Reconciling High Efficiency with Low Latency in the Datacenter

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PhD Oral Defense

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Fun facts about datacenters











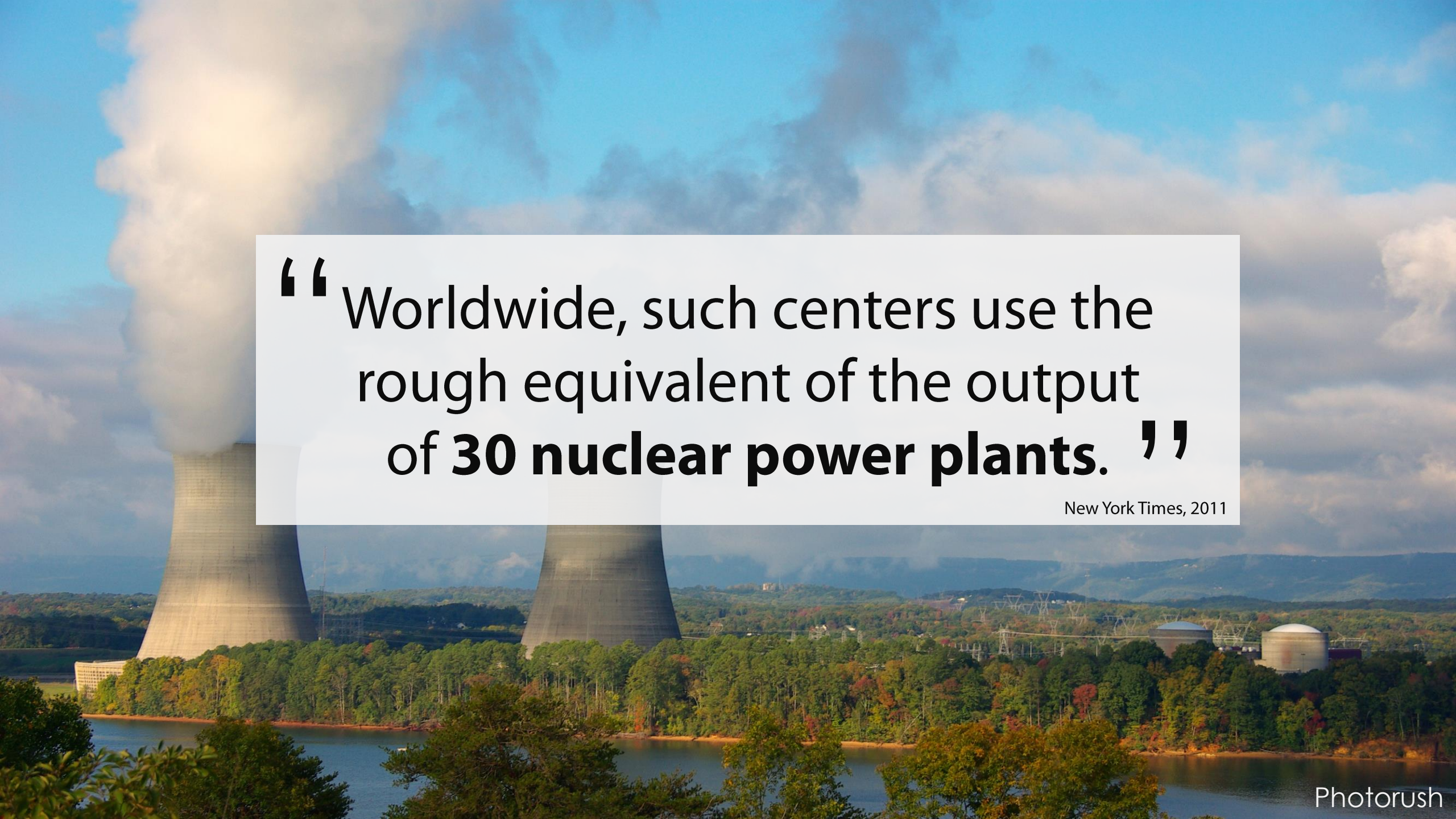



Microsoft Azure





“ Apple Inc. plans to invest **$2 billion** to build a data center… ”
Wall Street Journal, 2015
Google


