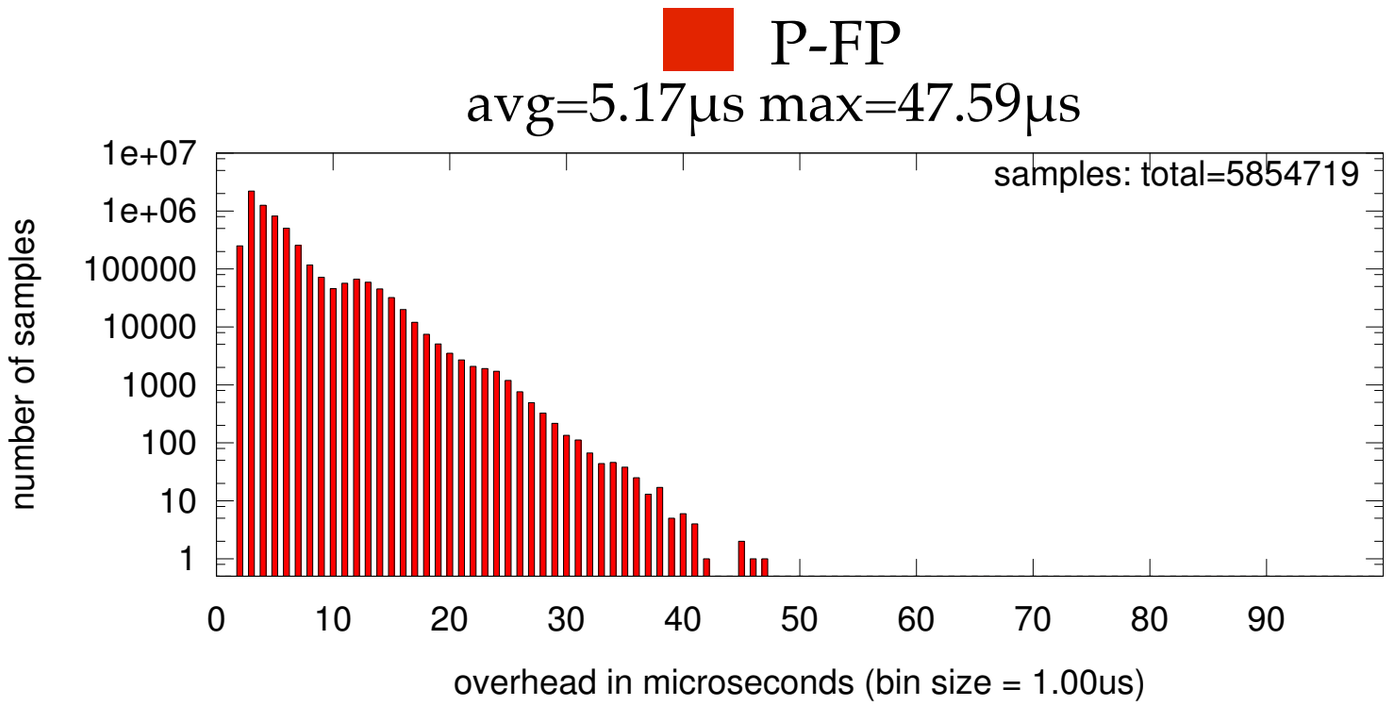

Similar shapes

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