Sleeping with One Eye Open: Fast, Sustainable Storage with Sandman

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NVSL

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The Dilemma in Storage Evolution

Evolve towards high-performance and high-density all-flash servers

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High performance

PCIe 5.0

NVMe SSDs

E.g., Samsung PM1743

Up to 2500K IOPS and 14GB/s BW

**Images and data from their official websites*

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Multi-layer (196)

TLC/QLC (3/4 bits / cell)

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Up to 122TB capacity per single drive

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Disaggregated

High performance

RDMA NICs

E.g., NVIDIA CX-7

Up to 400Gbps and four network ports

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Reason 1: high demand for processing power

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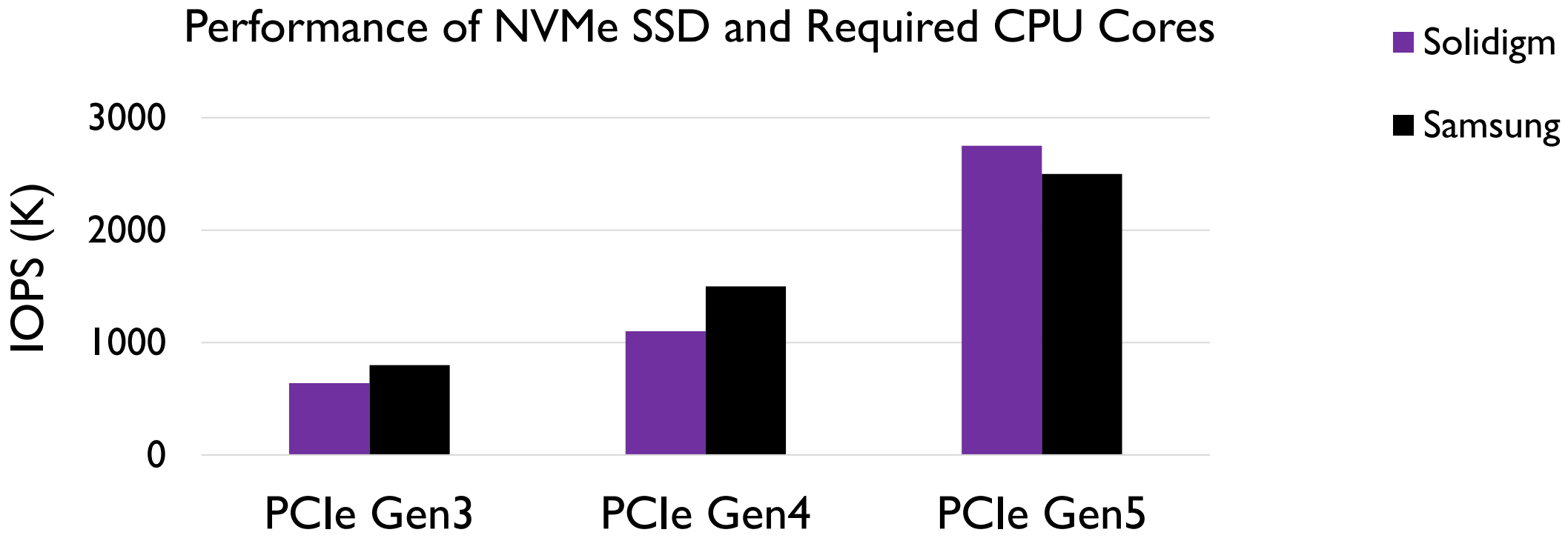
- SSD performance is almost **doubled** across PCIe generations



**Performance data are from official specifications from vendors and evaluated on SPDK*

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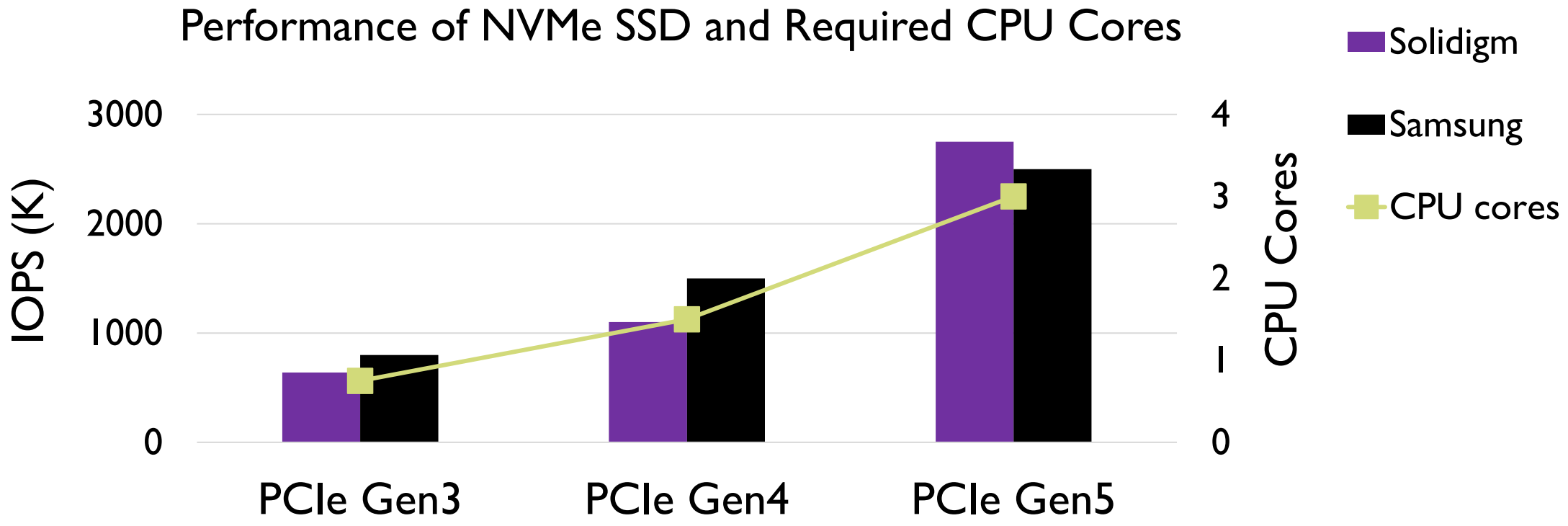
- SSD performance is almost **doubled** across PCIe generations
- Demand **more CPU cores** in host server to support such high performance



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Reason 2: high power consumption from processing I/O

- Cloud infrastructure today uses polling-based software stack for low latency
- Reserve CPU cores to operate in busy-polling state (100% util.) regardless of load

**SSD power is captured through upcoming NVMe TP4199 feature*

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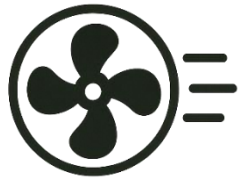

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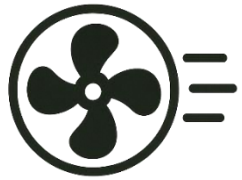

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- High power consumption is acceptable if I/O pressure is consistently heavy
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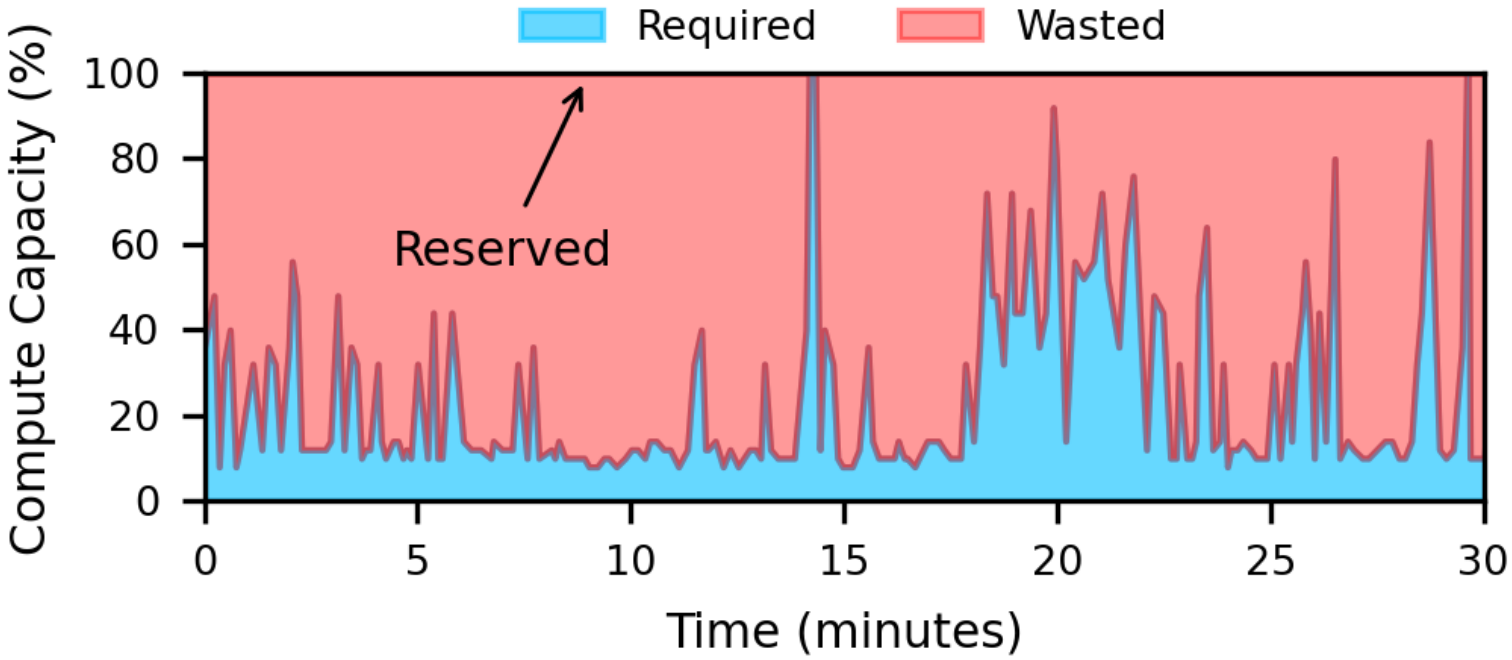

Reserved, required, and wasted compute capacity under real cloud workloads.

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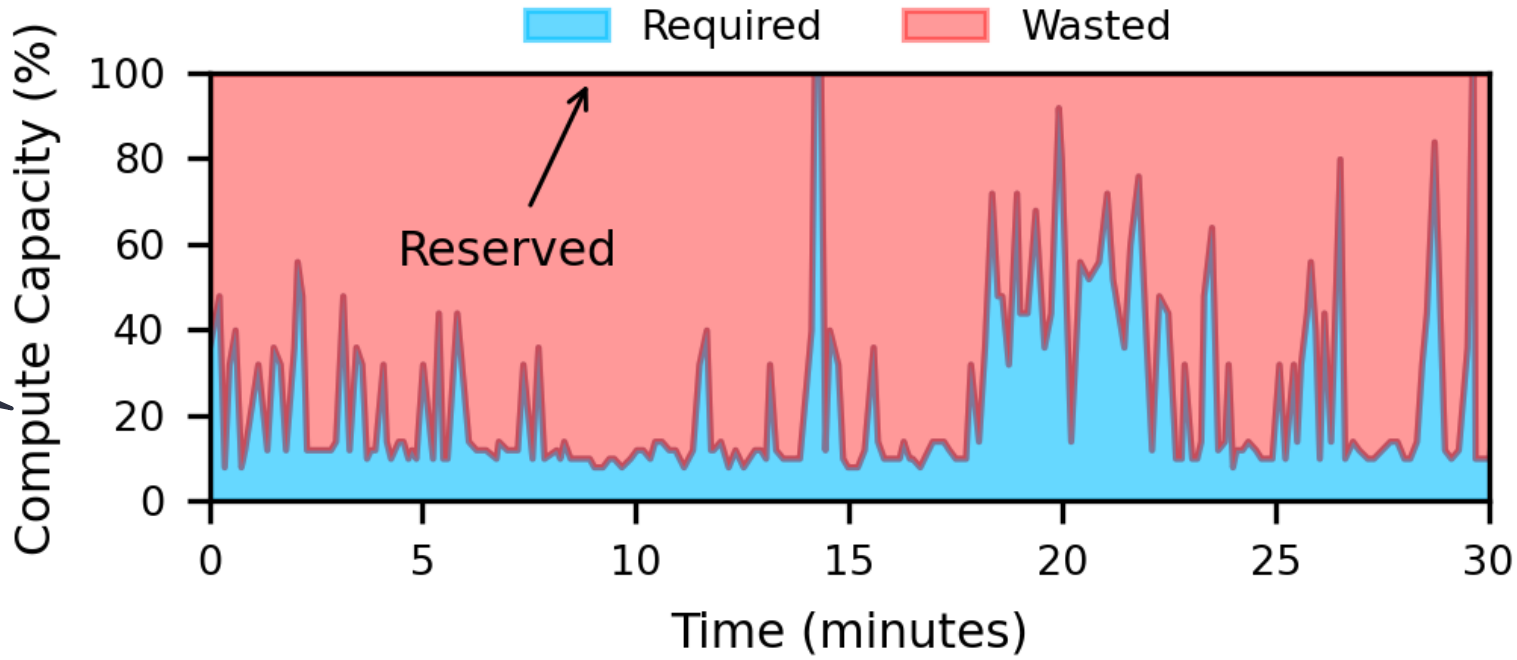

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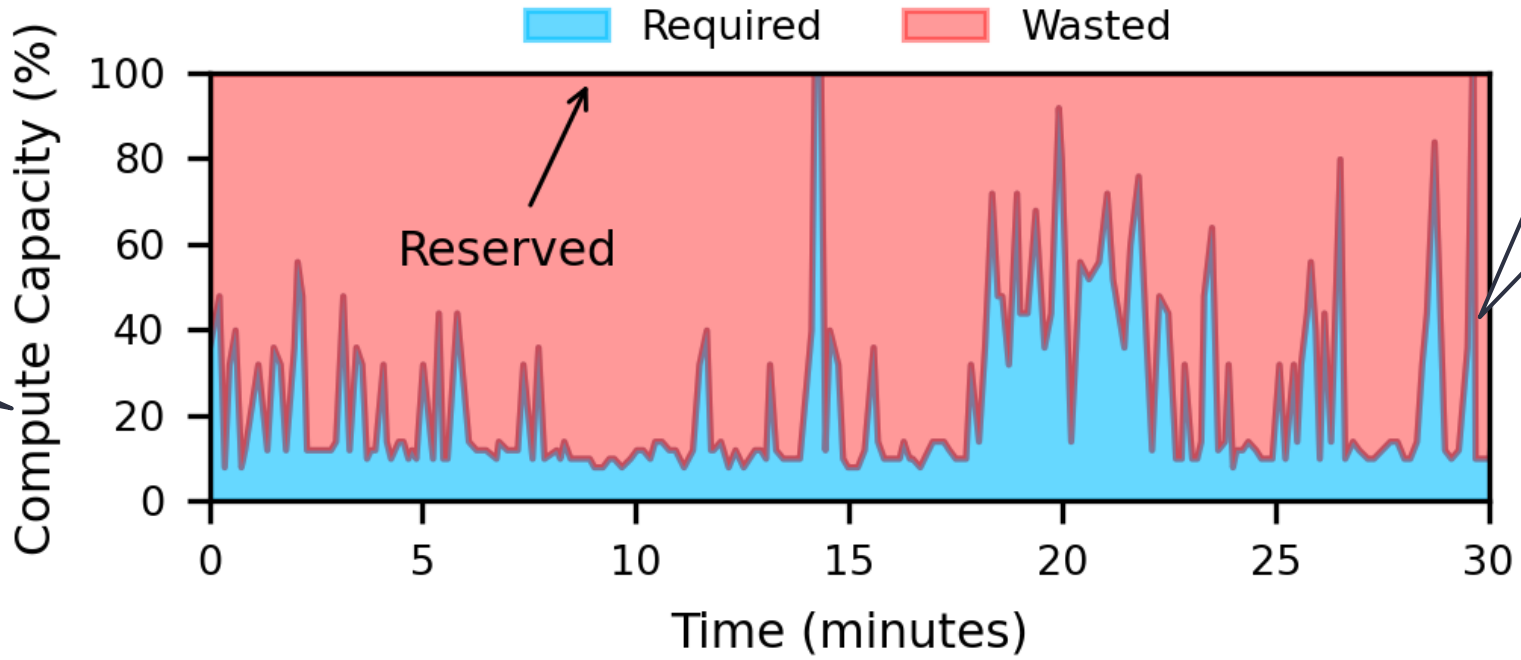

Polling cores improve performance under bursts but waste lots of energy

Reserved, required, and wasted compute capacity under real cloud workloads.

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Overview

- **Investigation**:
  - power consumption of all-flash servers

- **Measurement study**:
  - Measure four existing potential power saving solutions of storage stacks
  - Identify four major challenges to achieve high performance and energy efficiency

- **Our solution: Sandman**
  - A scheduling framework for modern storage
  - Achieve both high performance and energy efficiency

- **Evaluation**
  - Application study
  - Real cloud workloads

Measurement Study

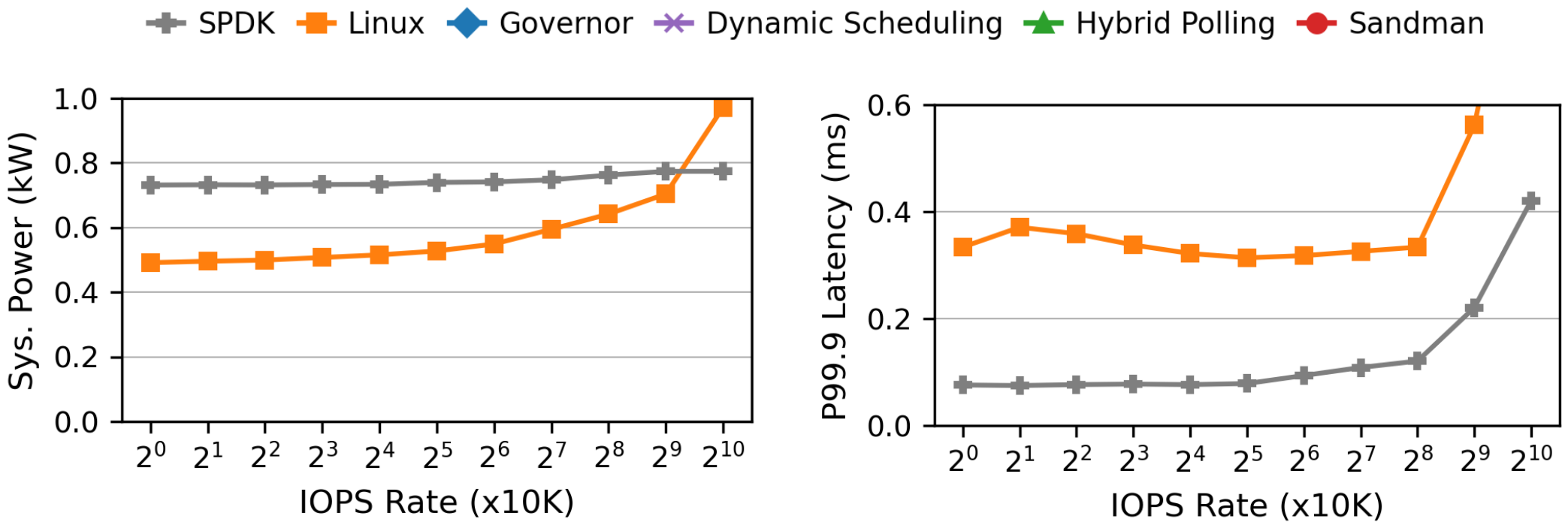
Ideal: comparable performance to busy polling with lower power consumption.