“Worldwide, such centers use the rough equivalent of the output of **30 nuclear power plants**.”
New York Times, 2011
Photorush

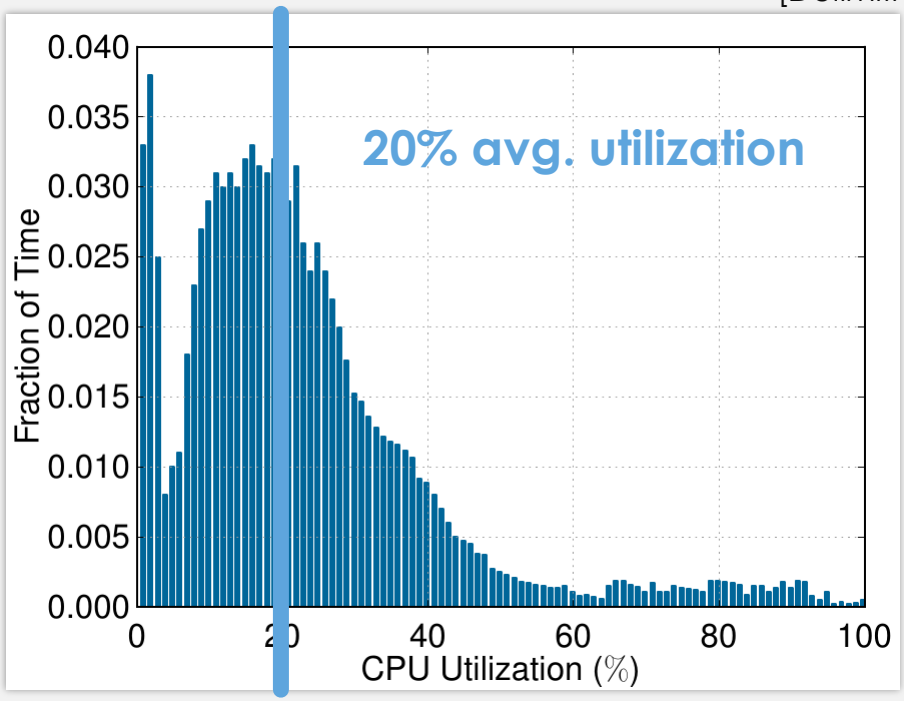

“ Overall data center workloads will nearly **double** from 2013 to 2018 ”
Cisco, 2013
Google

Potential roadblocks for future growth

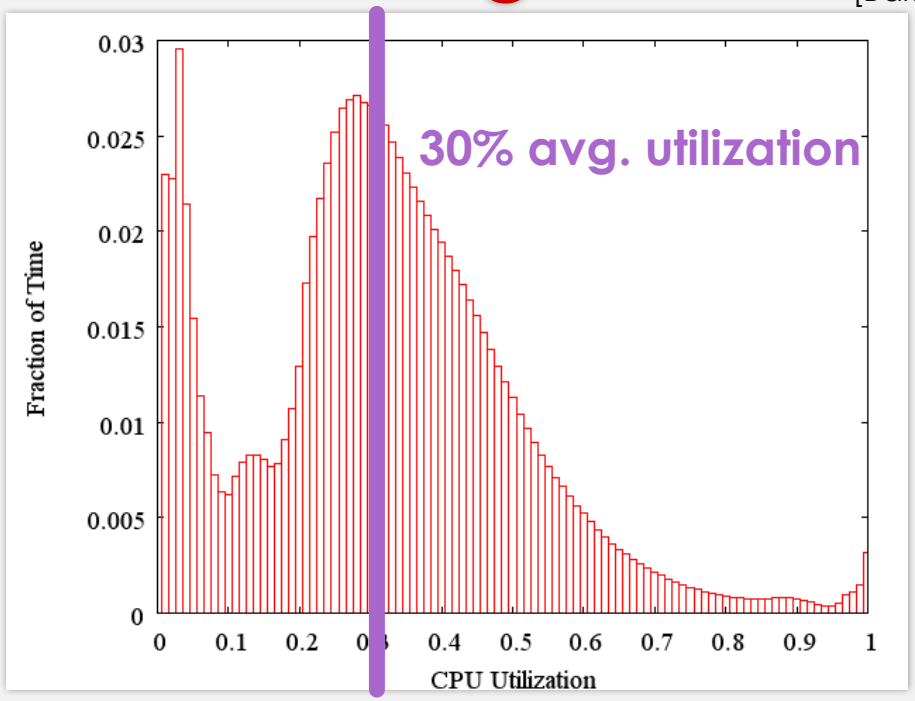
- Cost reduction
  - ~~Switch to commodity servers~~ — One time trick
  - ~~Improved power delivery & cooling~~ — Diminishing returns
- Capability scaling
  - ~~More datacenters~~ — >$2B per DC
  - ~~More servers per datacenter~~ — @60MW per DC
  - ~~CPU vendors will make better chips~~ — End of voltage scaling