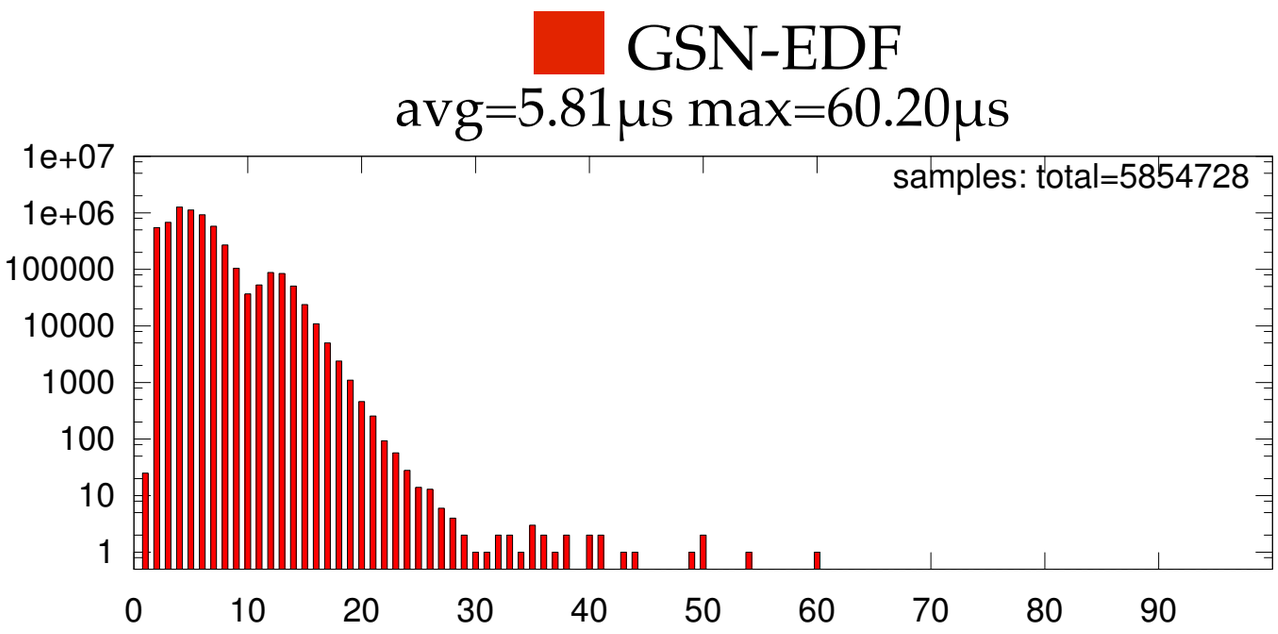
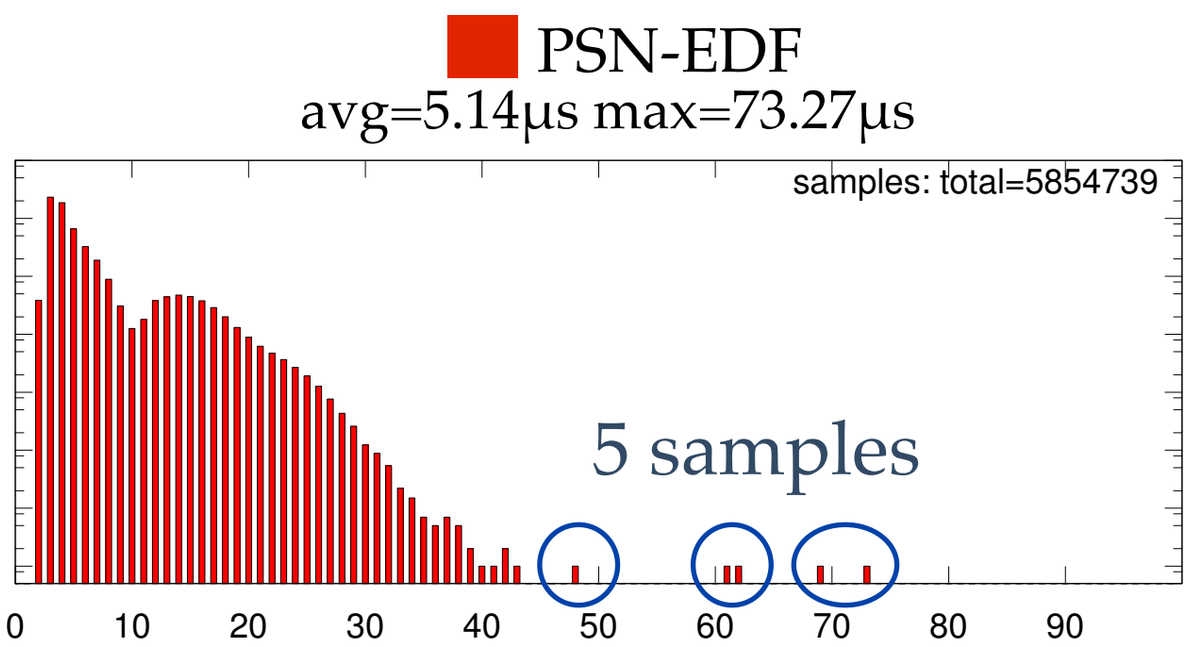
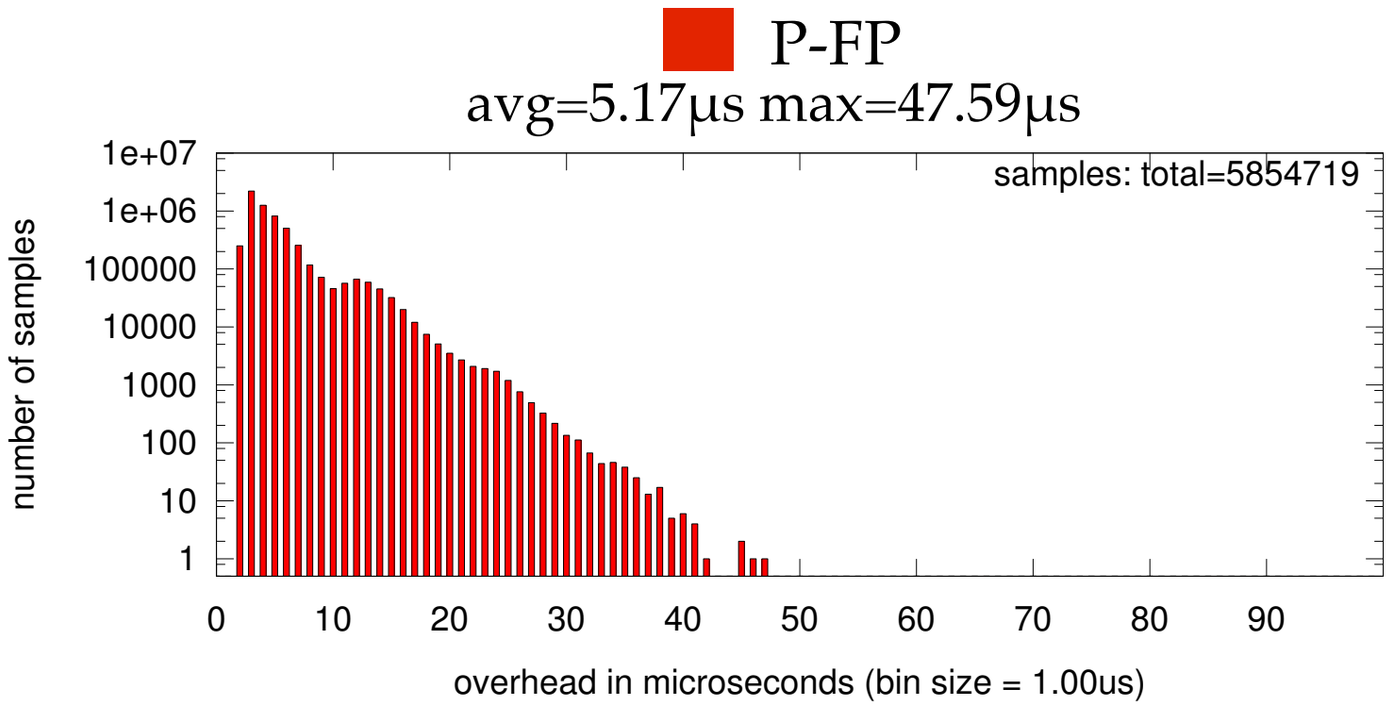