1. **SPDK**: busy-polling – best performance case
2. **Linux**: classic interrupts
3. **Governor**: adapting frequency of polling cores to workloads
4. **Dynamic Scheduling**: reallocating threads among polling cores
5. **Hybrid Polling**: alternating polling cores between sleep and active states

Workloads: 1) stable workloads at different IOPS rates and 2) bursty (1s) workloads

Setup: two nodes connected via NVMeoF (16x PM1743 SSDs and RDMA NICs with 2x 200Gbps ports)

Stable Workloads – Linux Interrupts



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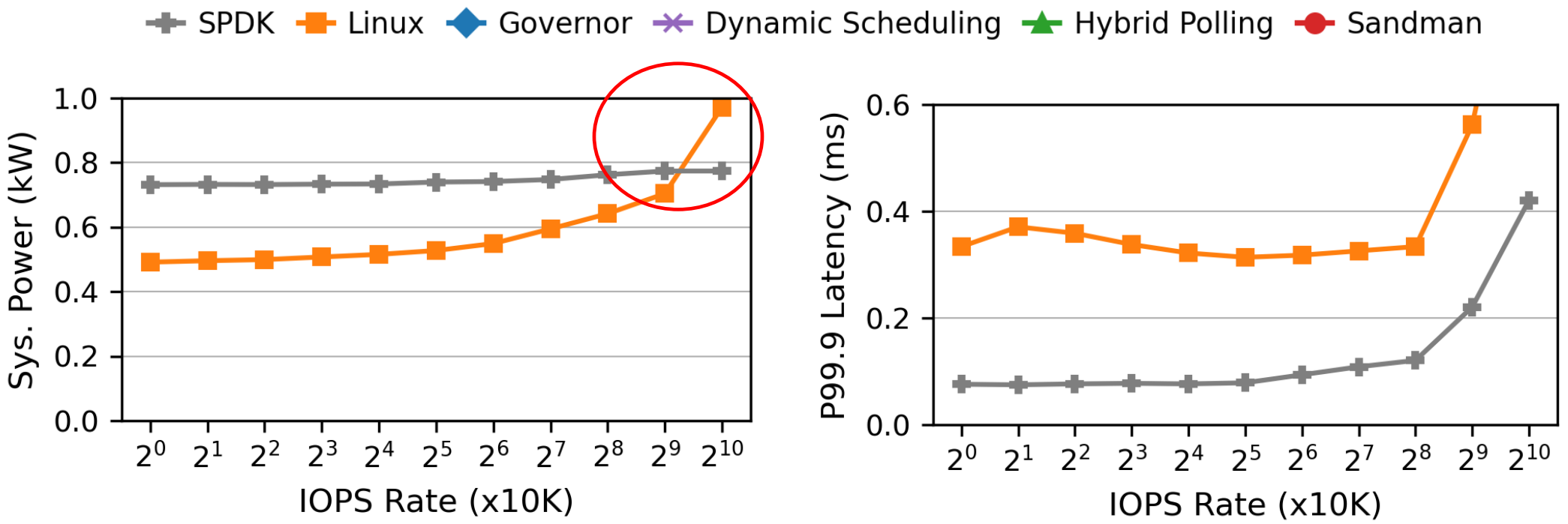
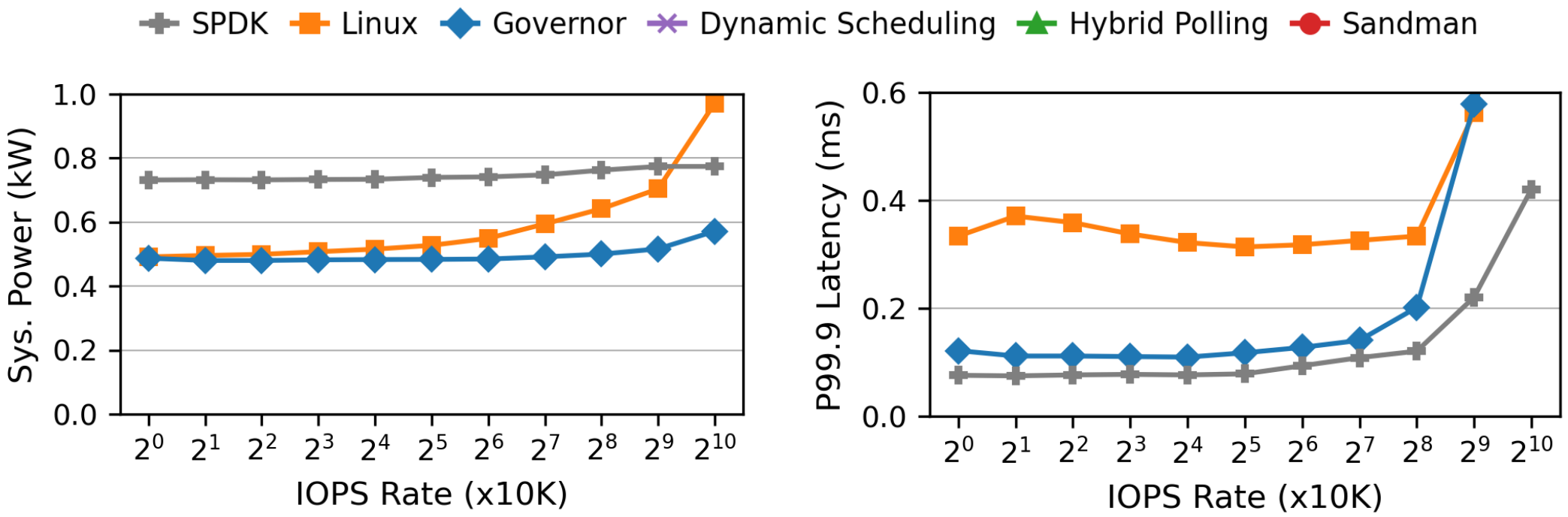


Observation: Interrupts can even consume ***higher-than-polling* power** and show lower performance due to context switches under heavy workloads

Stable Workloads – Governor Frequency Scaling



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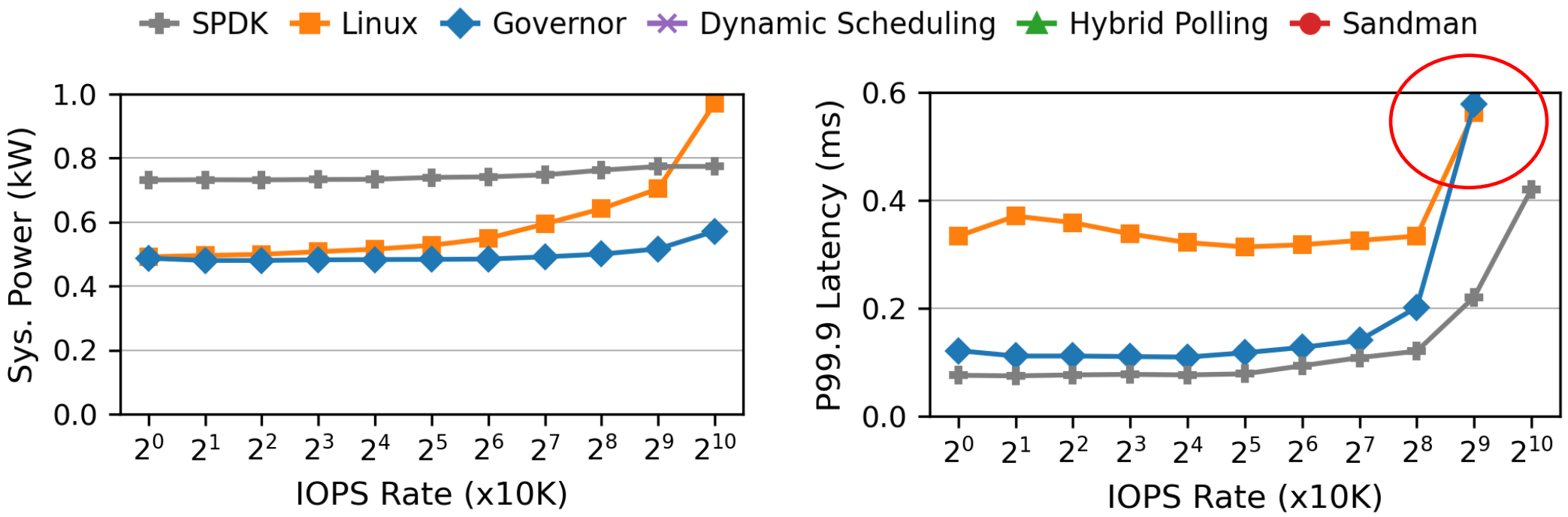
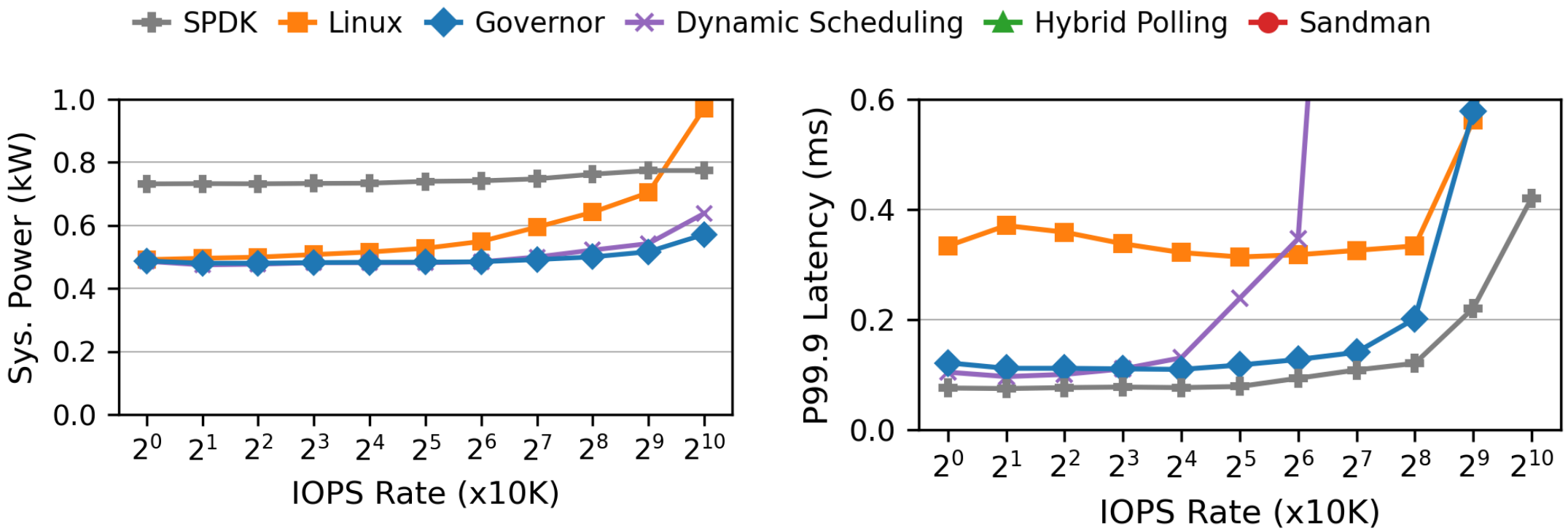


Observation: Governor reduces power consumption yet **increases tail latency** than busy-polling due to using low-frequency cores for processing

Stable Workloads – Dynamic Scheduling



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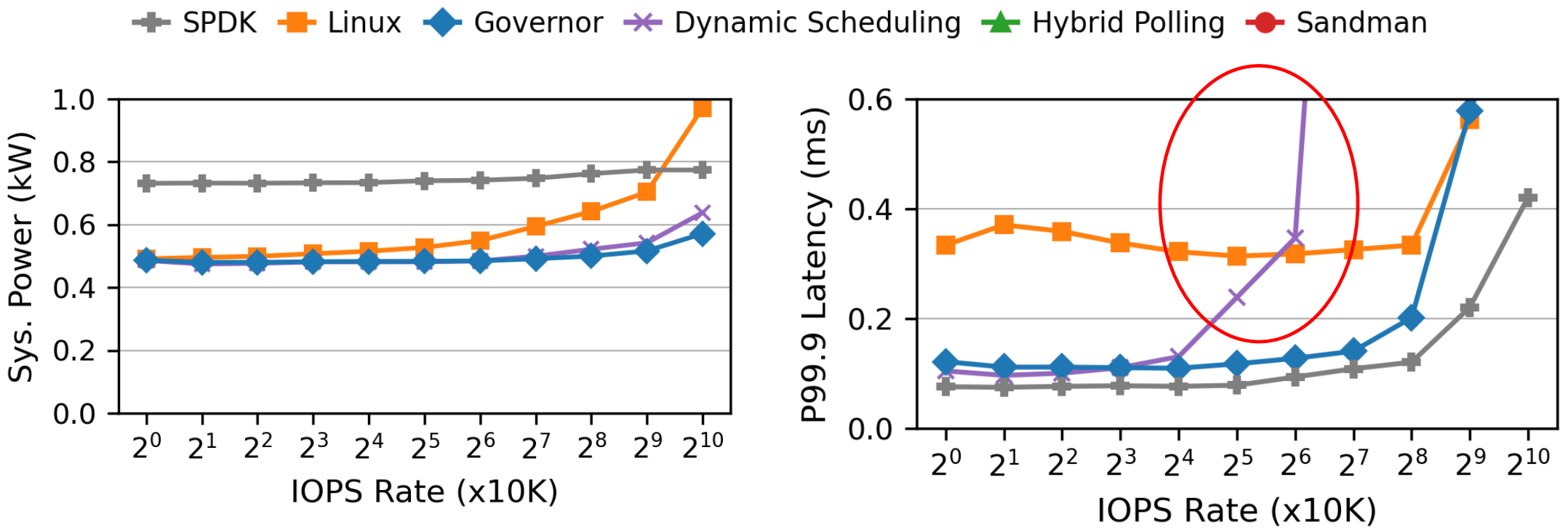
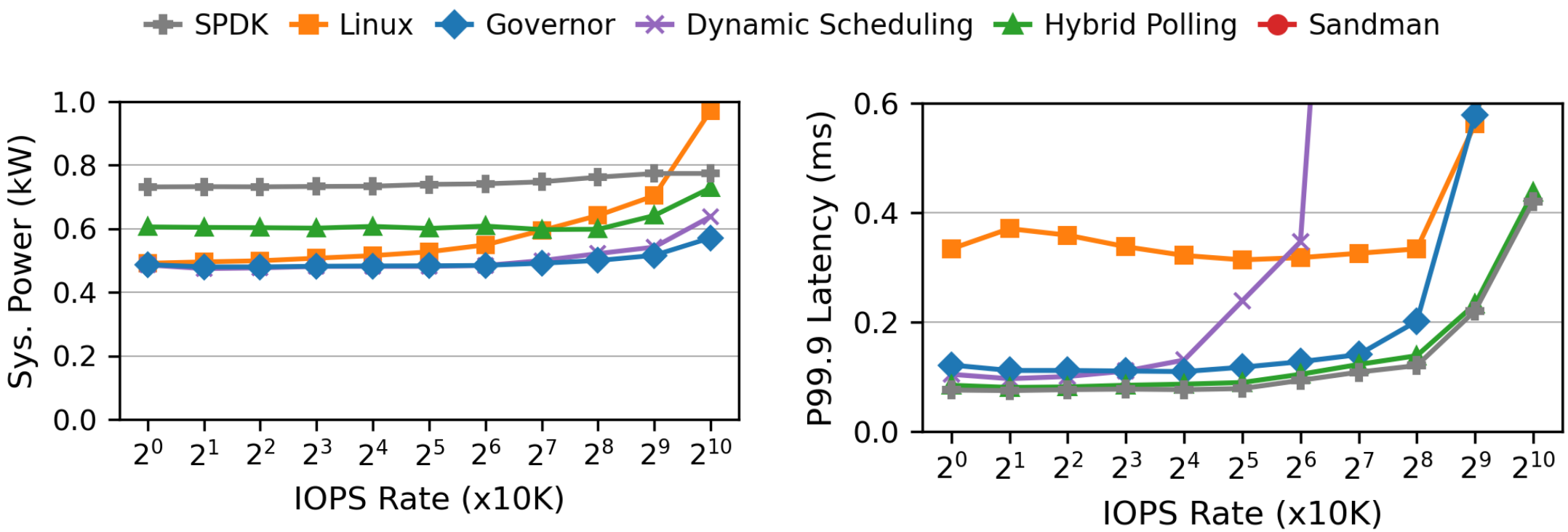


Observation: Adapting workload changes needs **microsecond-level detection**, incurring **frequent reallocation of tasks among cores.**

Stable Workloads – Hybrid Polling



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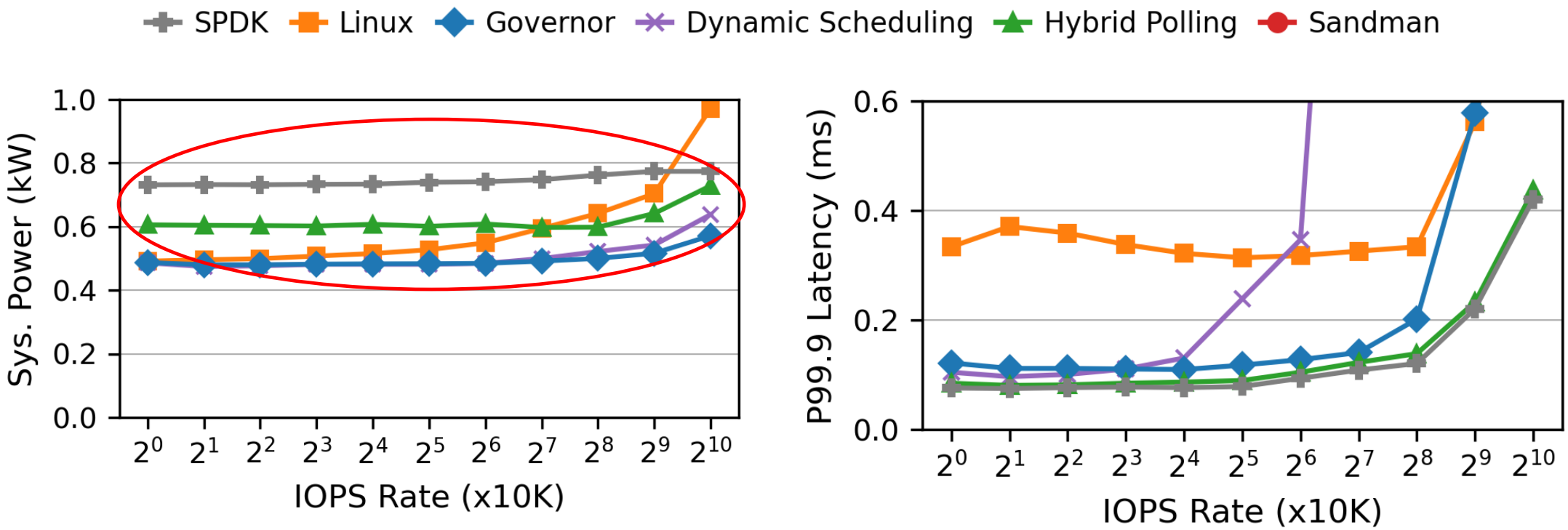
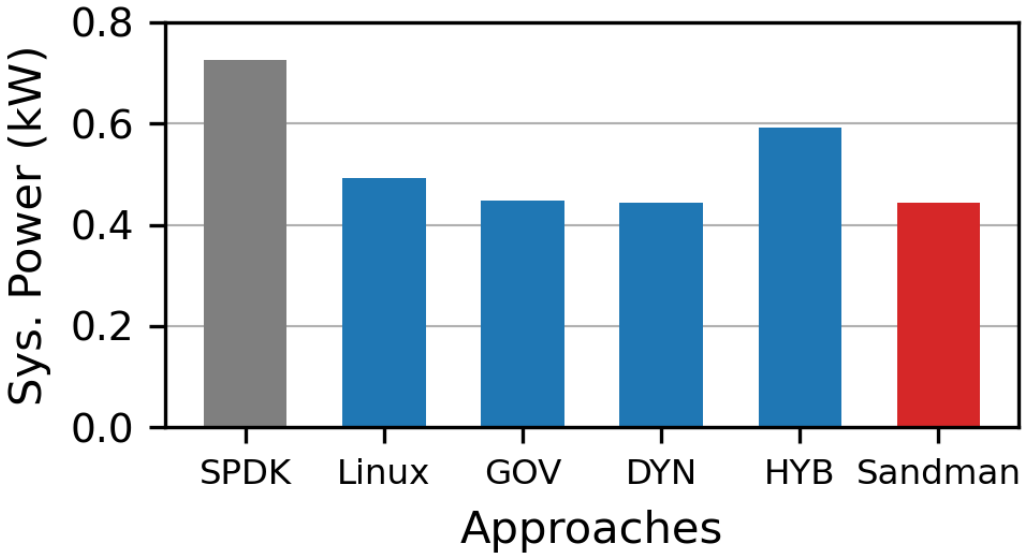
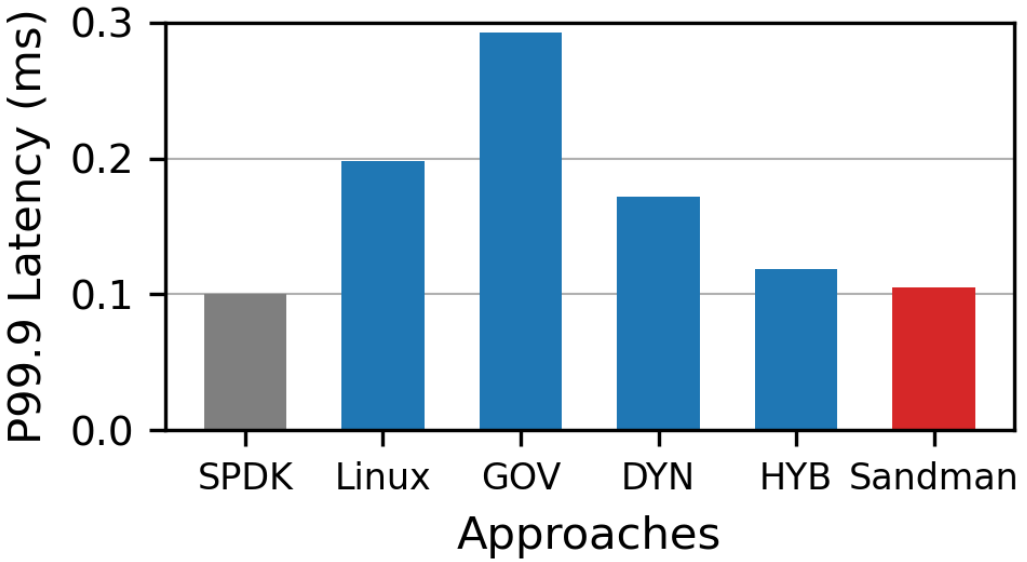


Observation: **Frequent transitions limit power saving**. Frequent transitions between low-power and high-performance states prevent CPU cores from staying in energy-saving mode for longer durations.