But the datacenters are poorly utilized!

Twitter [Delimitrou'14]

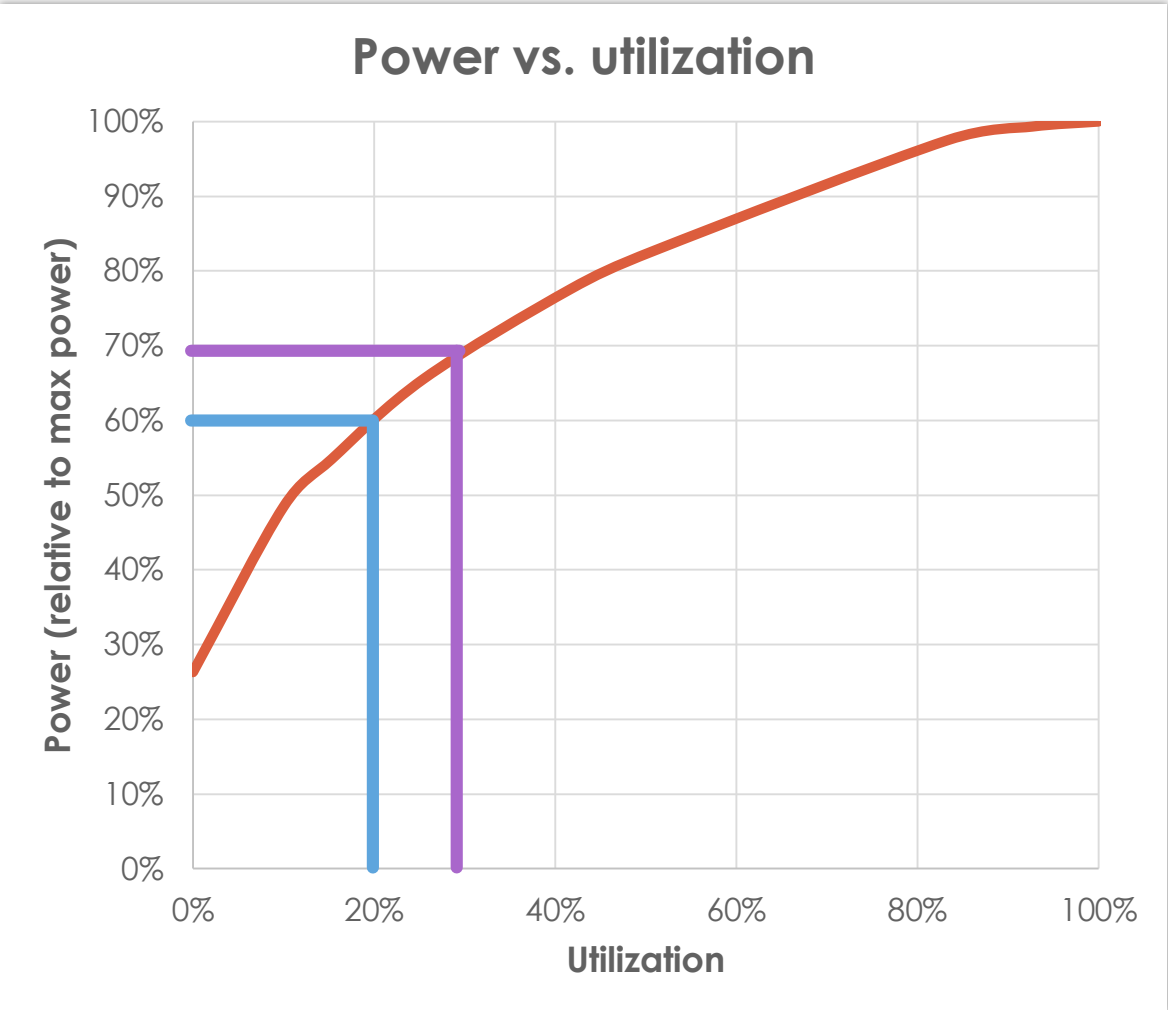


Google [Barroso'09]