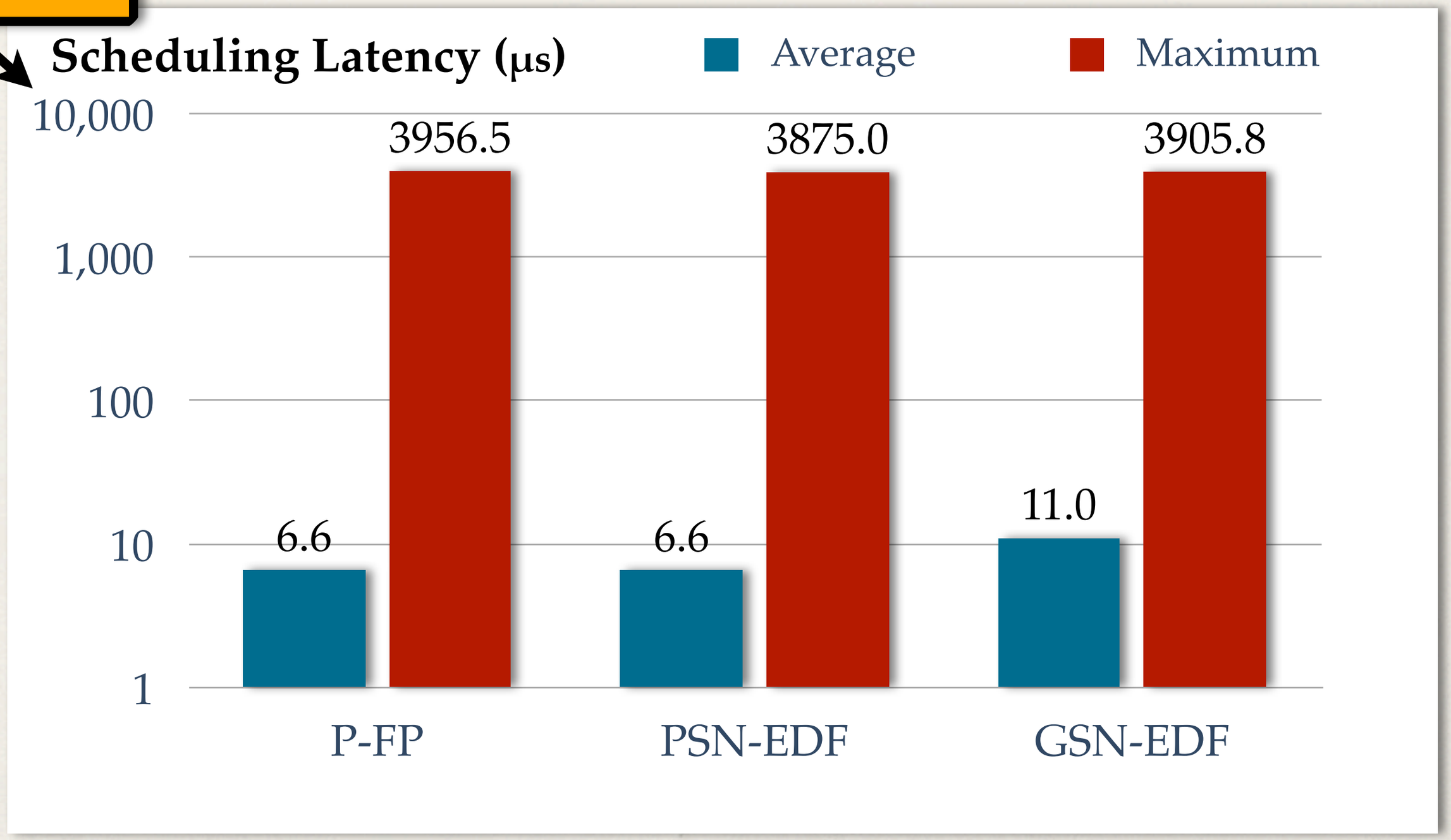




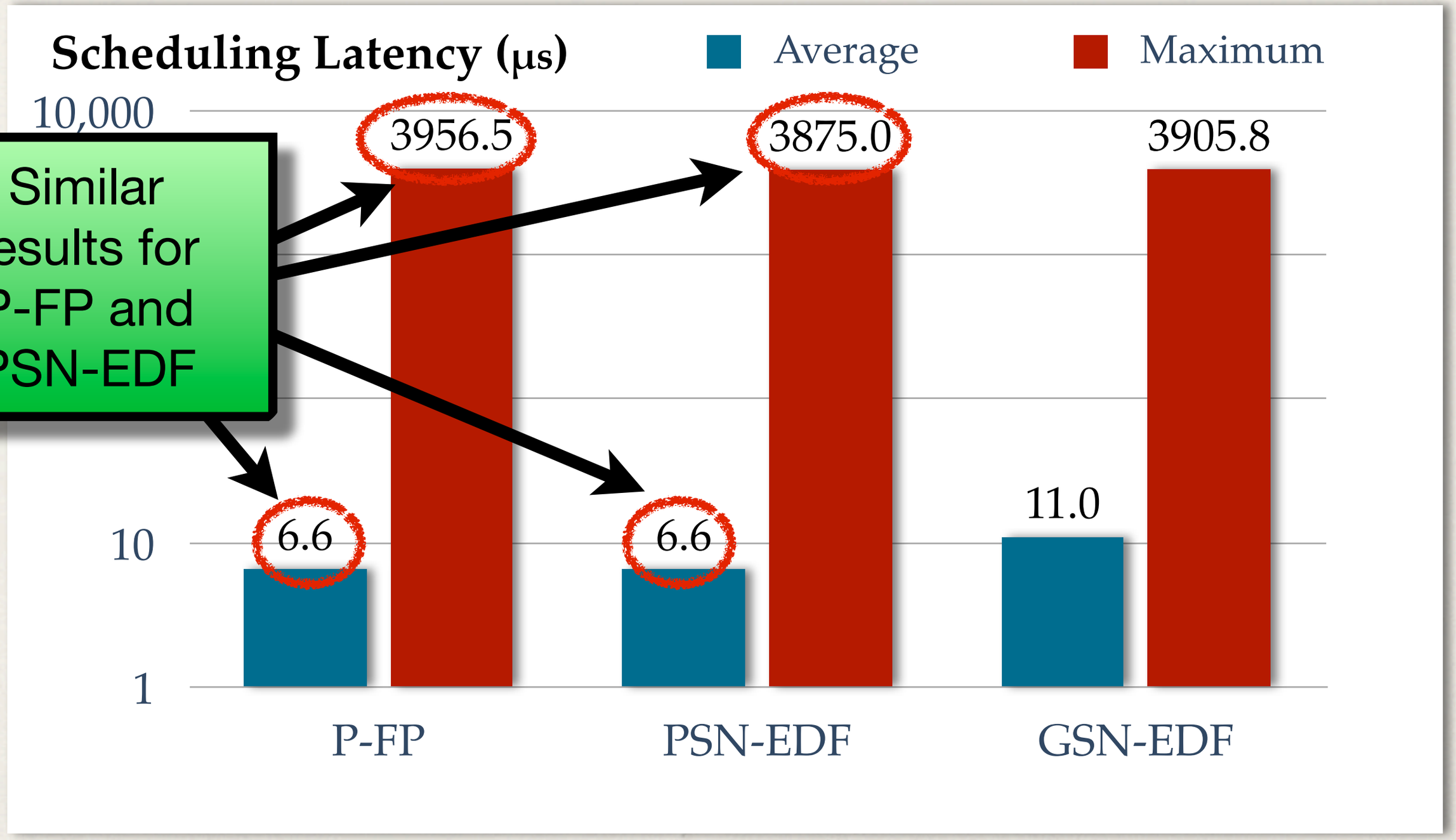