Bursty Workloads

We expect system scales compute resource ASAP under short-term bursts





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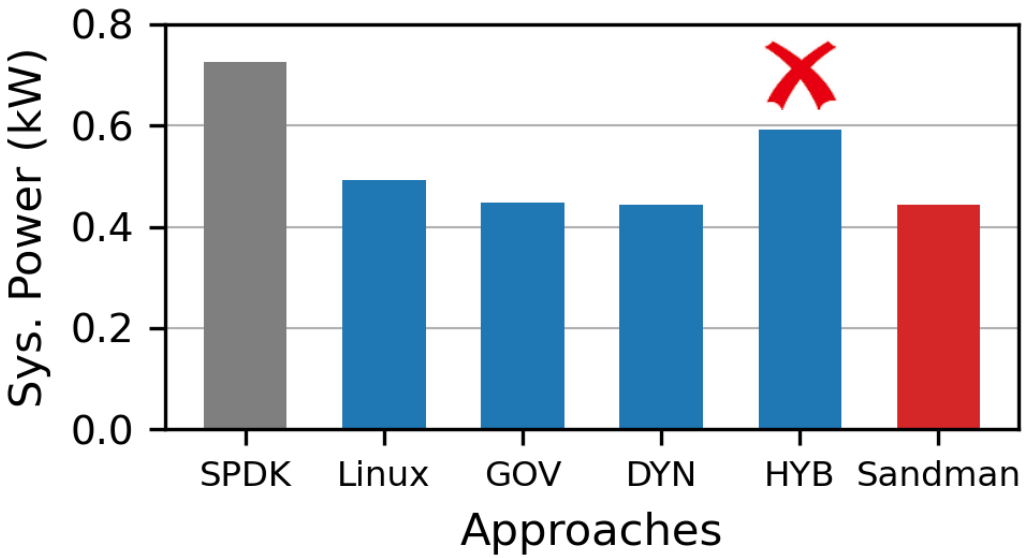

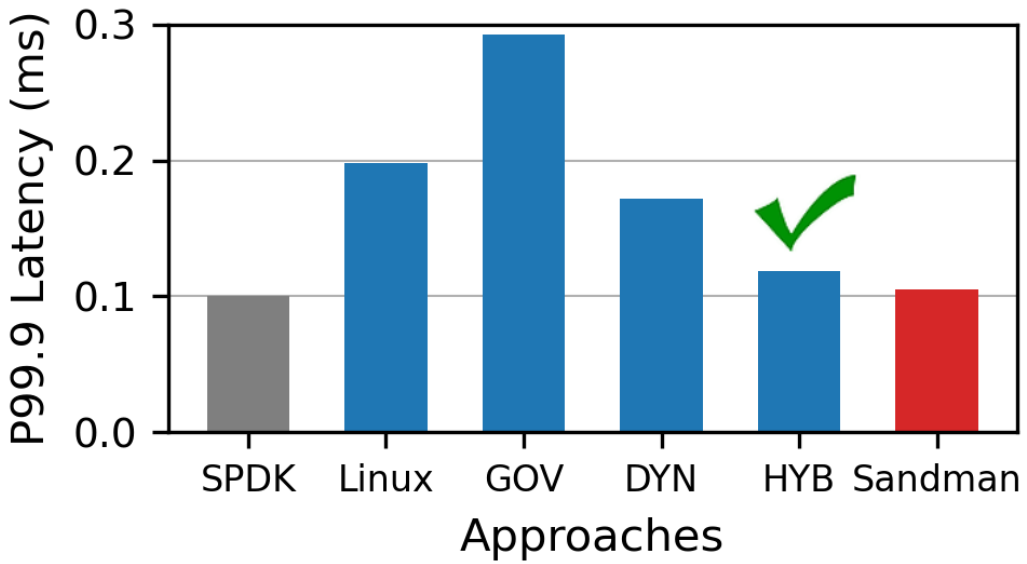

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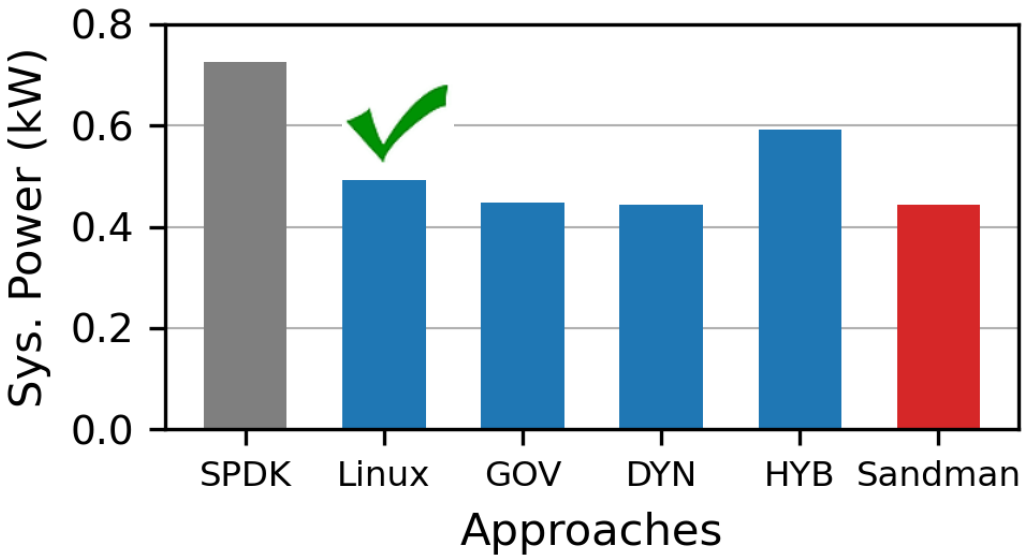

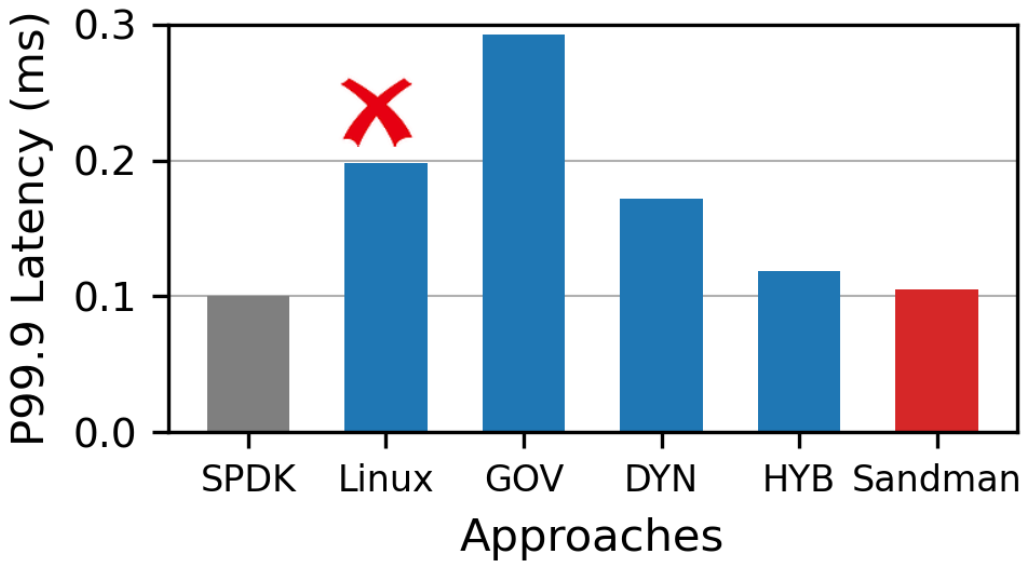

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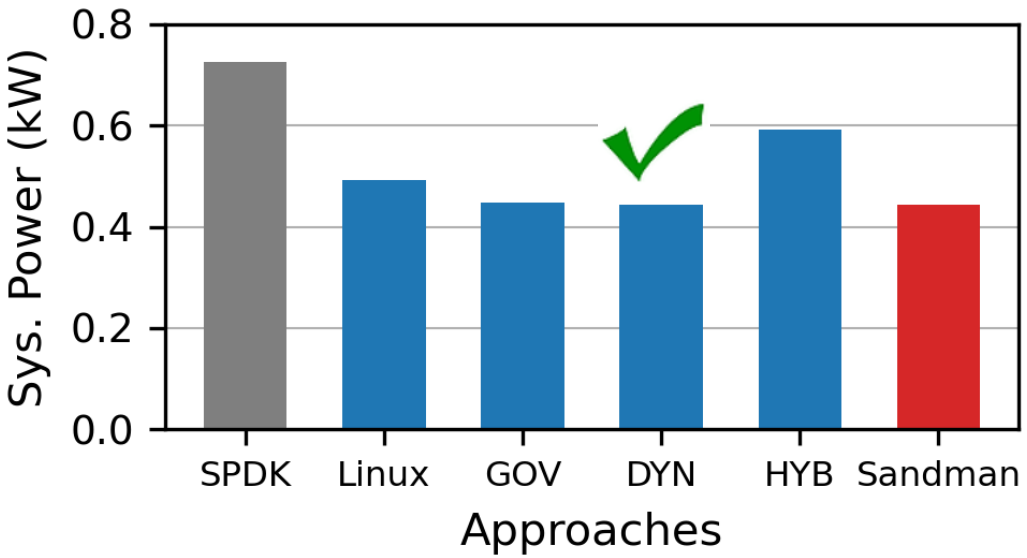

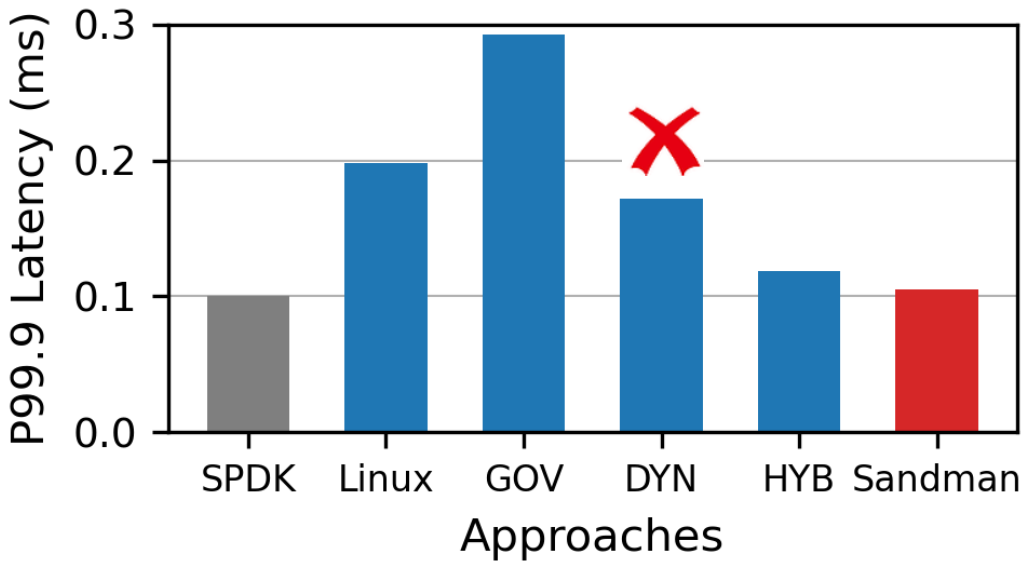

Observation: Dynamic scheduling wakes up sleeping cores through **software-based interrupts**, further leading to high tail latency

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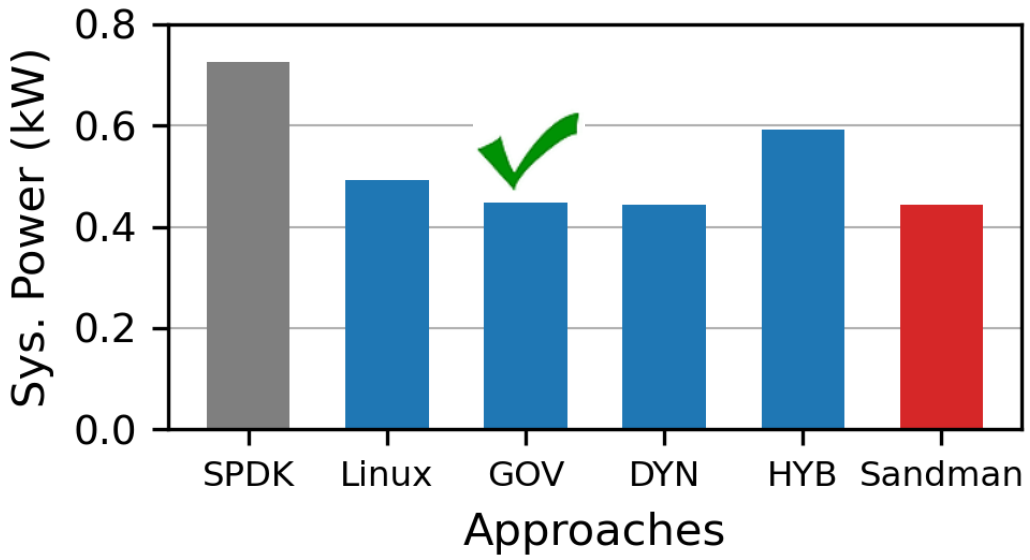
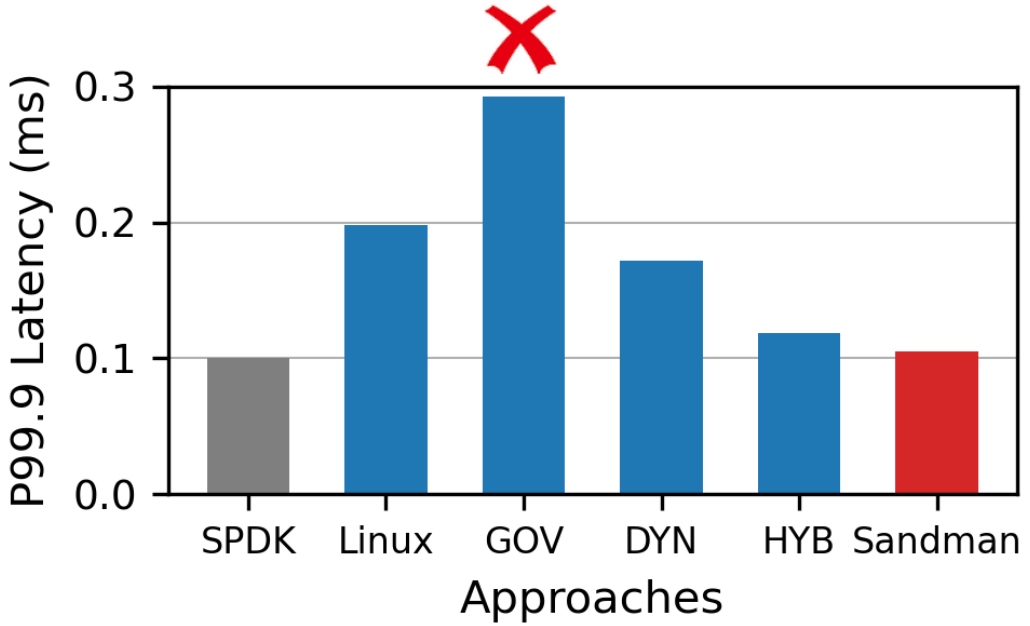
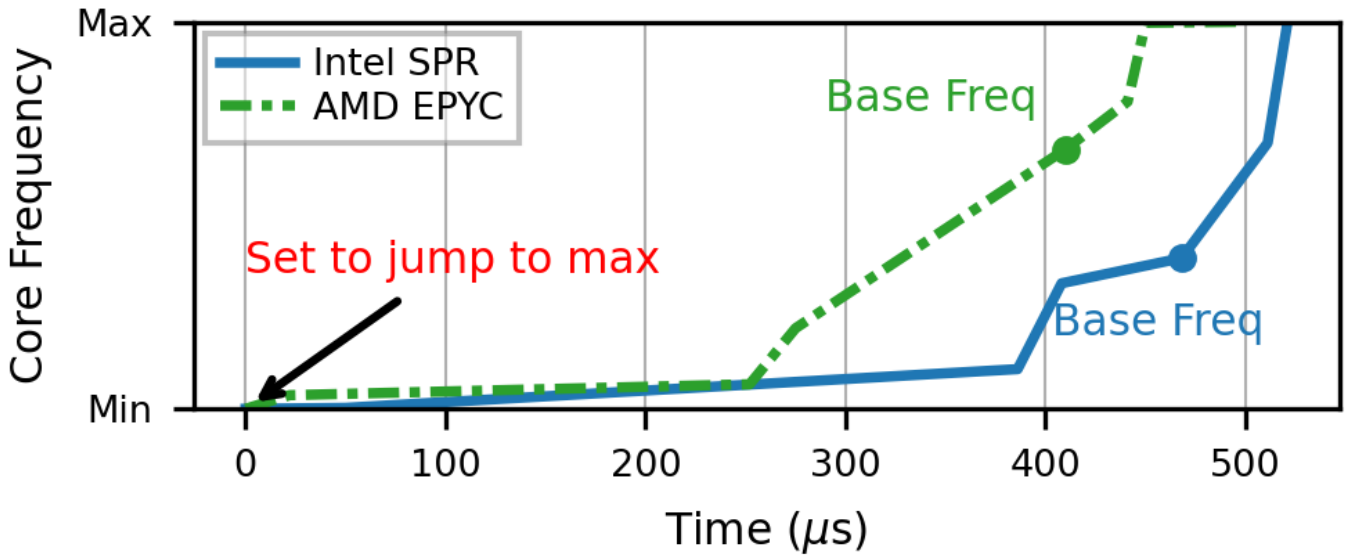