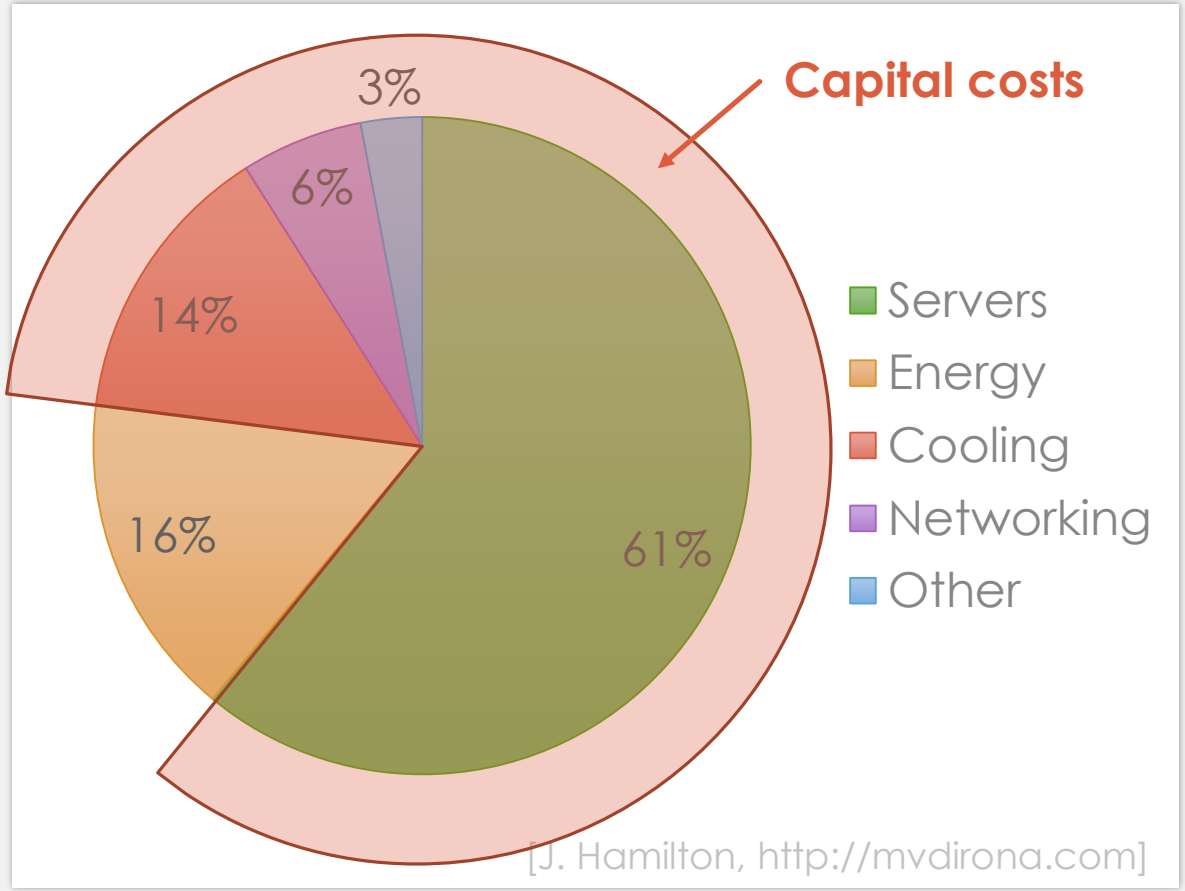
- Low utilization in large-scale clouds, even with automated management systems