Similar shapes

I/O-bound Background Tasks

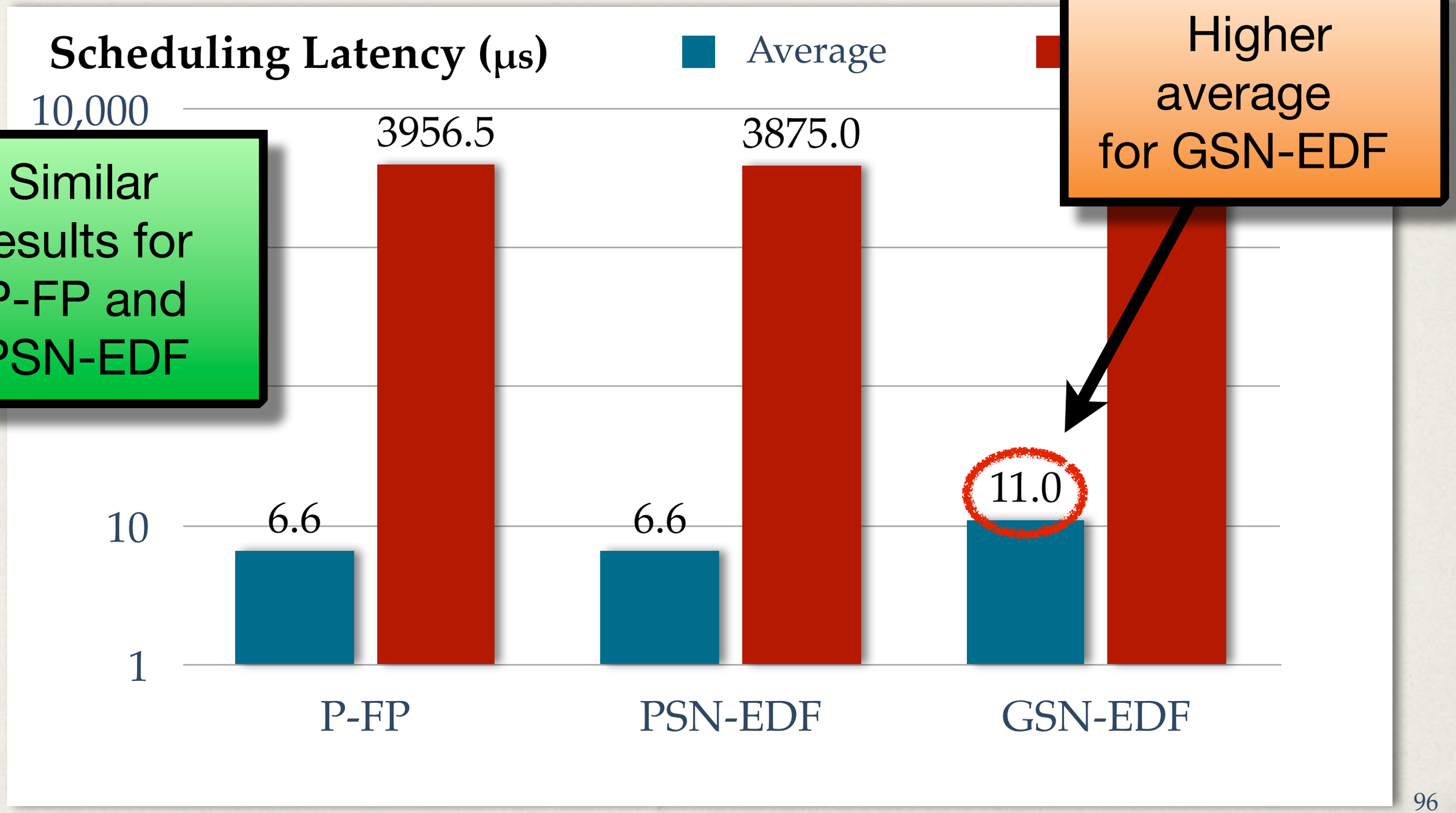
log scale!