Observation: Governor increases core frequency to handle bursts, but **adjusting cores frequency takes time,** thus leading to high tail latency

Dive Into Core Frequency Scaling Overhead

- Effective CPU frequency is invisible to users
- CPU takes time to increate to high frequency



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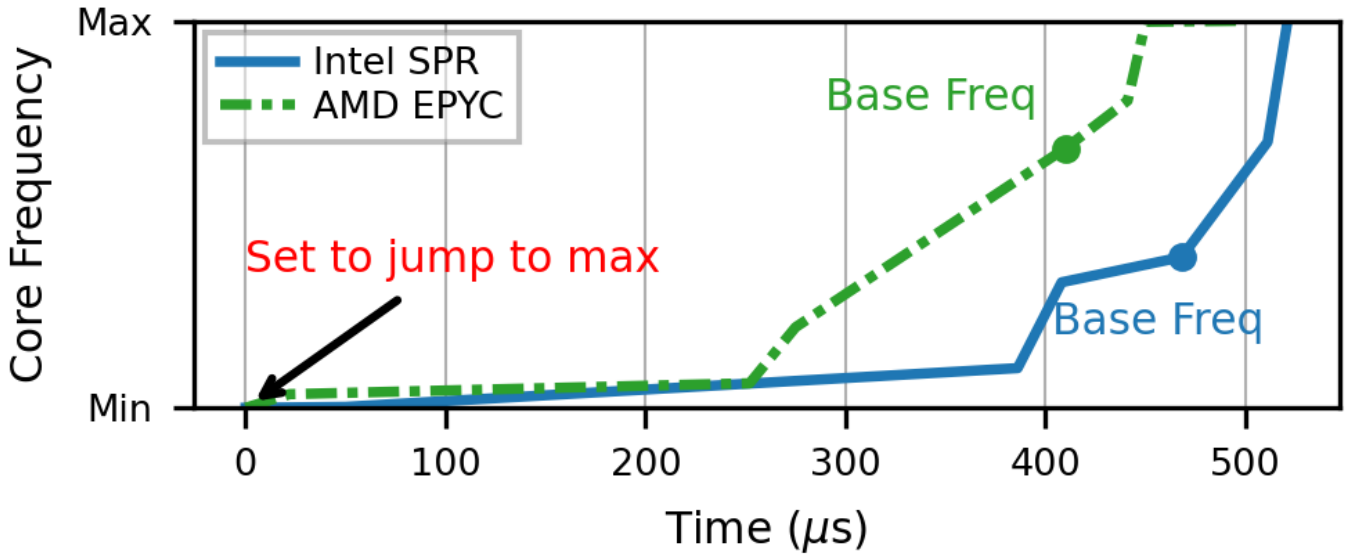
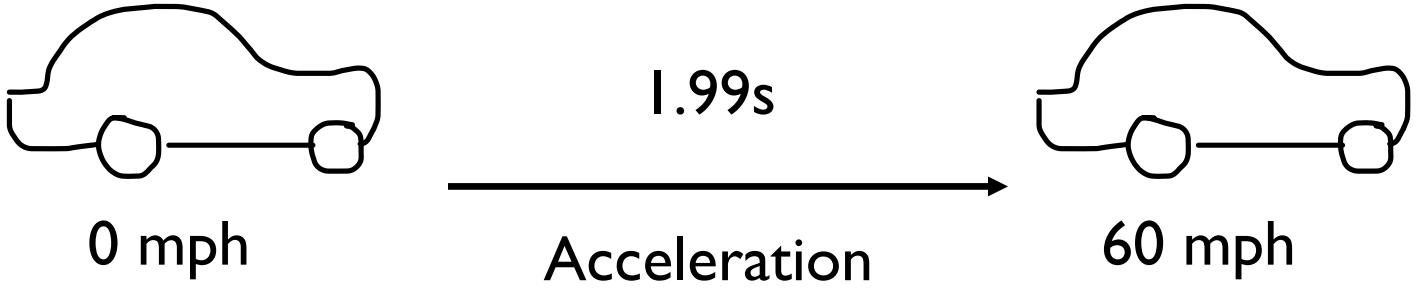




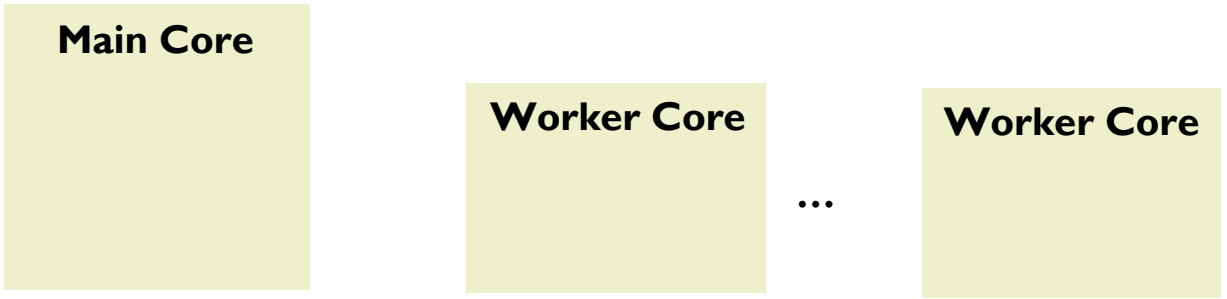
Challenges and Design Guidelines

Challenges	Guidelines
Changing core from low to high power states takes time	Shallow sleep cores NOT lower their frequency
Wake up sleeping cores via SW-based interrupts → high latency	Avoid system calls/interrupts for waking up cores
Frequent transitions from sleep to polling limit power saving	Schedule sibling HT-cores together for longer sleep
Unprecise workload estimation leads frequent thread reallocation	Measure short-term bursts from network queues

Sandman: Scheduler for Fast, Sustainable Storage

System architecture

- Reserve CPU cores as ***worker cores*** and a ***main core*** running in polling mode



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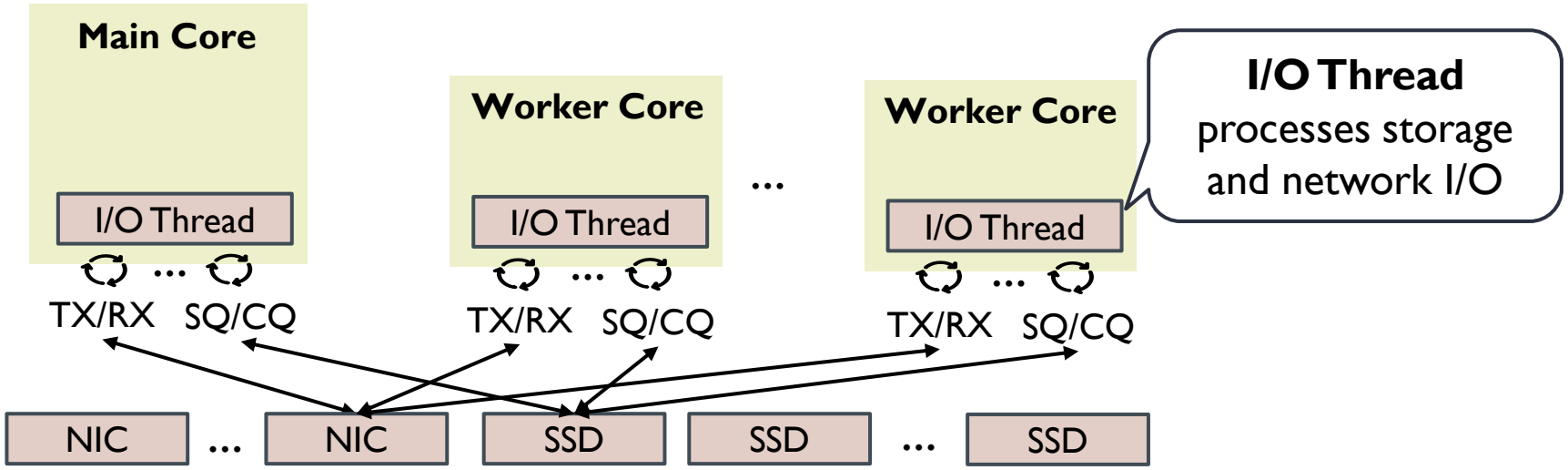

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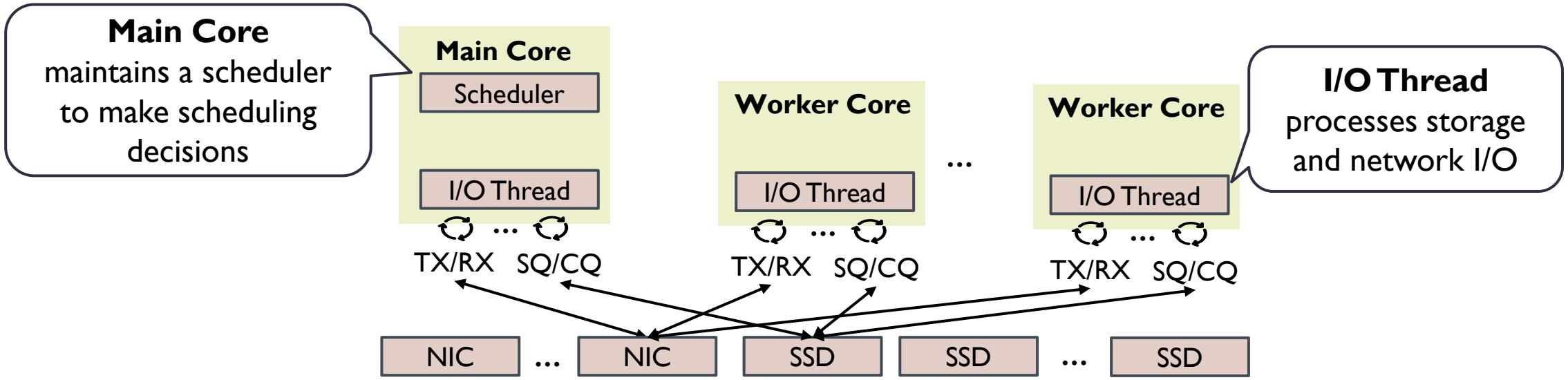

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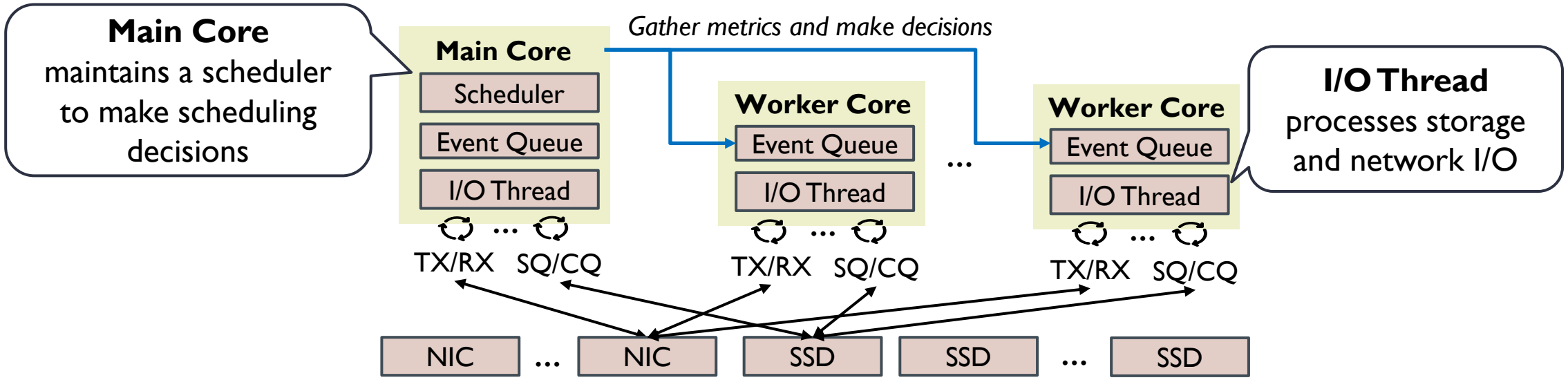

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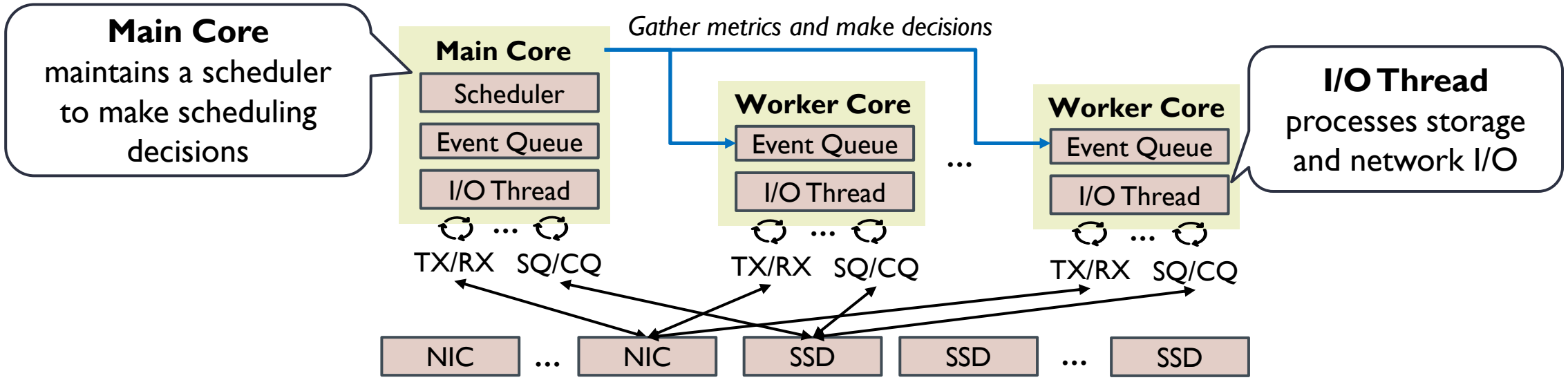

Key design

- Fast Resource Scaling **Mechanism**
- Resource Monitoring and Burst Detection **Policies**

Fast Resource Scaling Mechanism

1. Lightweight I/O threads

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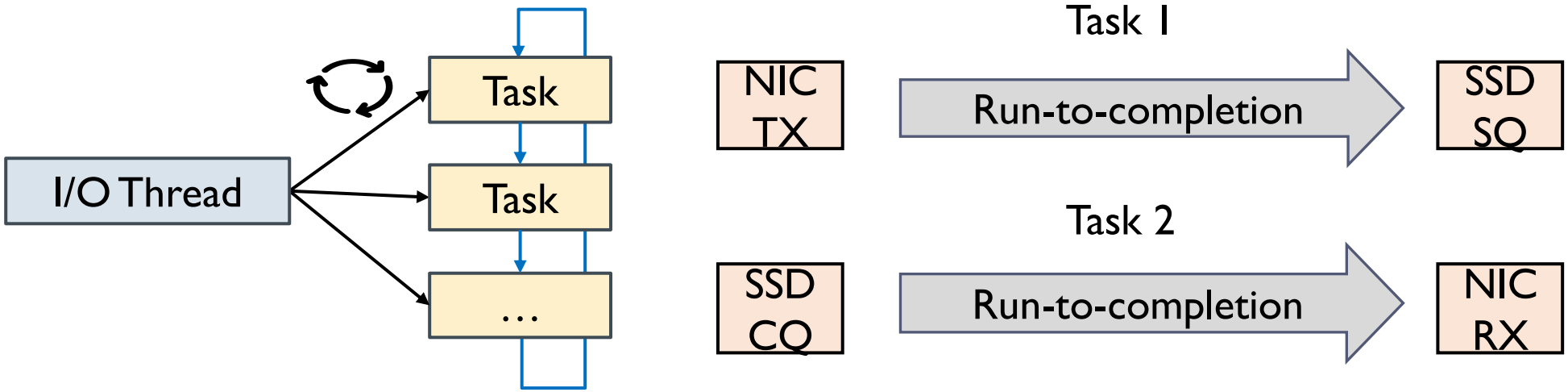

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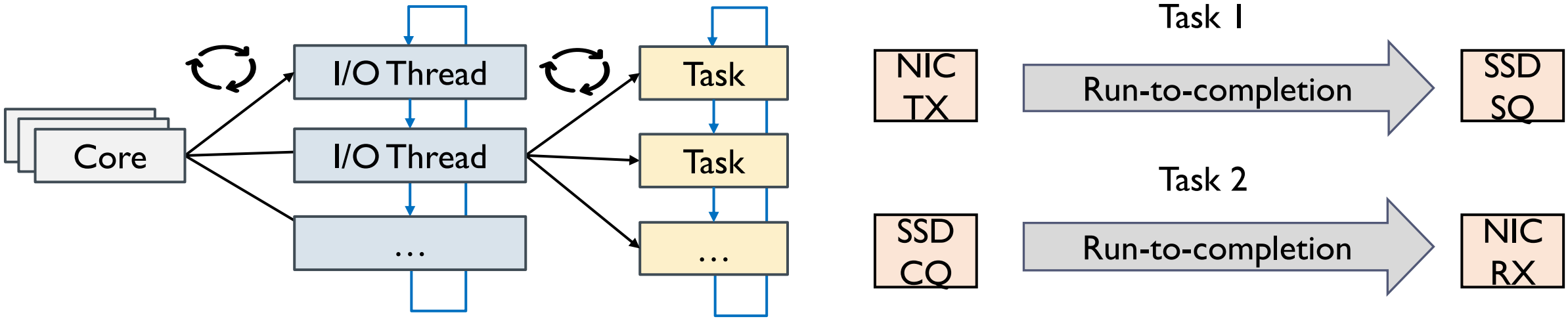