Which is bad for energy efficiency



- Servers still use lots of power when not running at peak
- Google: 70% peak power
- Twitter: 60% peak power
- Using 30 nuclear plants, but should only be using 10-15

Bad for cost efficiency



- Most of the costs are in capital equipment
- Google: 59% wasted $
- Twitter: 67% wasted $
- > $1B potential waste on one datacenter

What datacenters need to do better

- Better energy efficiency
  - Lessen/eliminate wasted power at lower utilizations
- Better resource efficiency
  - Improve utilization in the datacenter

Outline

- Causes of low efficiency in the datacenter

- My contributions towards improving efficiency
  - Autoturbo: improving energy efficiency [HPCA '14]
  - OLDIsim: scale-out benchmark [Released by Google]
  - PEGASUS: improving energy efficiency [ISCA '14]
  - Heracles: improving resource efficiency [To appear ISCA '15]

Causes of low efficiency in datacenters

The applications running in a datacenter

- Batch workloads
  - Examples: analytics, log processing, training neural networks
  - Throughput oriented

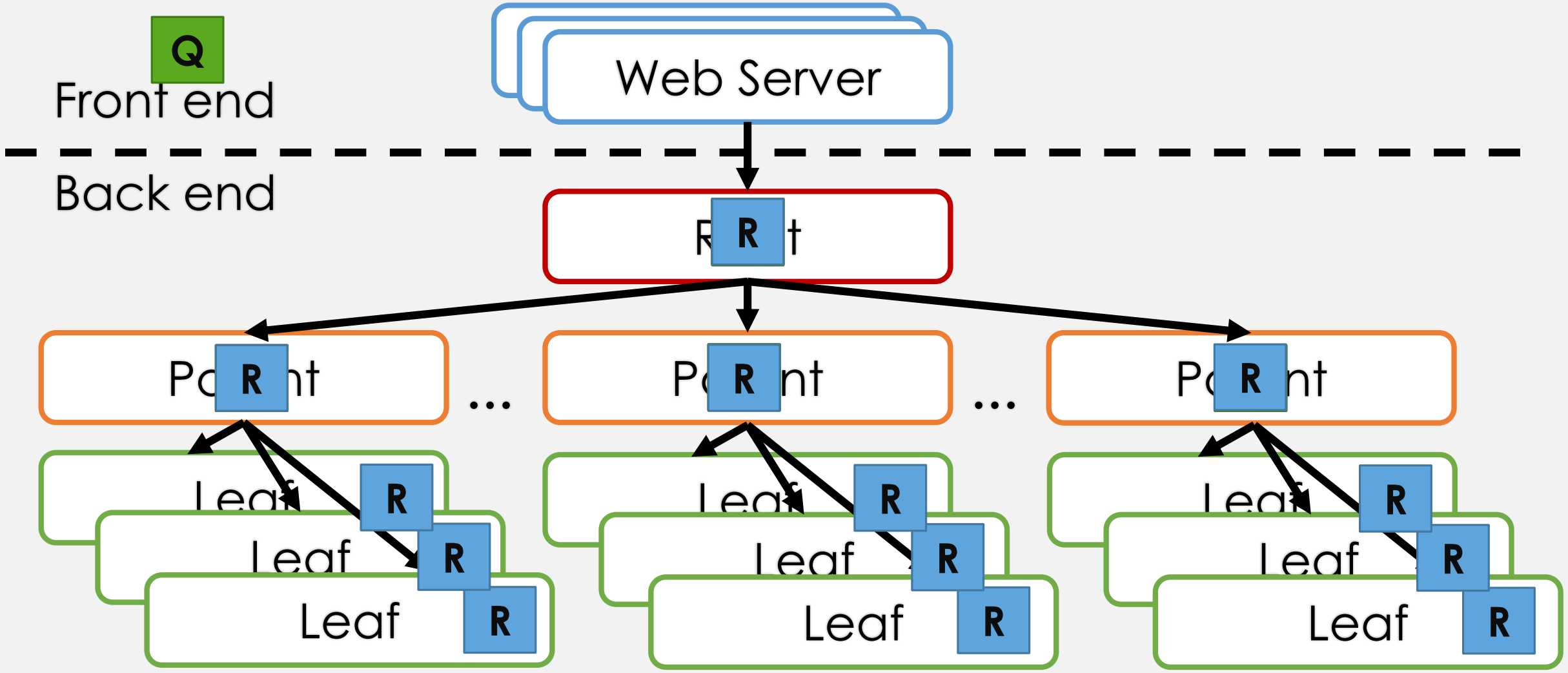
- Latency-critical workloads
  - Examples: Google.com, Facebook.com, Twitter.com
  - User-facing, extremely sensitive to latency