I/O-bound Background Tasks



I/O-bound Background Tasks



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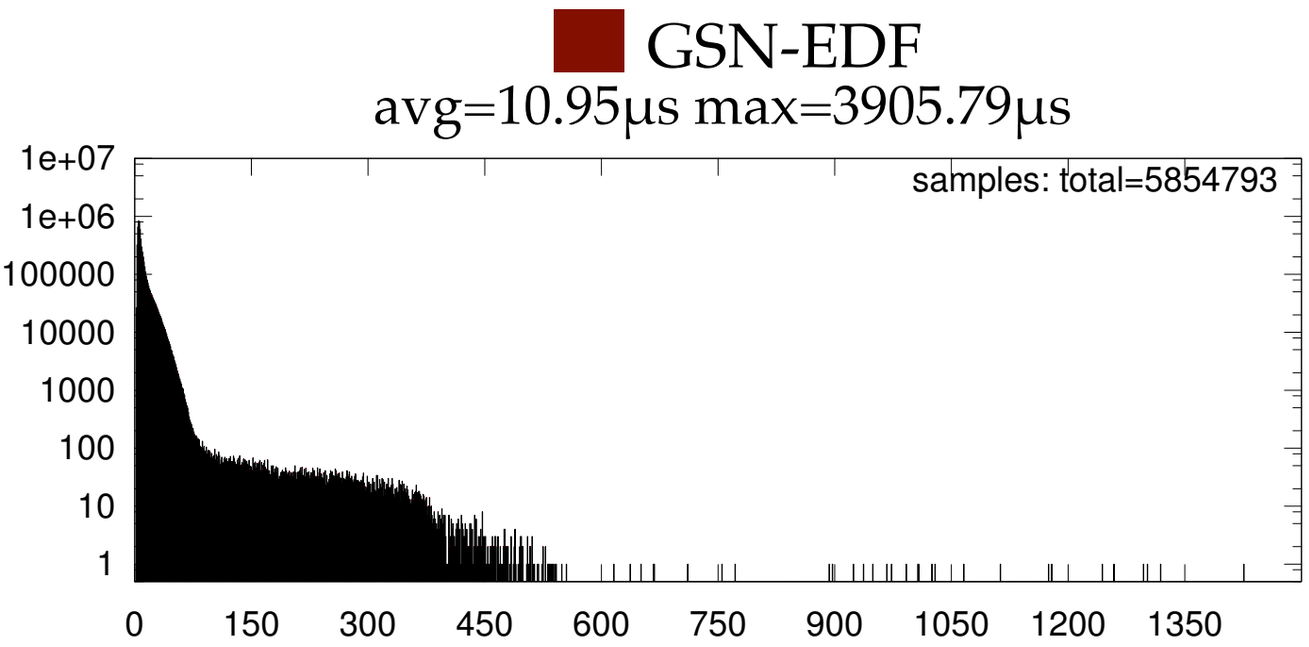