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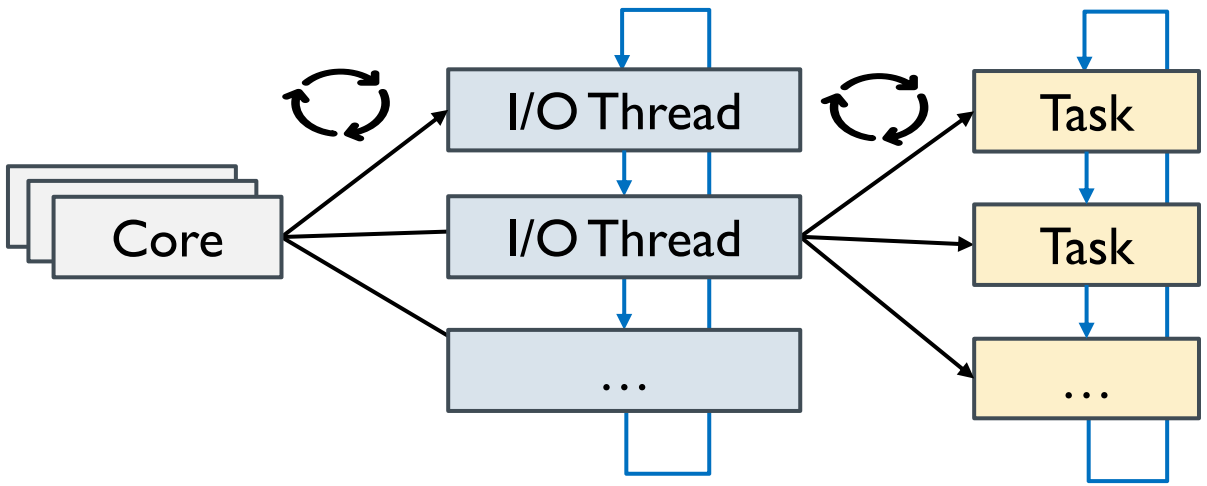
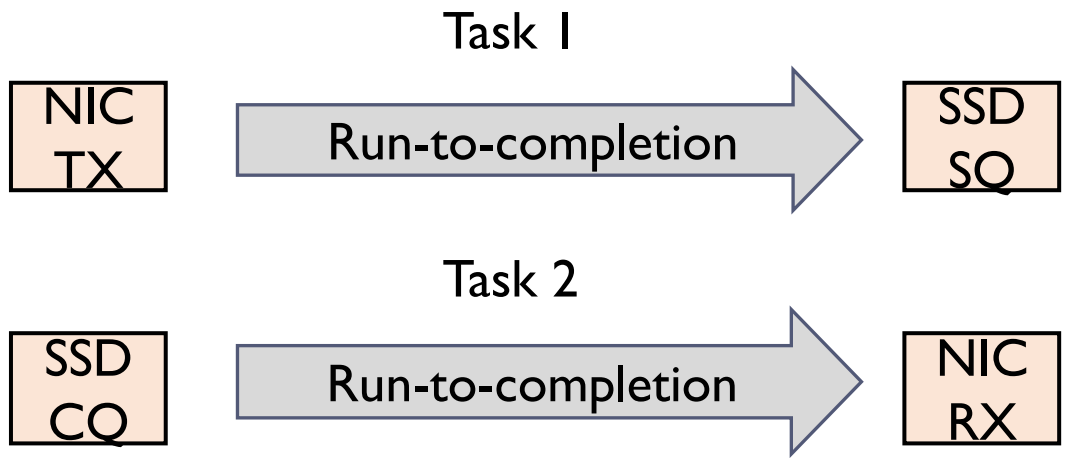
- **CPU Core**: one core maintains multiple threads through linked list
- **Migration**: removing a thread from the core's list and insert to another core's list

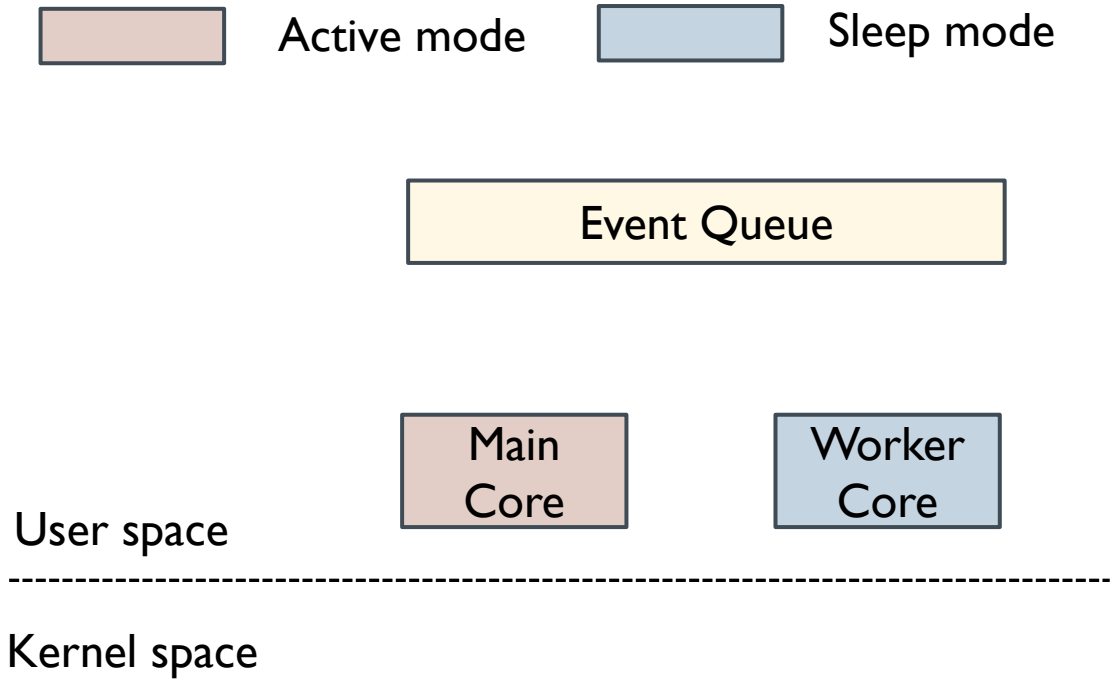




Fast Resource Scaling Mechanism

2. Shallow sleep with instant transition

- **Goal**: wake up CPU core rapidly without overhead
- Wake up core through **HW cache-coherency** instead of **SW interrupts**



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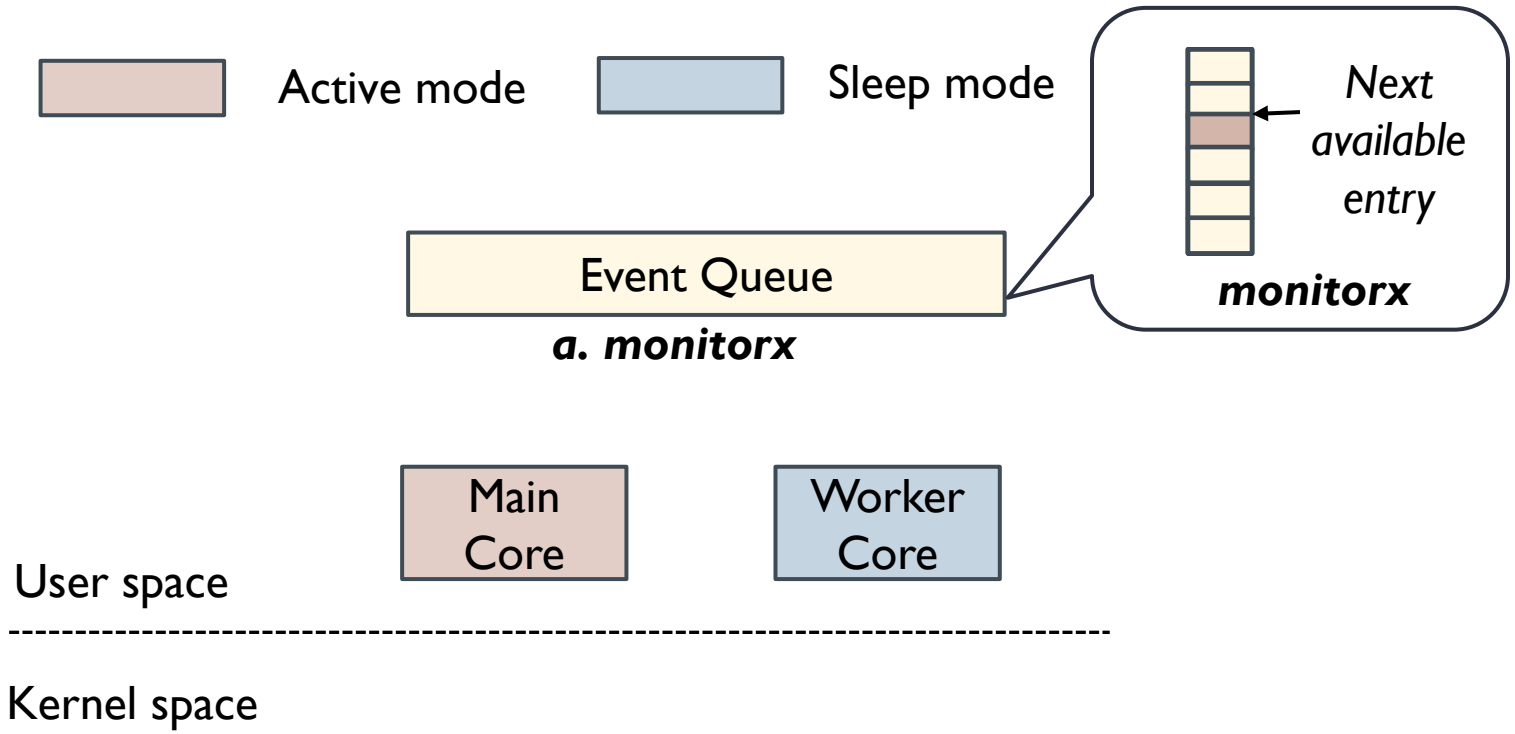

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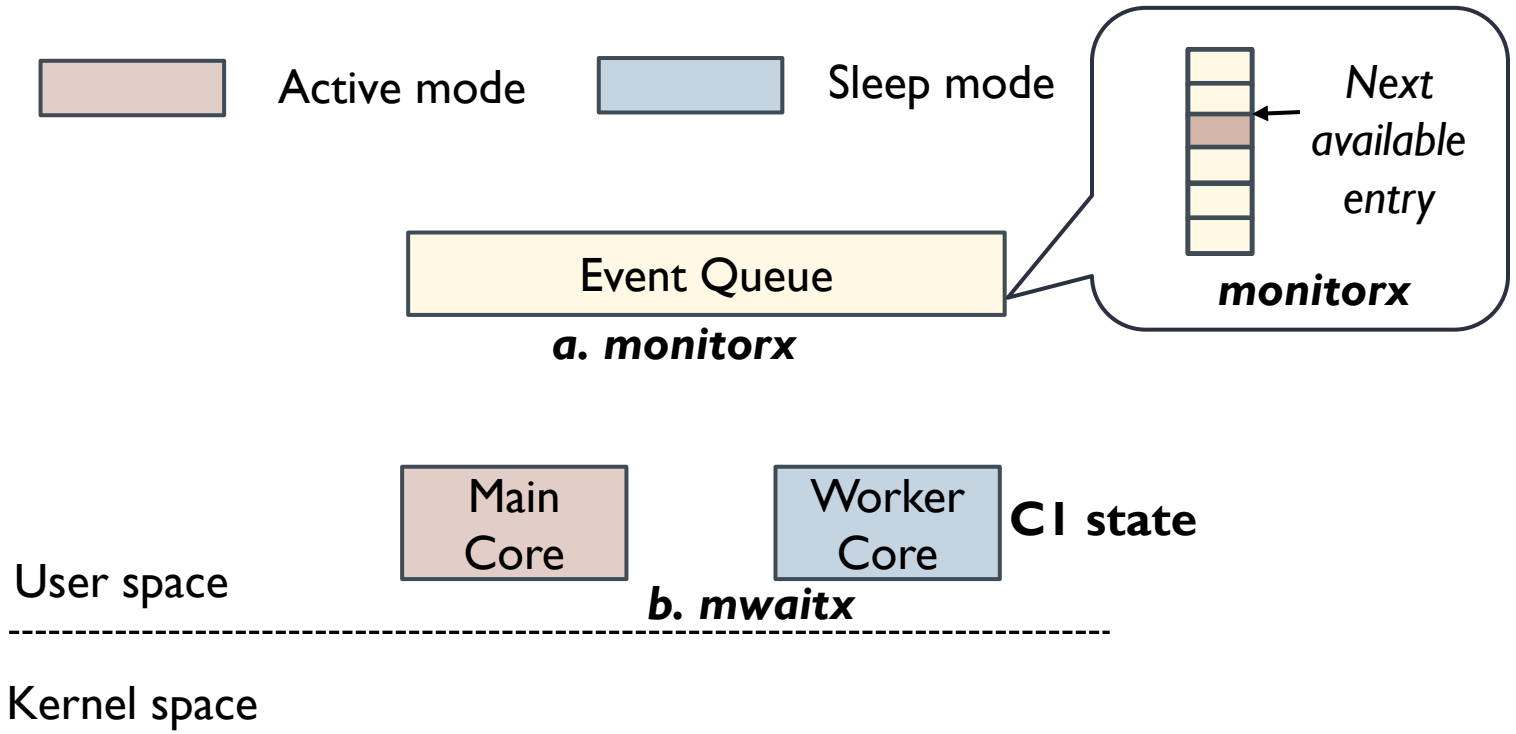

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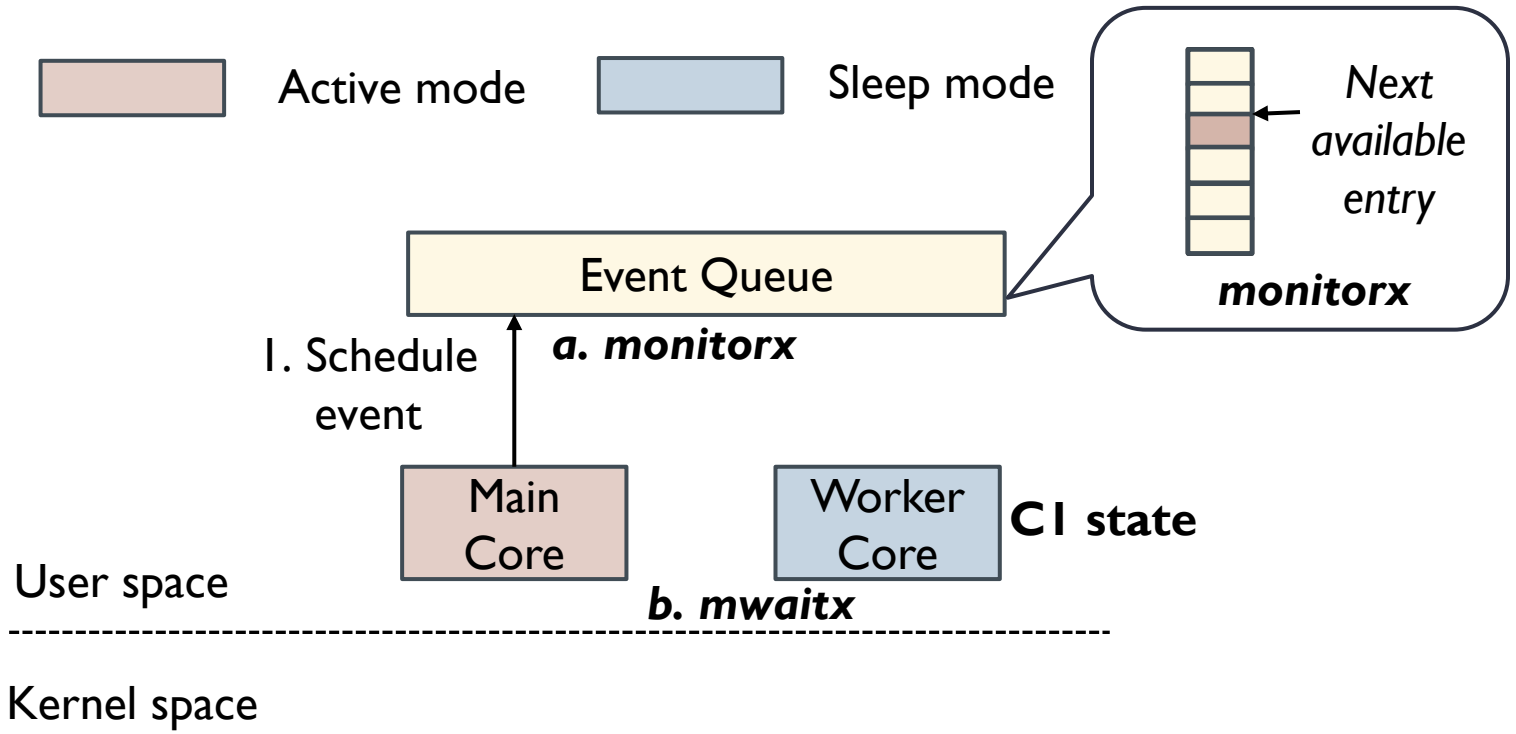

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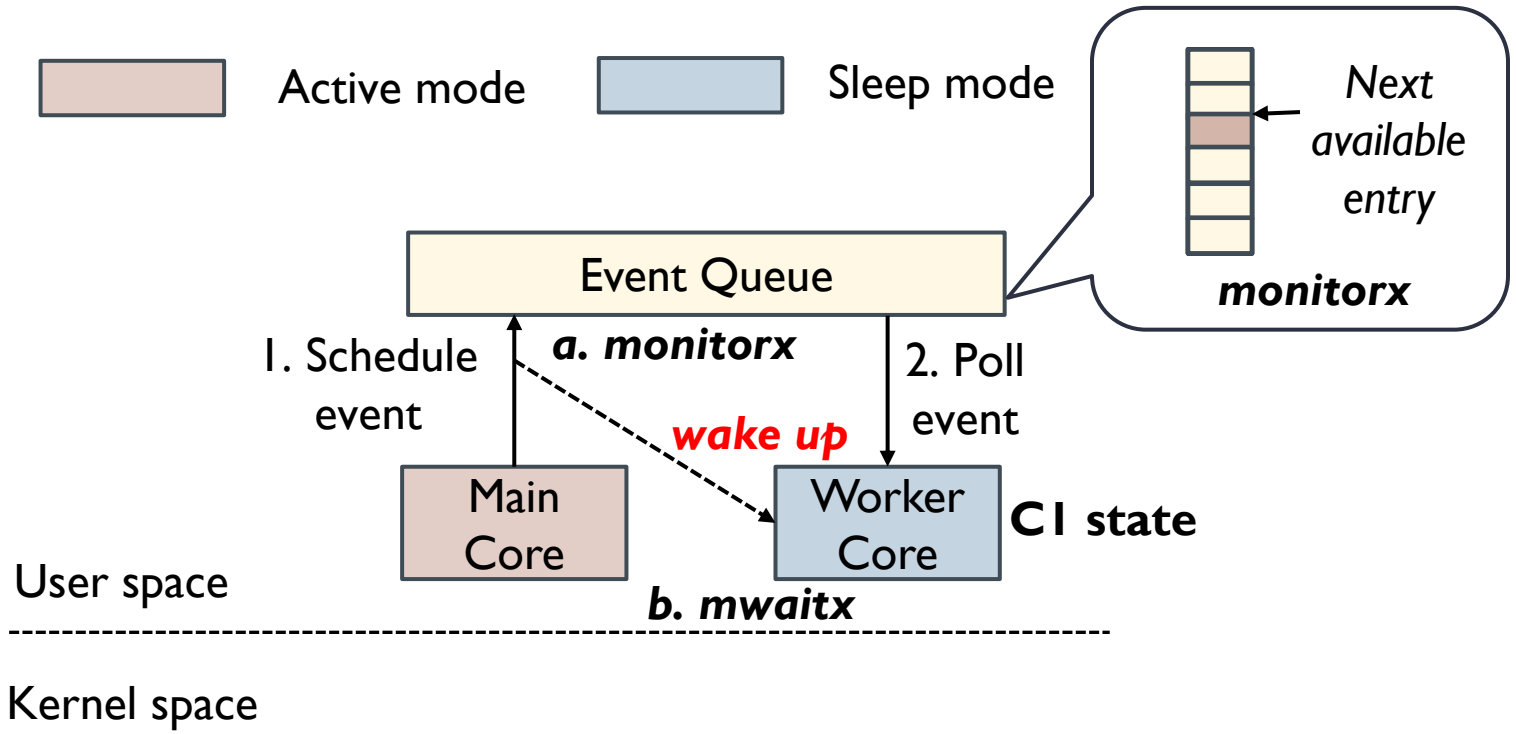