Largest class of latency-critical workloads

- On-line Data Intensive (**OLDI**) workloads are user-facing workloads that mine massive datasets across many servers
  - Strict Service Level Objectives (**SLO**): e.g. 99%-ile tail latency is 5ms
  - High fan-out with large distributed state

- A substantial class of workloads in the datacenter
  - Driven by growth in web services and cloud computing
  - Google, Facebook, Twitter, RAMCloud, etc.

An example OLDI workload: websearch



Why is utilization so low?

- **Underutilization is structurally ingrained in OLDI workloads**

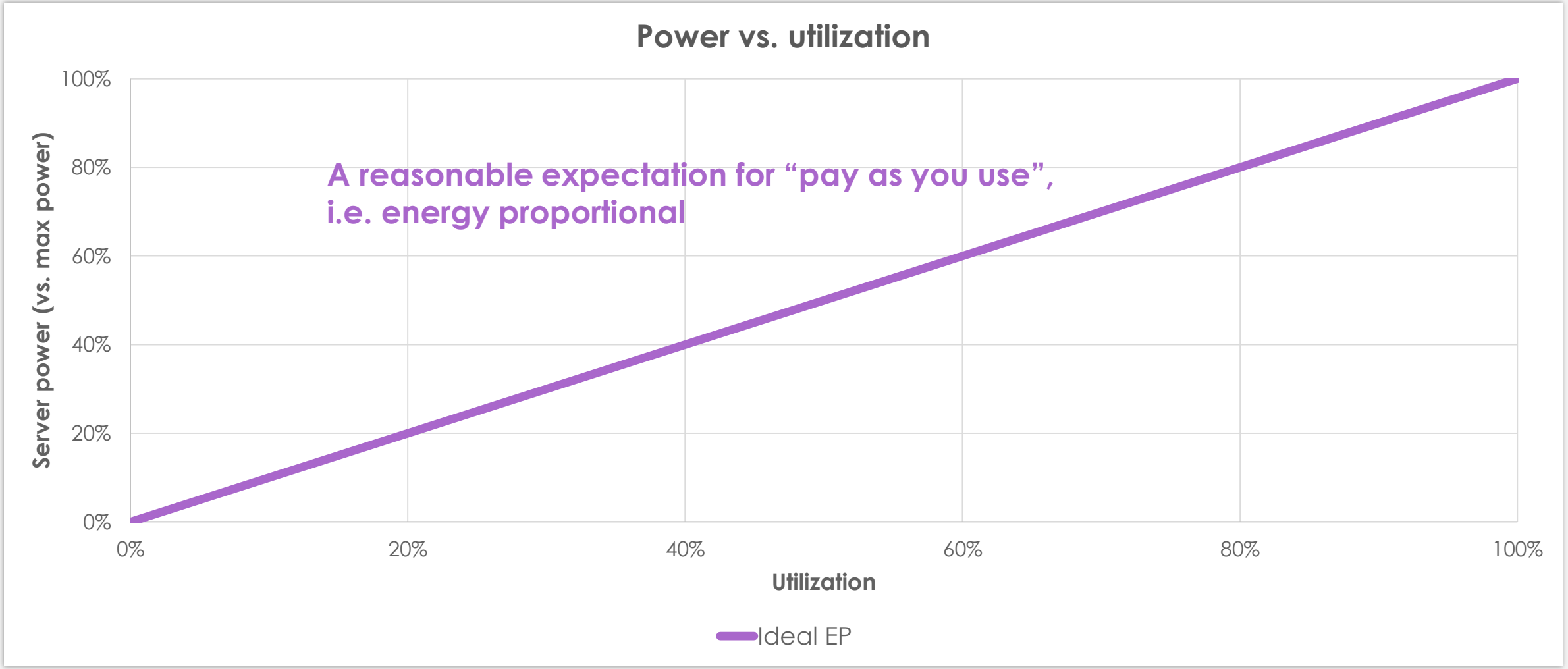
- Diurnal user traffic (e.g. users are sleeping at 3am)
- Planning for high traffic events (e.g. Black Friday)