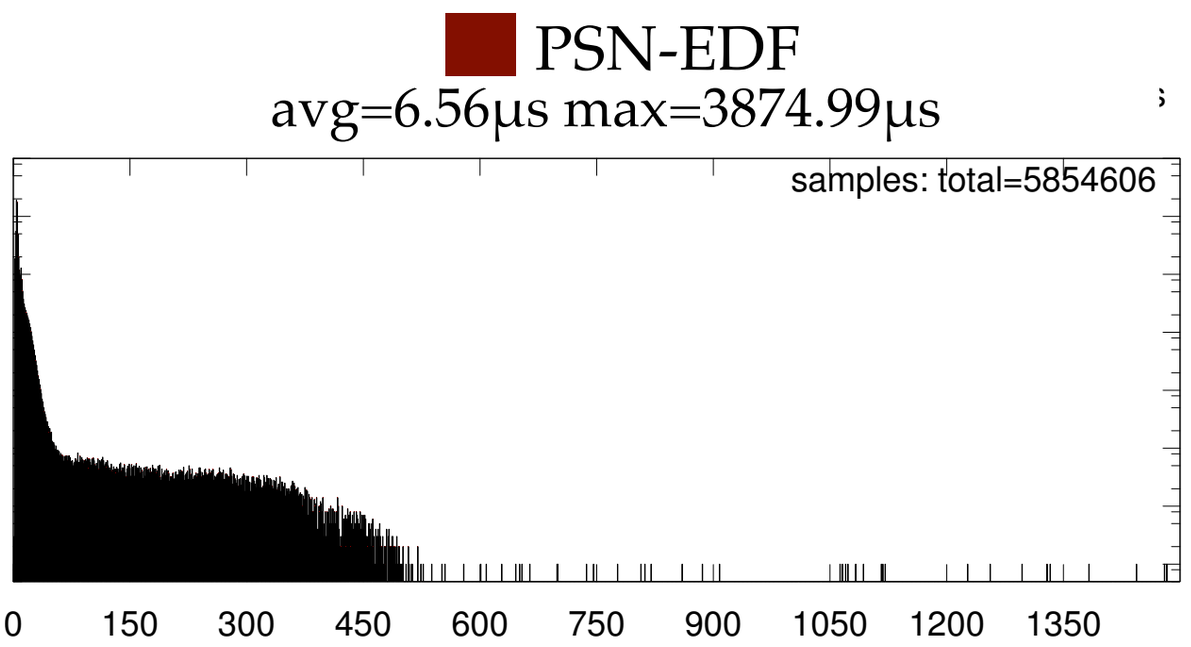

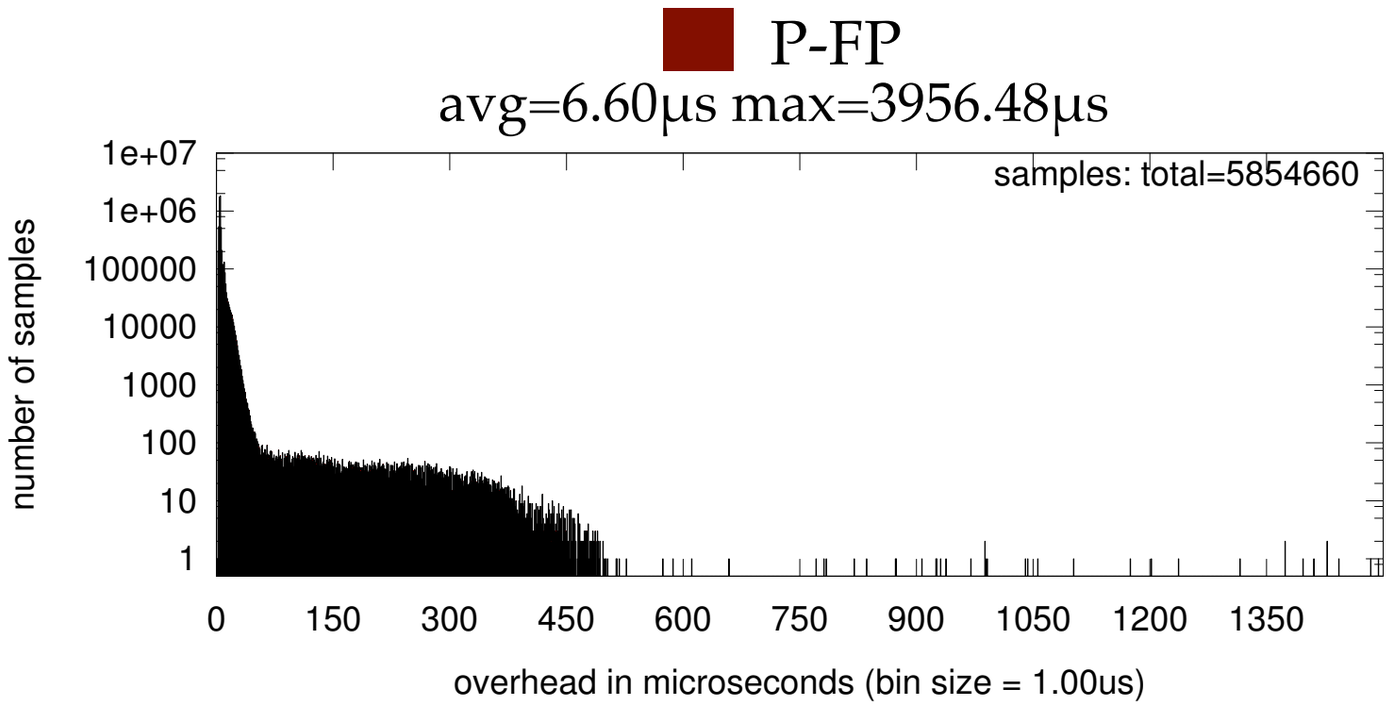

Similar shapes

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