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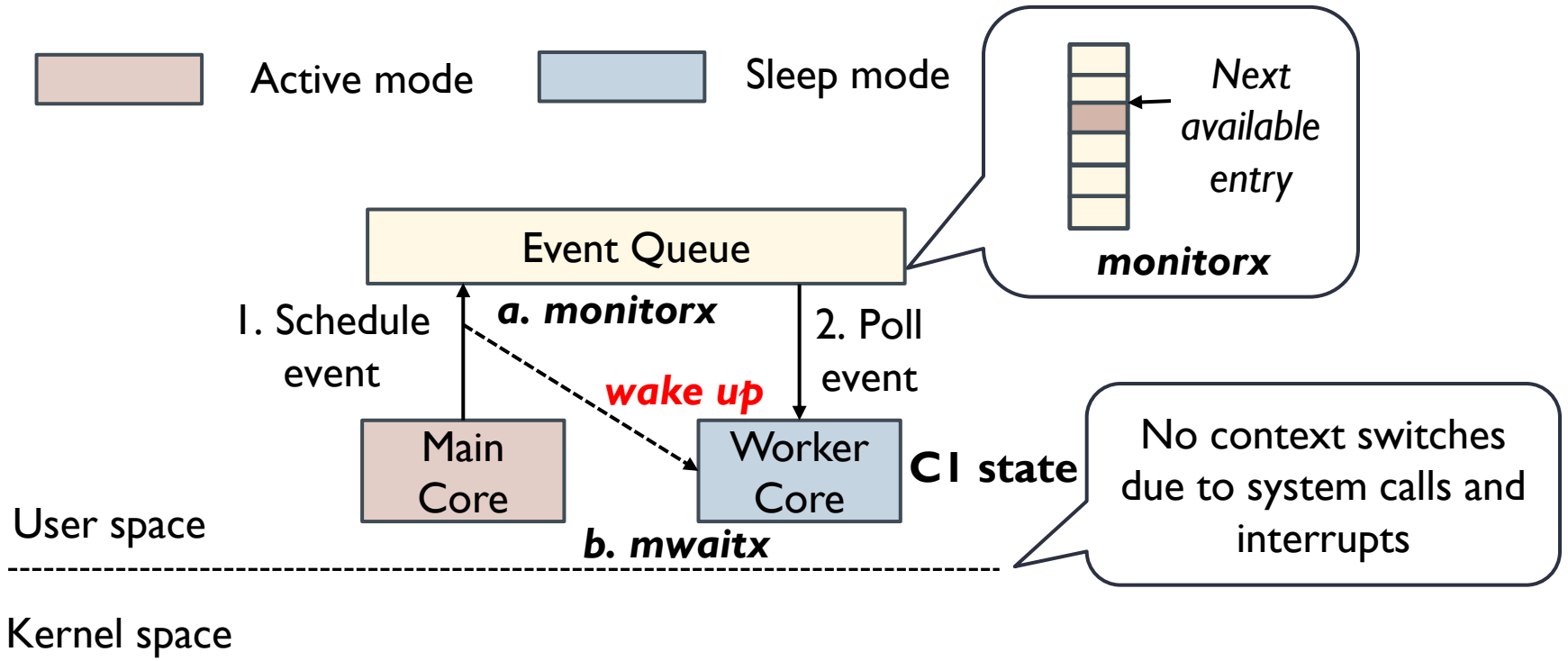
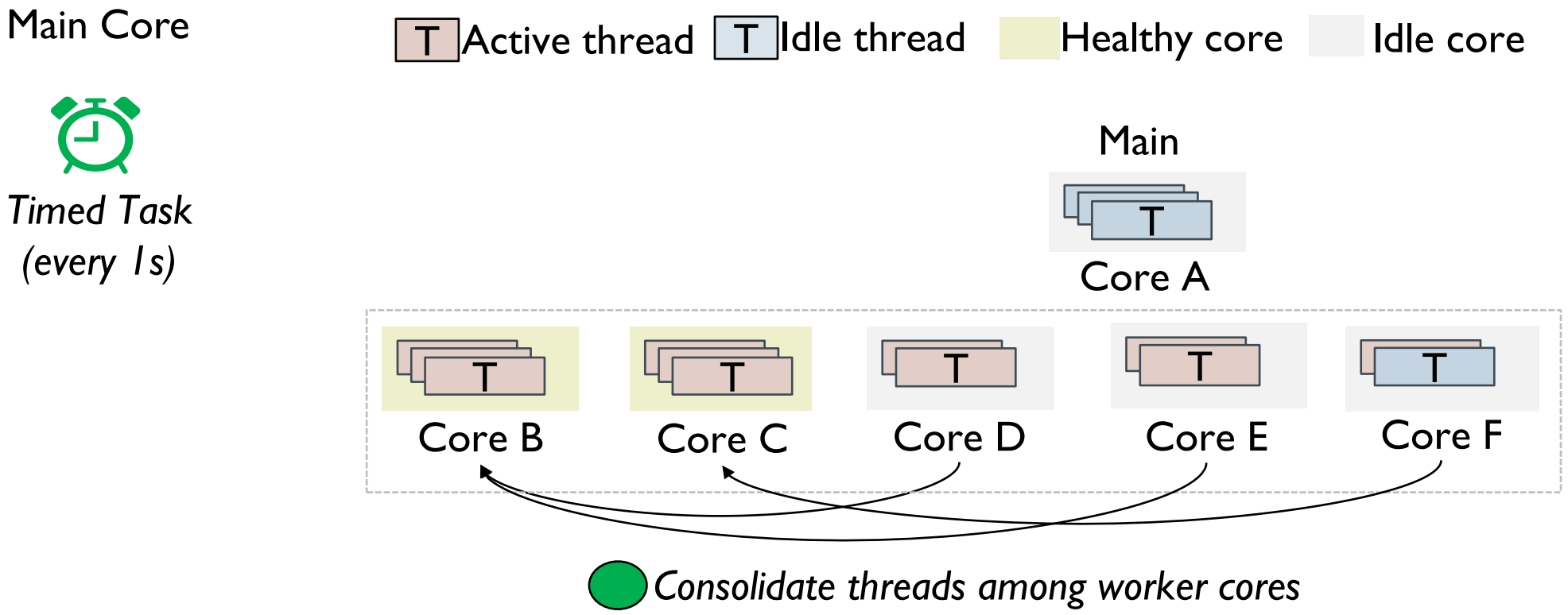


Scheduling Flow Overview

Two granularities of scheduling

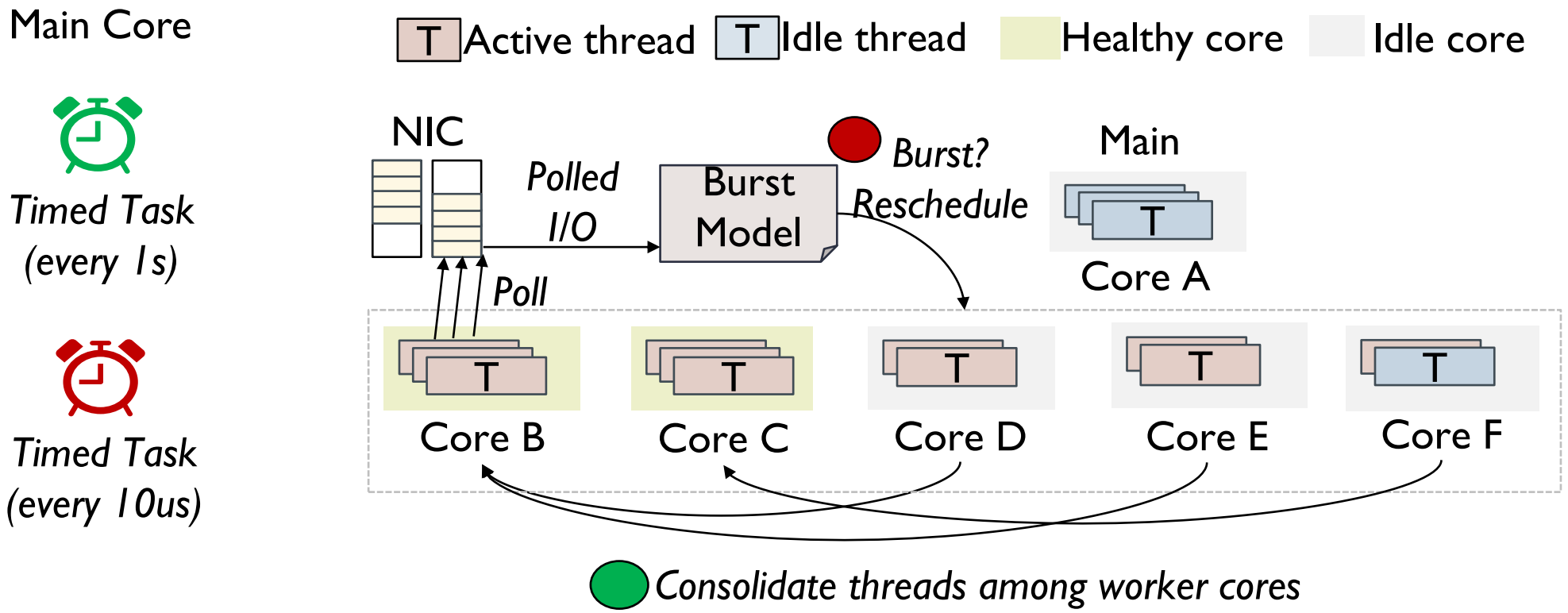
- Coarse-grained (1s): monitor resource wastage for power saving



Scheduling Flow Overview

Two granularities of scheduling

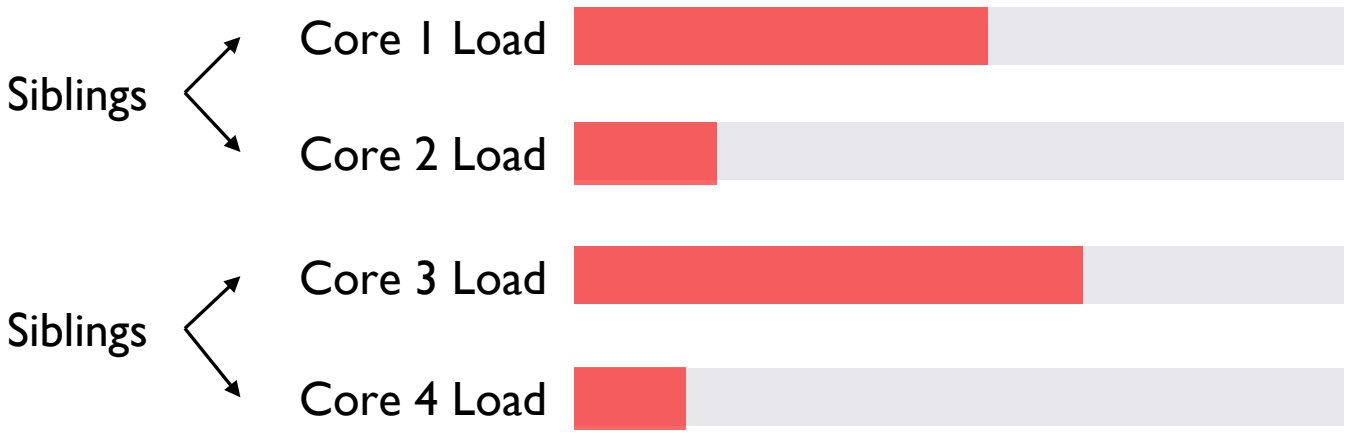
- Coarse-grained (1s): monitor resource wastage for power saving
- Fined-grained (10us): detect I/O bursts for performance



Monitoring Resource Wastage

Goal: let more (physical) cores to sleep and thus save power

1. Consolidate threads of idle cores into healthy cores



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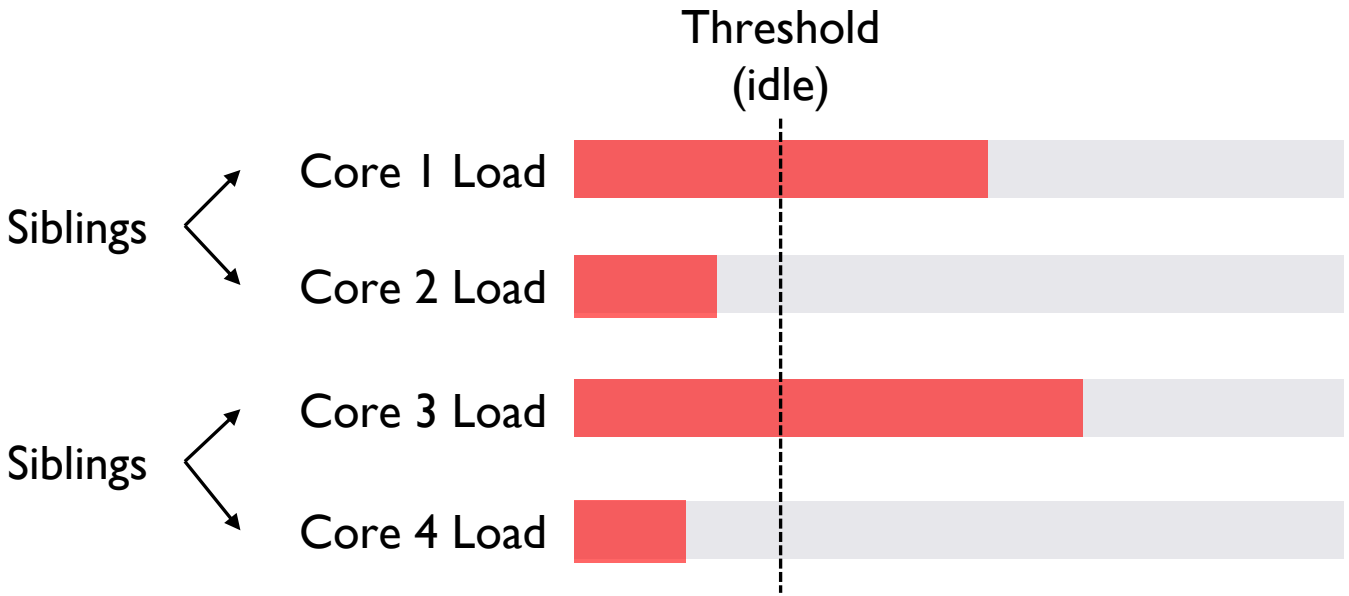

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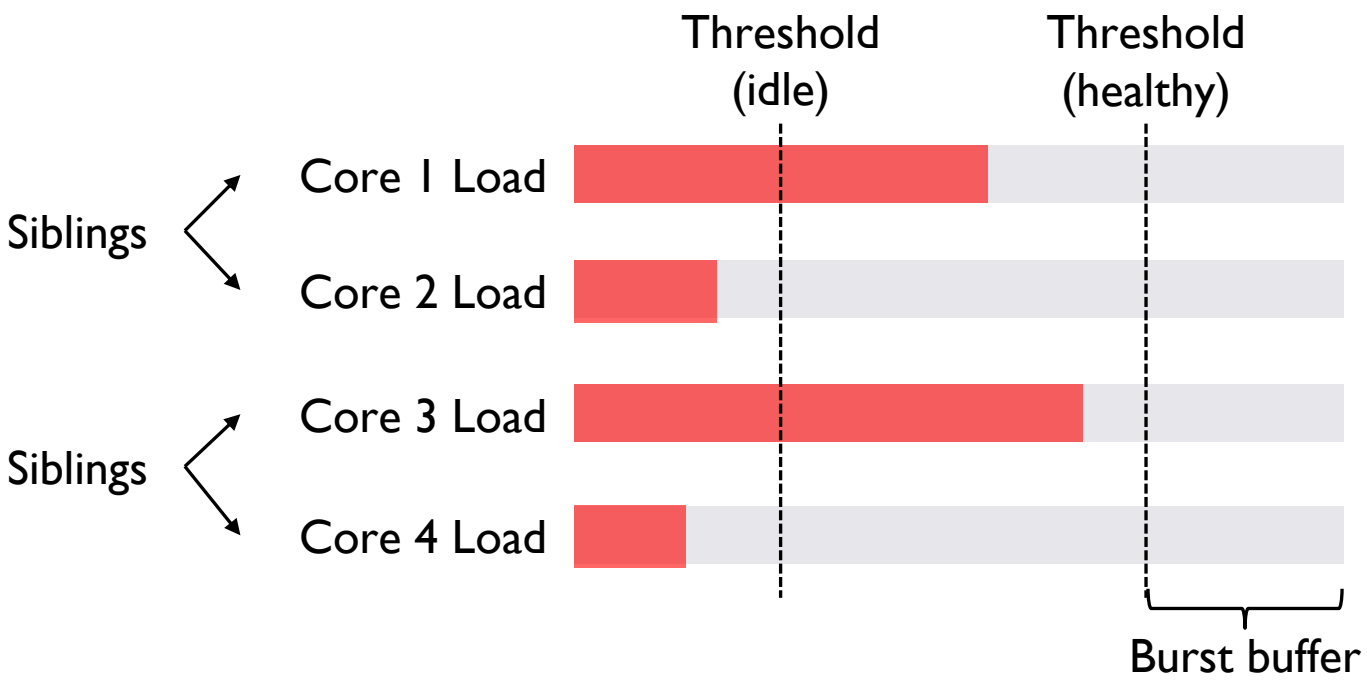

Reserve burst buffer (CPU cycles) shared by all threads on the same core for handling bursts

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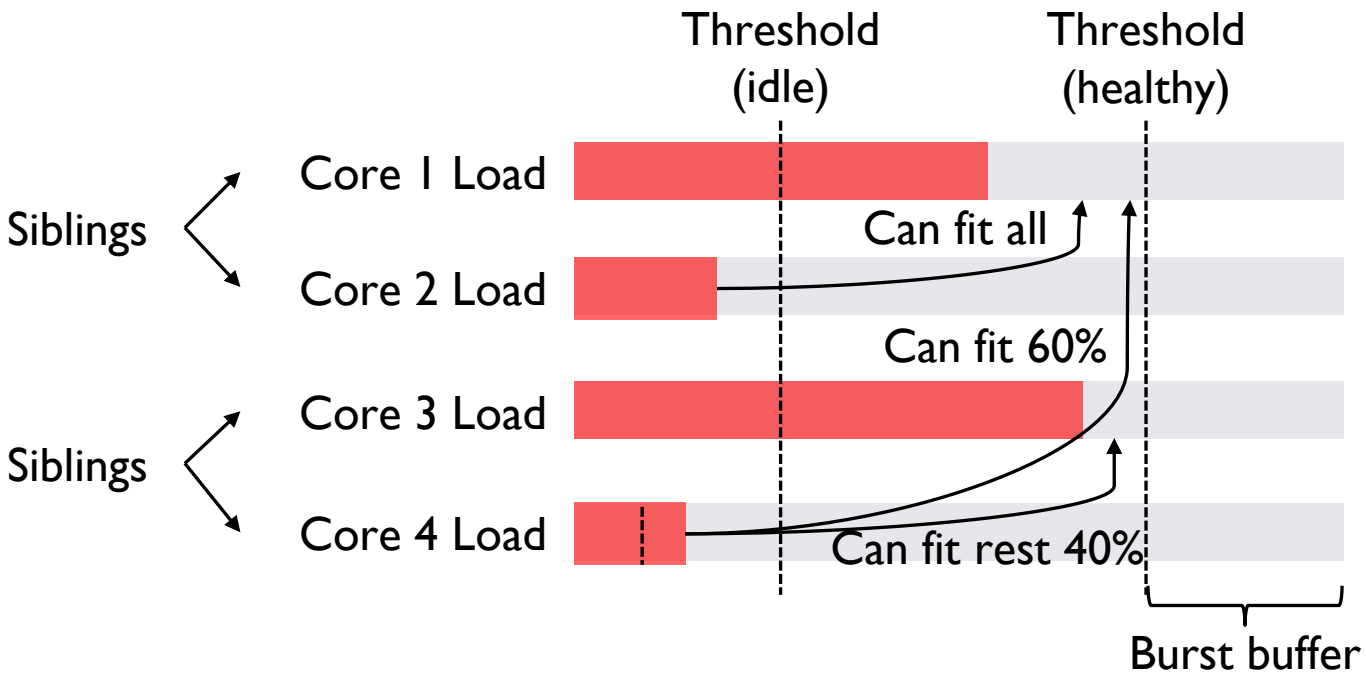

Reserve burst buffer (CPU cycles) shared by all threads on the same core for handling bursts

Check whether core can fit thread based on thread load and core load

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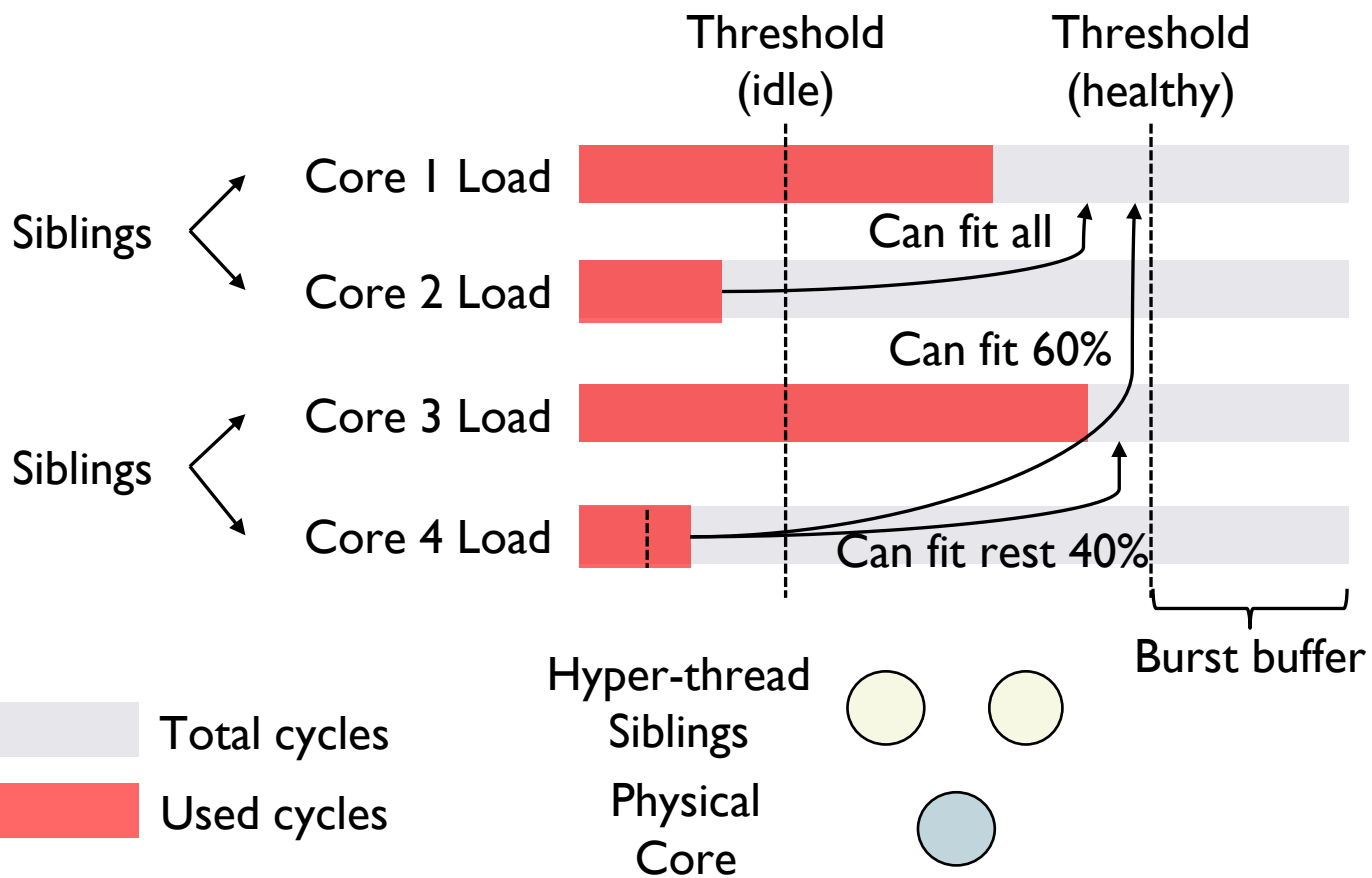
2. **Schedule sibling cores to sleep together**



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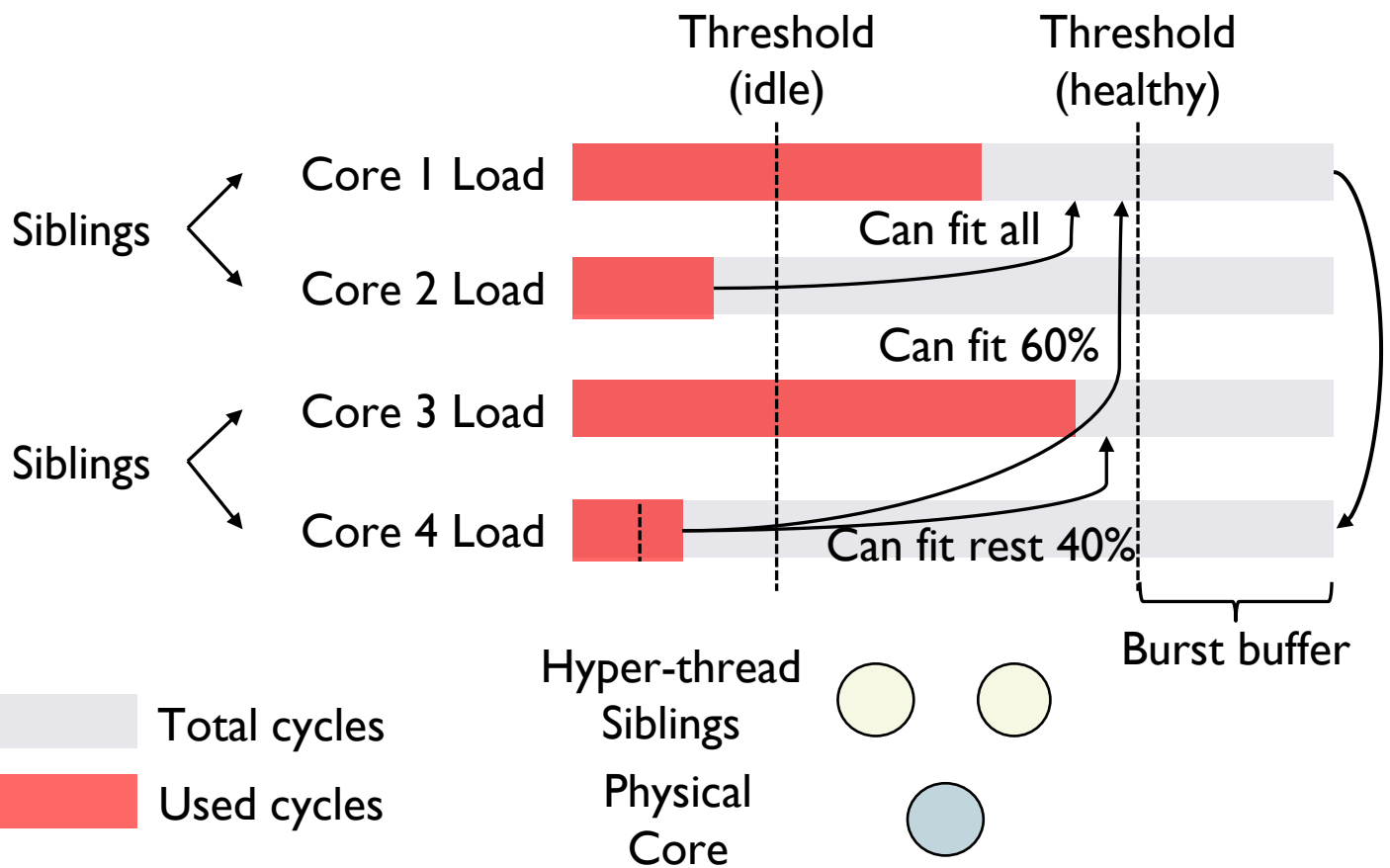


Reserve burst buffer (CPU cycles) shared by all threads on the same core for handling bursts

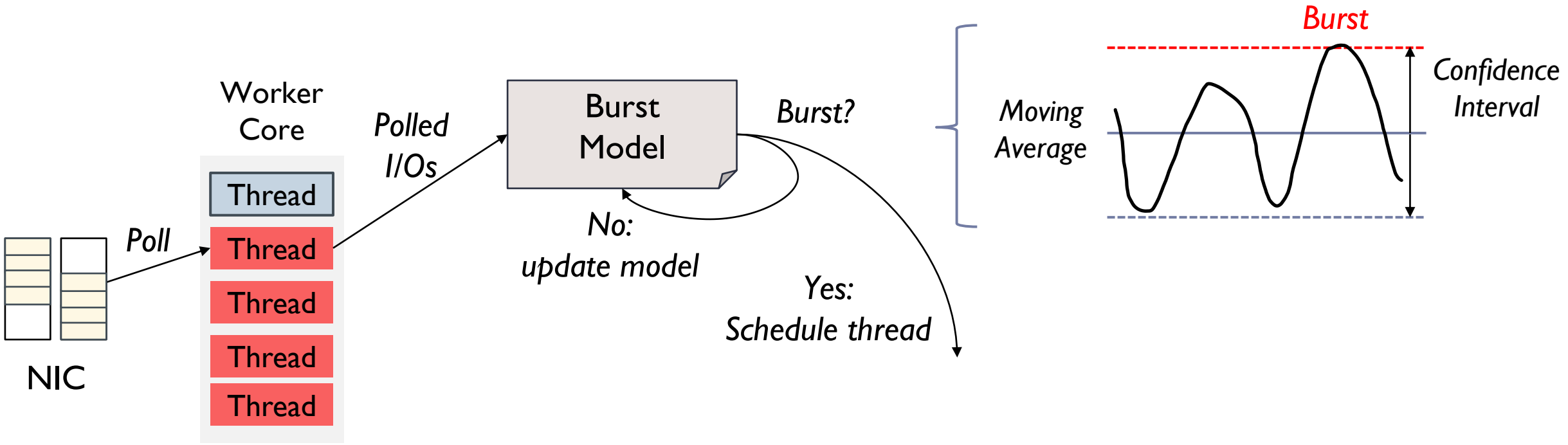
Check whether core can fit thread based on thread load and core load

Move threads of an active core to another free core if its sibling is idle and ready to sleep

Detecting I/O Bursts

Goal: scale compute resources timely for performance

1. Spread out threads that require more compute resource

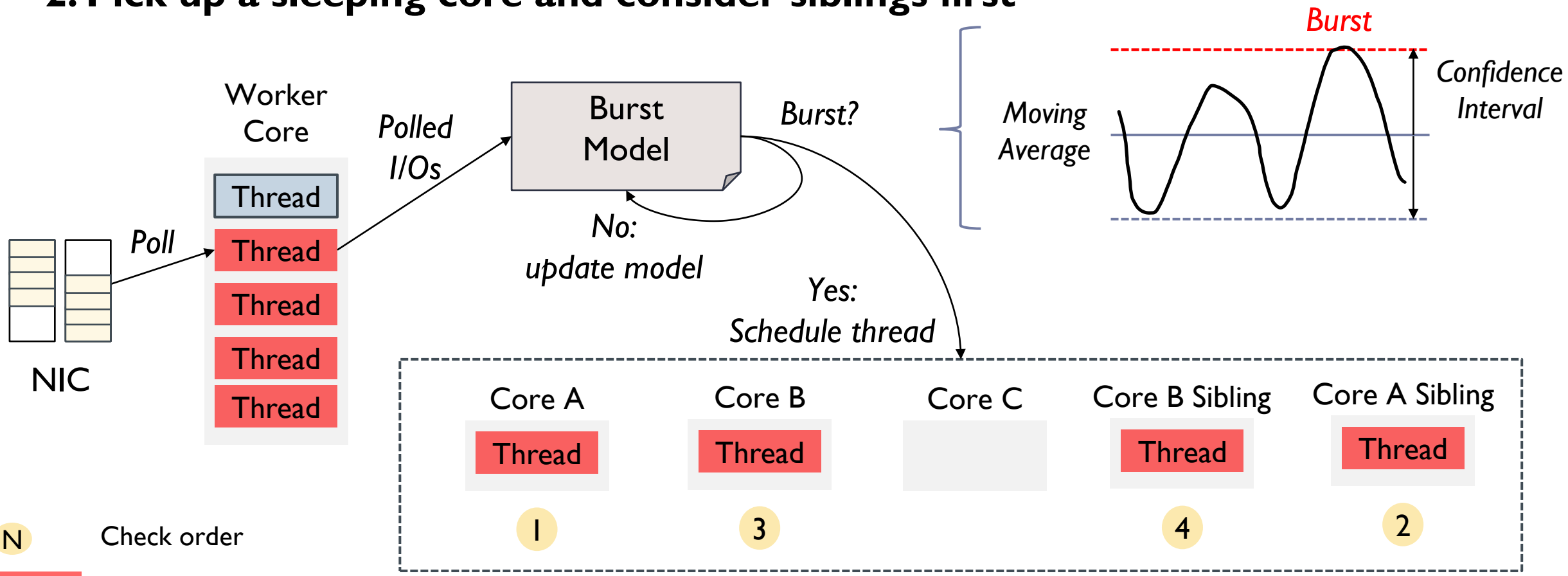


Thread Thread to be scheduled

Detecting I/O Bursts

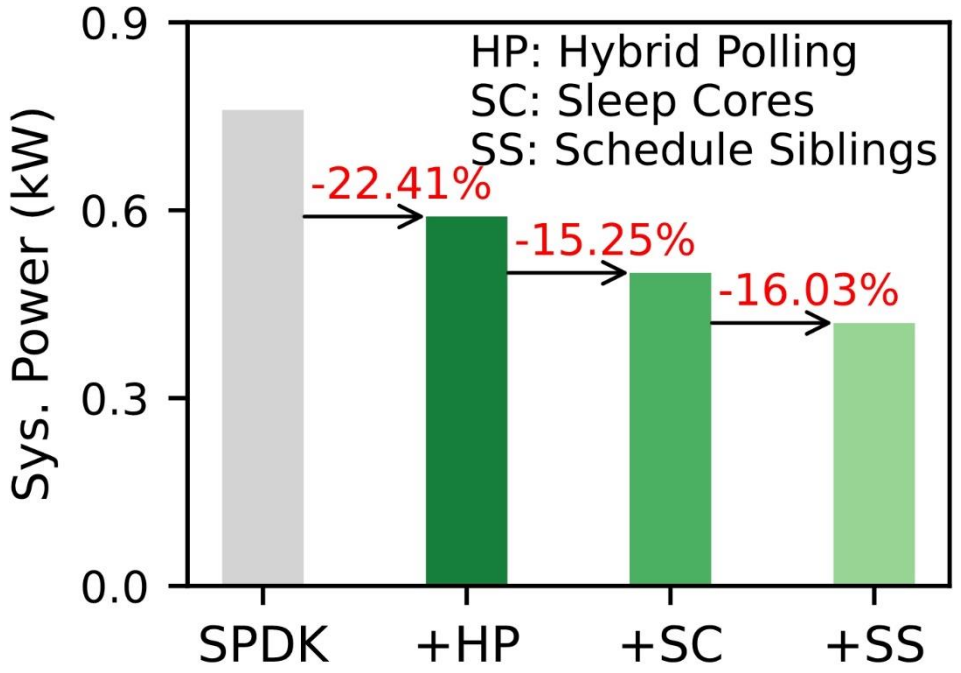
Goal: scale compute resources timely for performance

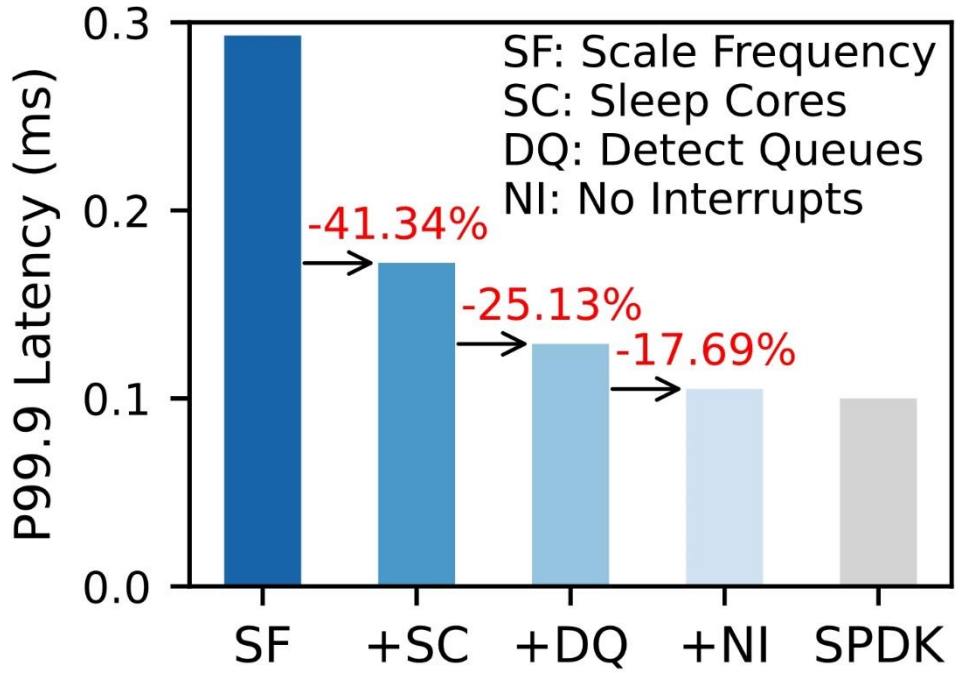
1. Spread out threads that require more compute resource
2. **Pick up a sleeping core and consider siblings first**