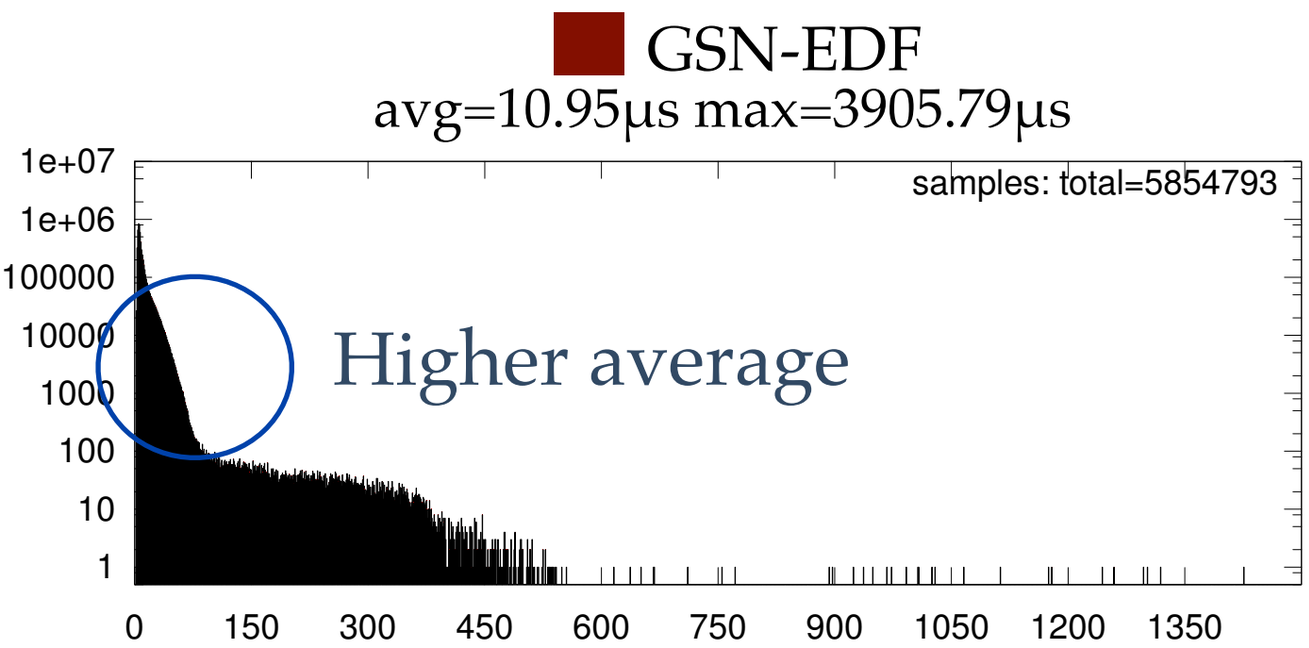
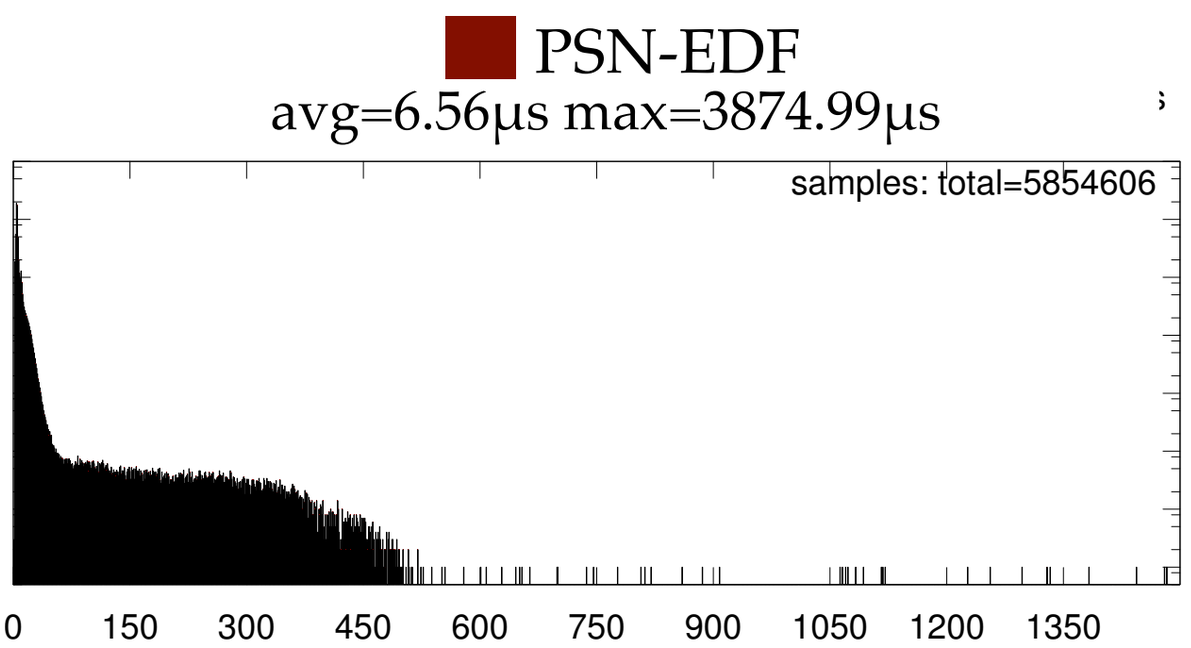
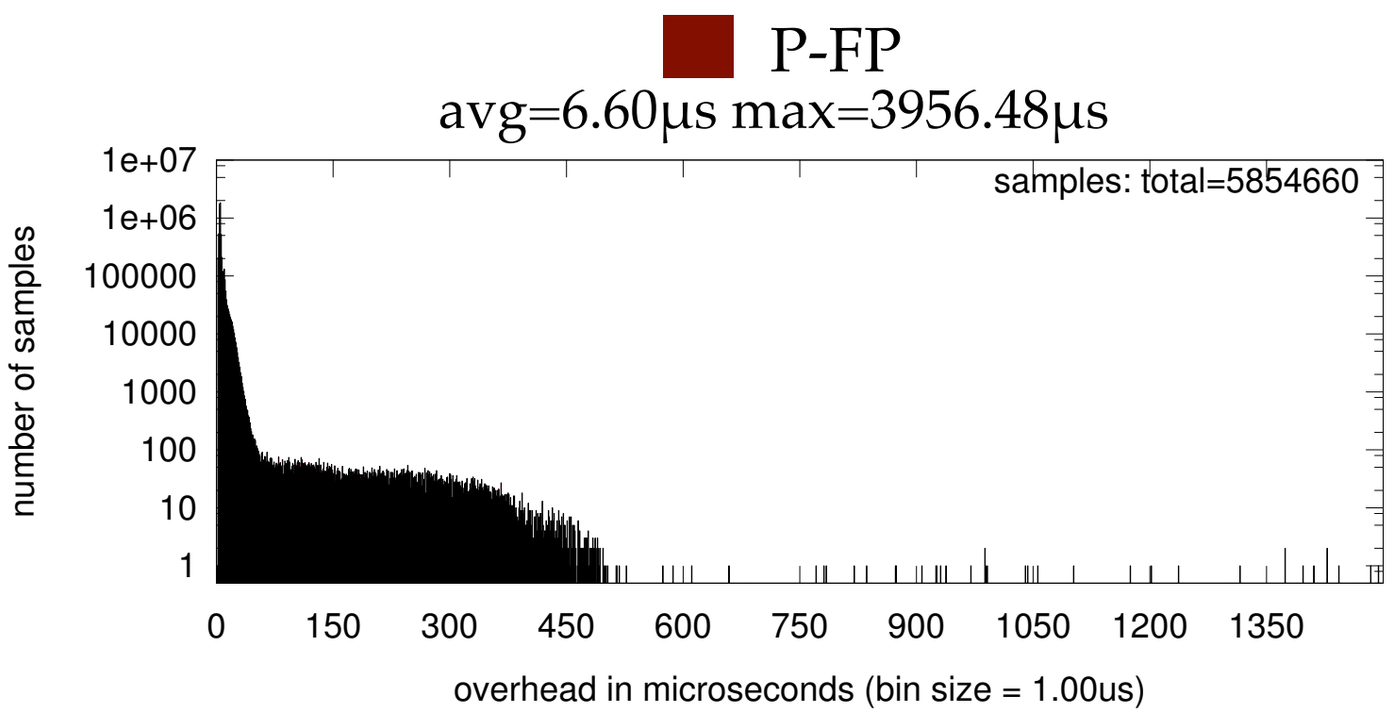