Evaluation

Ablation study – under bursty workloads





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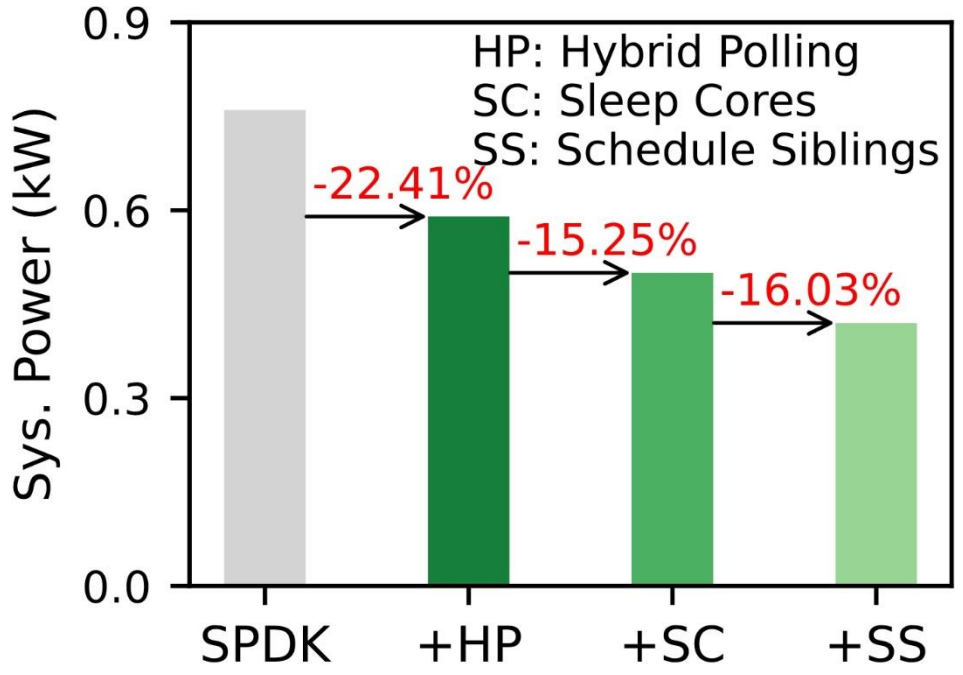
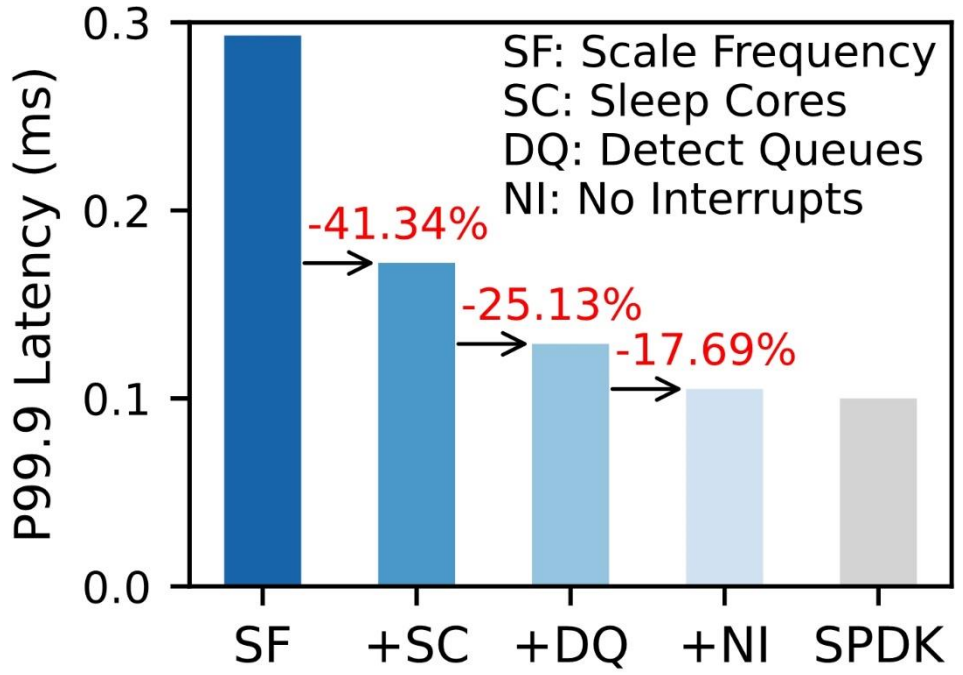
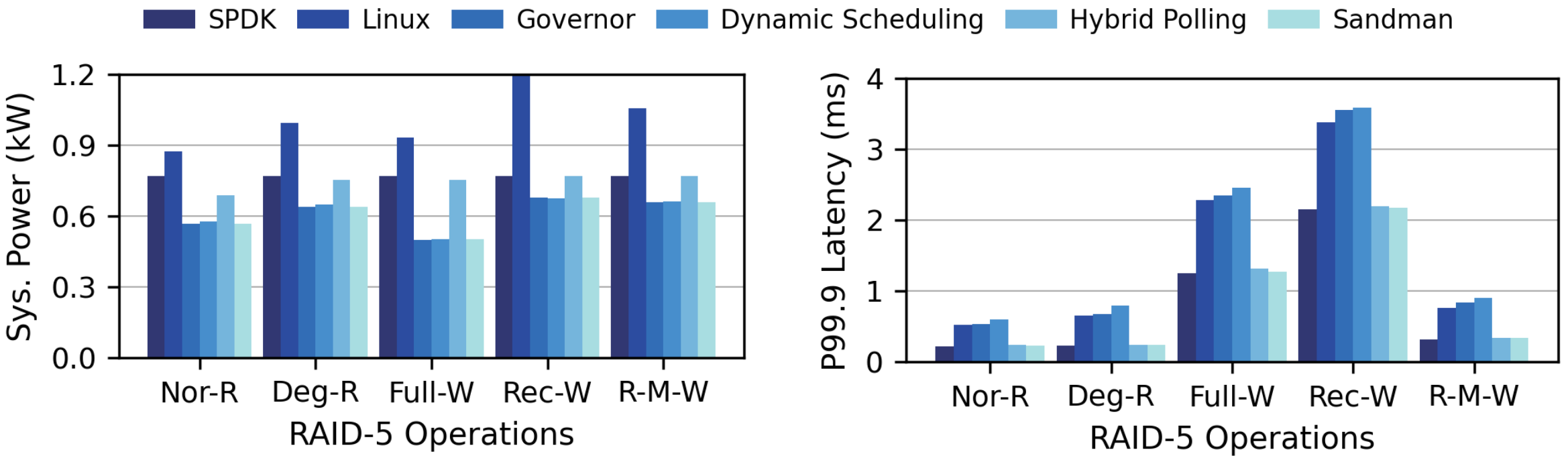




Putting everything together, Sandman achieves **latency comparable to the busy-polling stack**, while significantly **reducing power consumption**.

Application Benefits

Flash array configured with RAID-5



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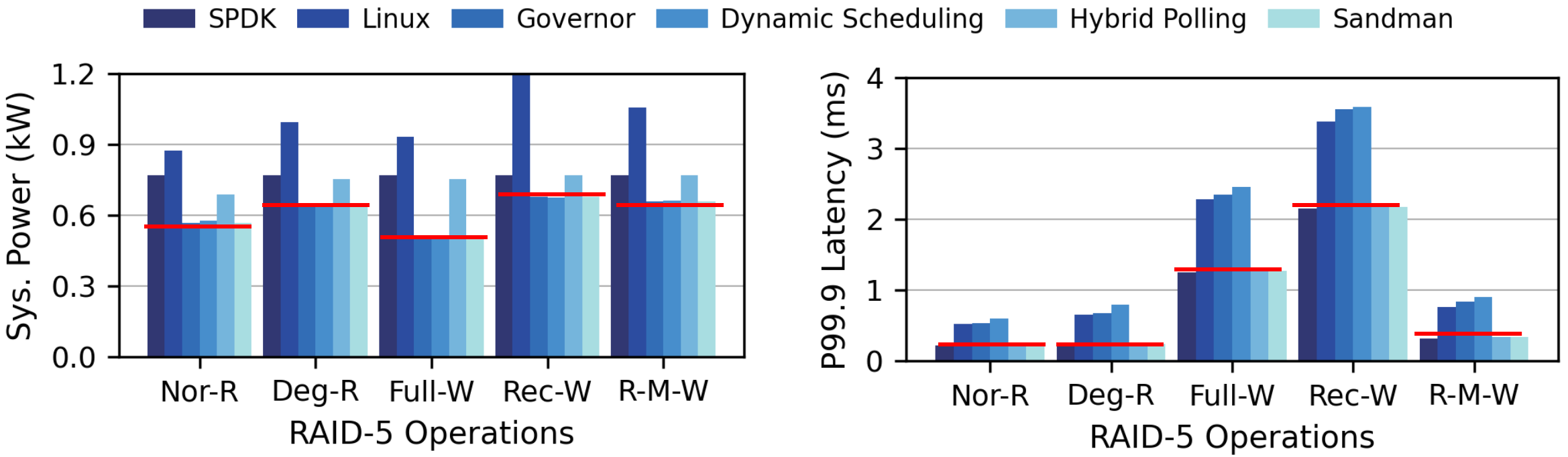
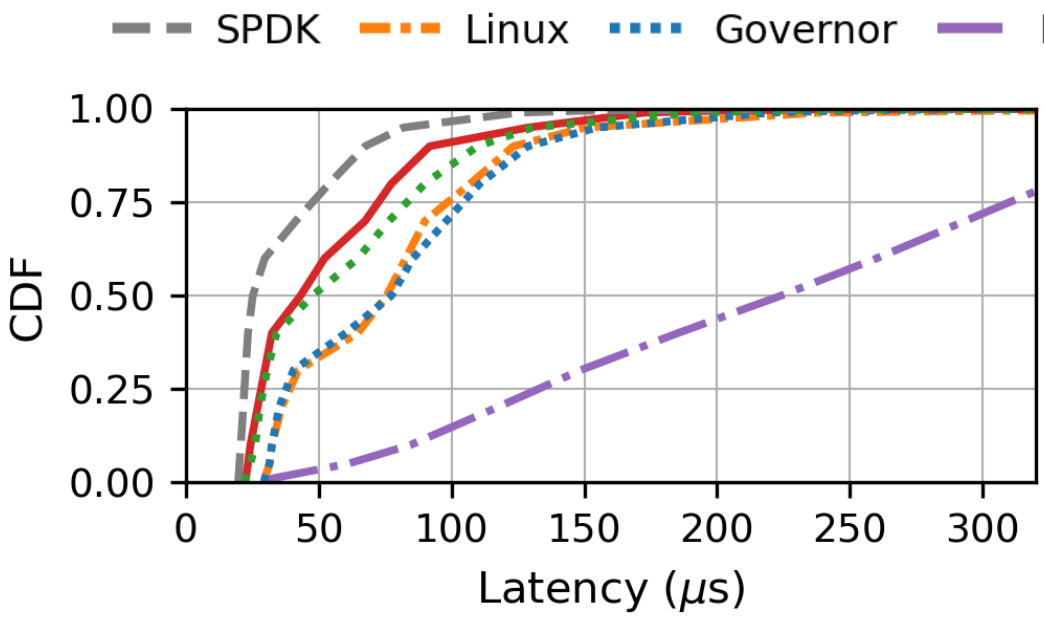


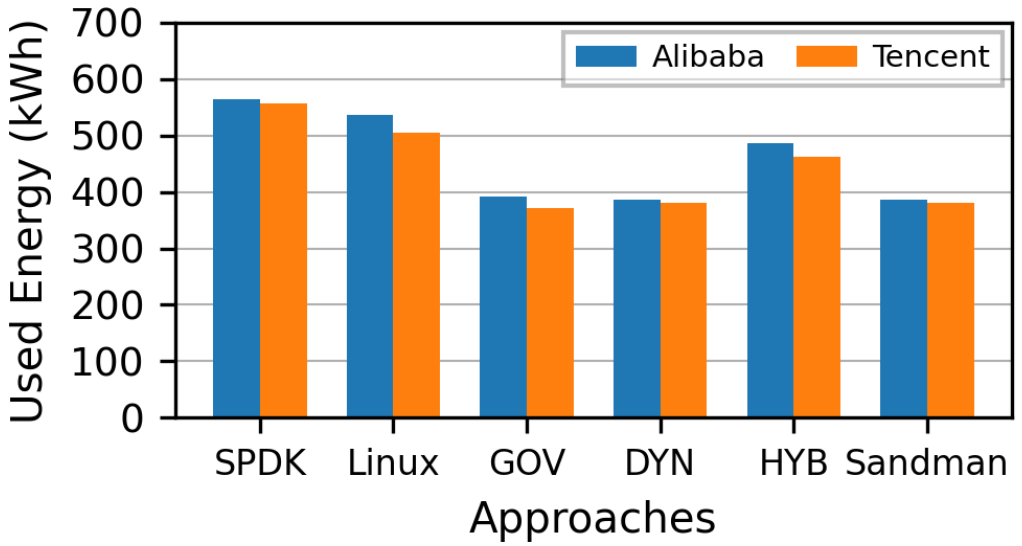
Sandman achieves comparable latency to SPDK but reduces power consumption **up to 39.38%** under flash array with RAID-5

Benefits under Cloud Workloads

Replaying block-level traces from two public cloud vendors



Latency CDF under Alibaba's Trace



Monthly Energy Consumption

Benefits under Cloud Workloads

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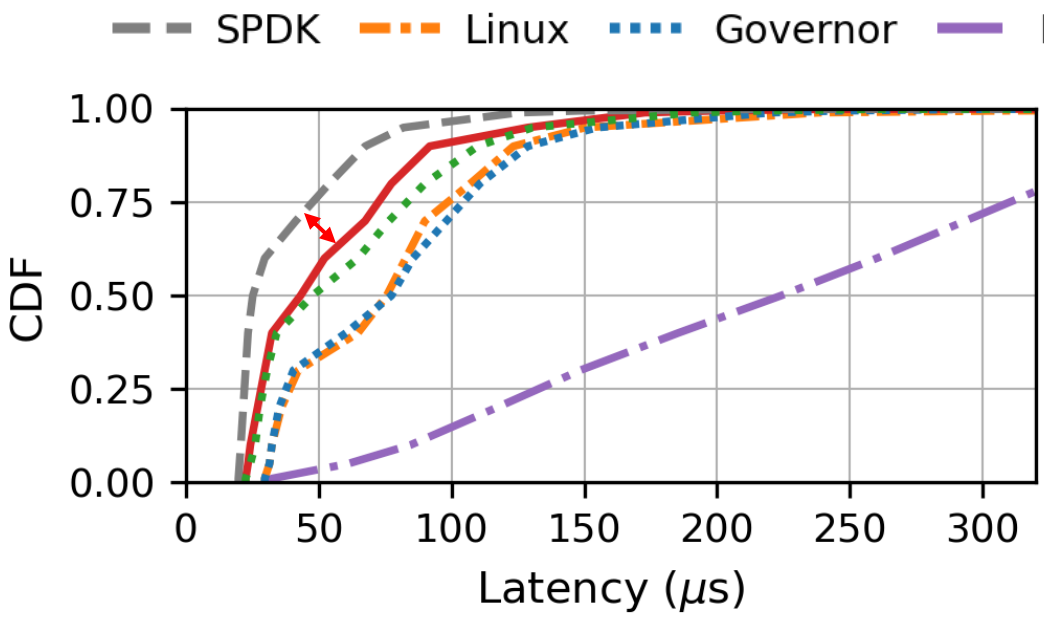

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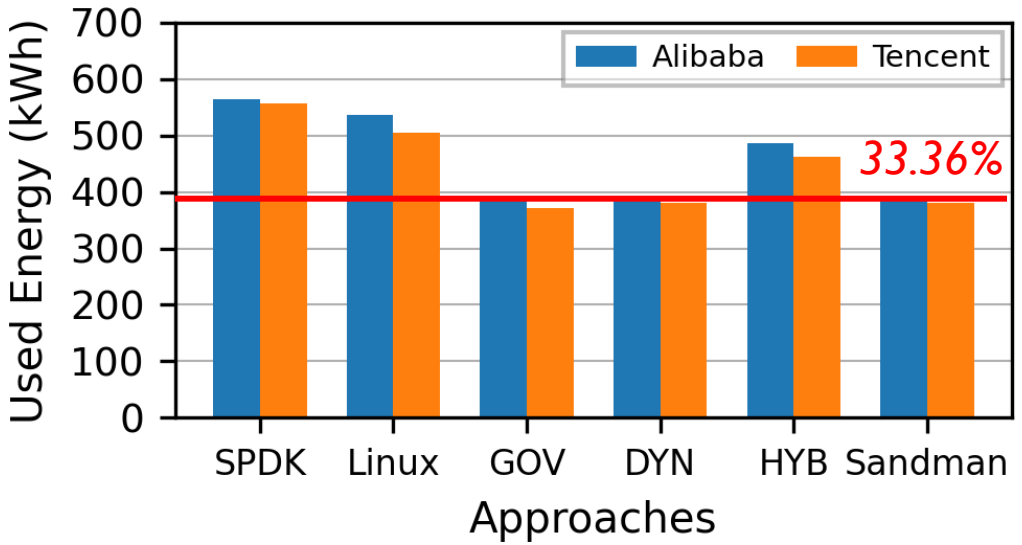


Monthly Energy Consumption

Sandman achieves latency close to SPDK while reducing energy consumption by **33.36% vs. SPDK** under cloud workloads

Takeaways

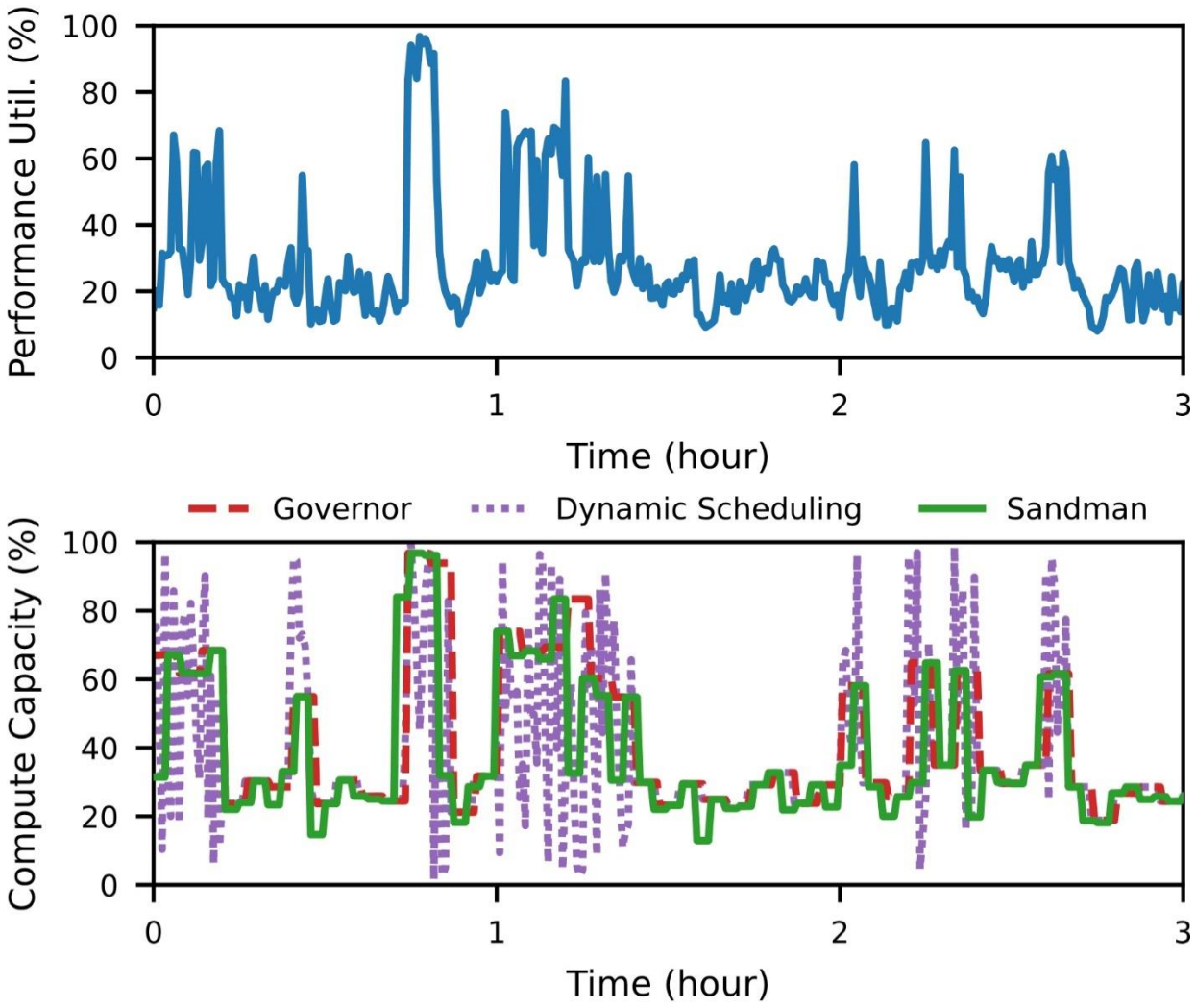
- Storage trends to consume more energy with evolving towards high performance and high density
- Current storage stacks either consume more power or sacrifice performance
- Storage stacks can be both high performance and energy efficiency with a carefully designed scheduler with hardware assistance.

Thank You!

Q & A

More details are in the paper

What about Runtime Behaviors?



Runtime resource allocation under cloud workloads

- Workload varies over time
- Sandman can (almost) follow the workload changes and allocate required resources timely
- The governor and dynamic schedulers shows delay and jitter

What about User Interrupts?

- **User-level interrupts from I/O devices (e.g., NICs and SSDs)**
  - Hardware cannot directly support
  - **Industry**
    - userspace NVMe SSDs -> VFIO -> Kernel eventfd forward to user applications
      - SPDK NVMe-over-TCP
  - **Academia**
    - Userspace NVMe SSDs -> MSI-X interrupts –> remapping to user applications
      - Aeolia (SOSP'25), SPDK+ (HotStorage'25)
    - Modify hardware
      - xUI (ASPLOS'25)
- **User-level Scheduler**
  - Used for inter-processor communication
    - Achieving low-overhead preemption scheduling in network (e.g., head-of-line blocking)
      - Aspen (NSDI'25), Skyloft (SOSP'25), uProcess (SOSP'25)