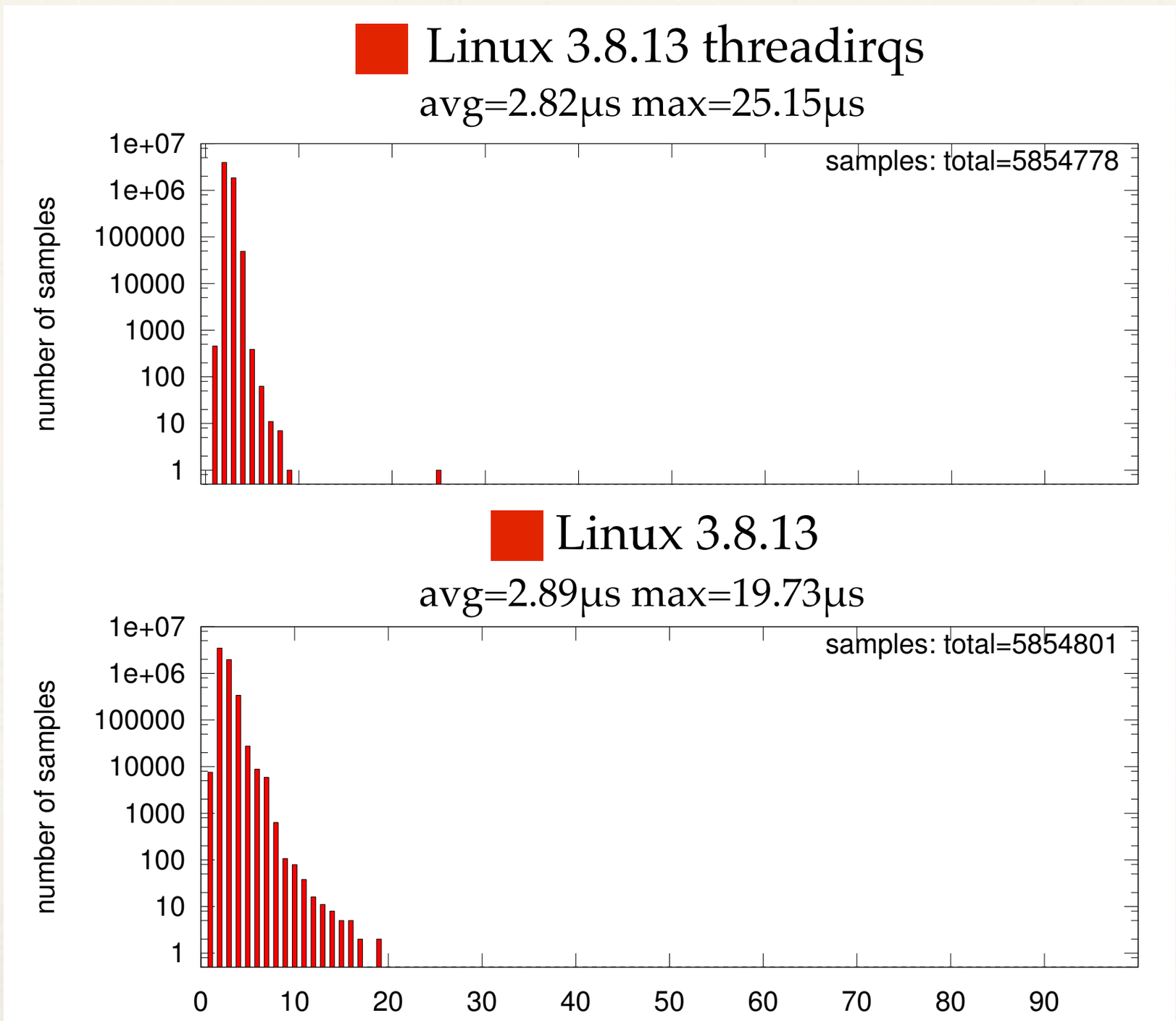




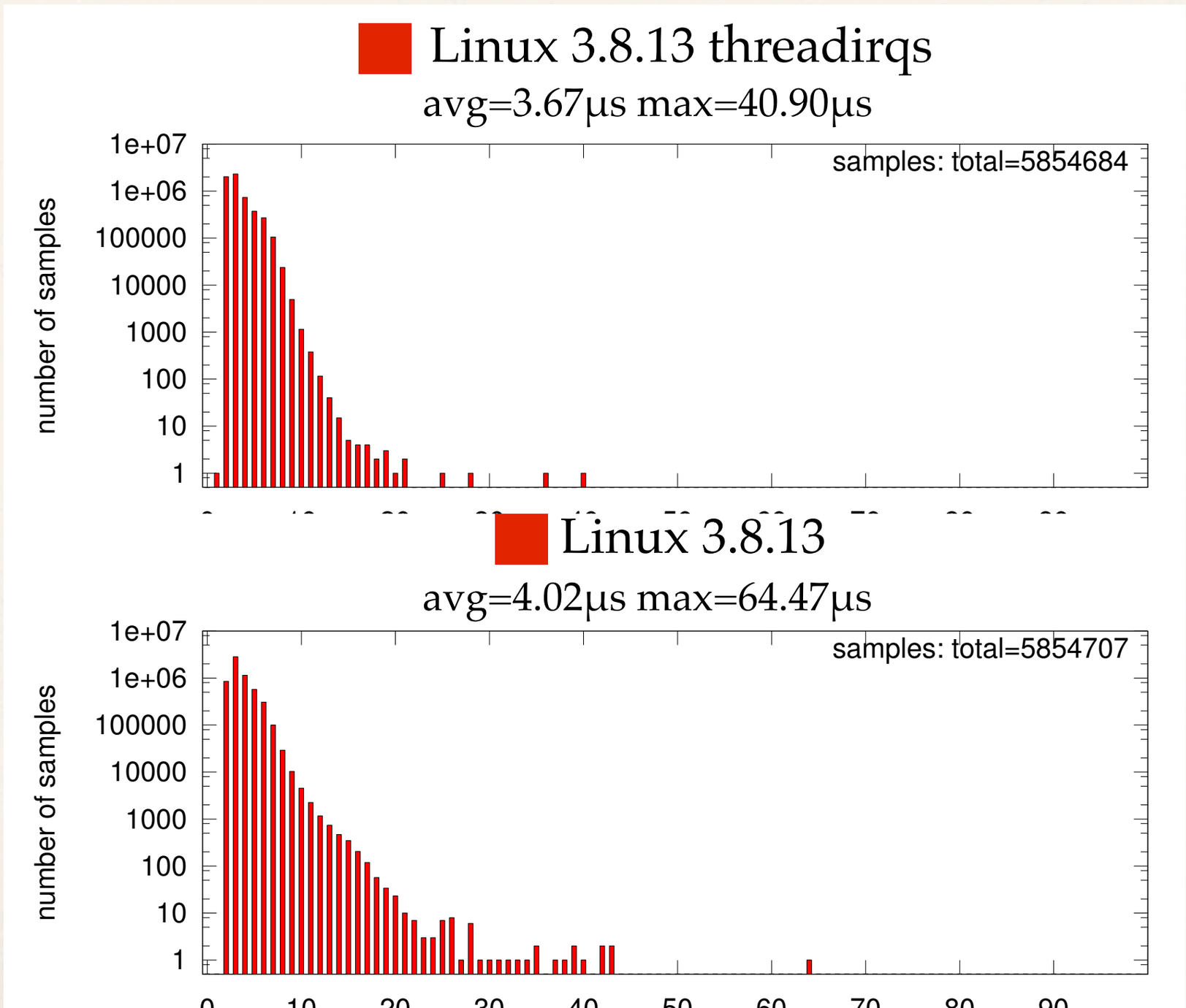
Similar shapes

threadirqs in Linux 3.8.13

No Background Tasks



CPU-bound Background Tasks



I/O-bound Background Tasks