} Fundamental

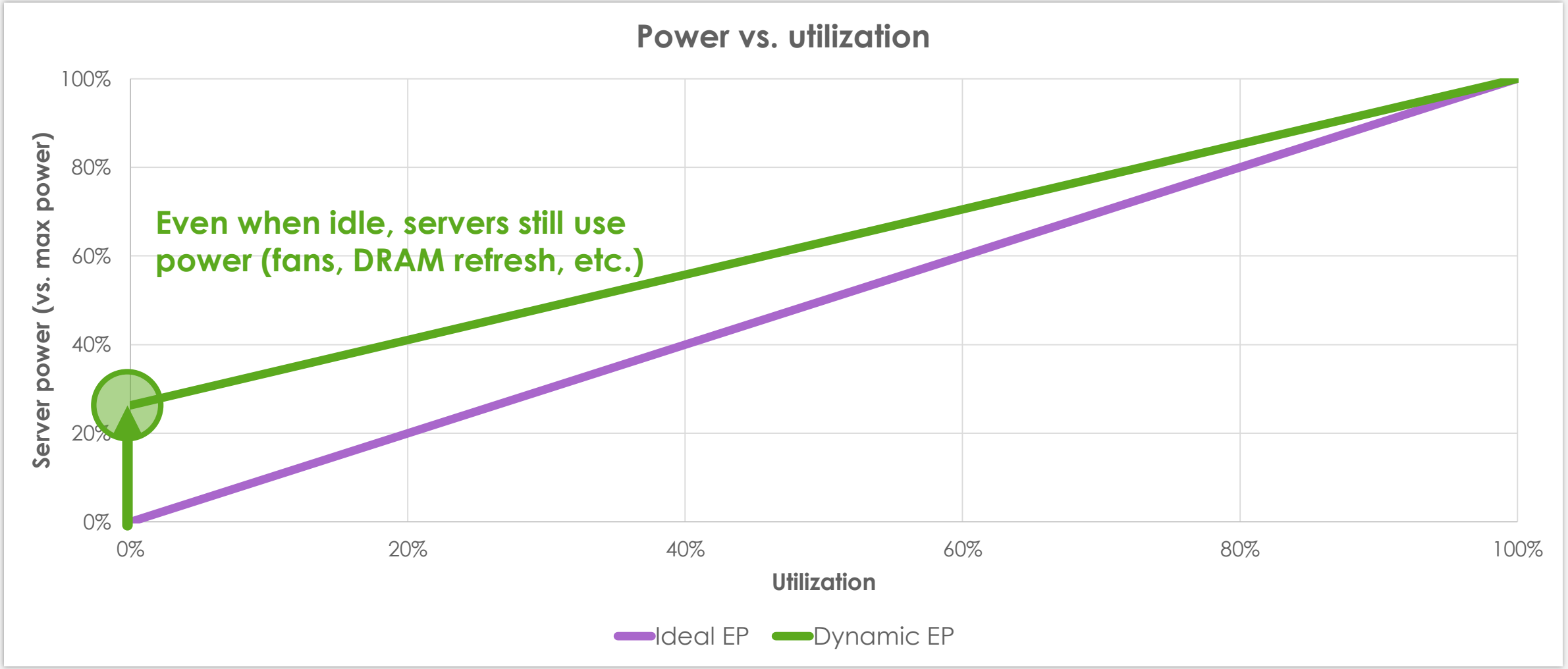
- OLDI workloads are run on dedicated servers

} By design

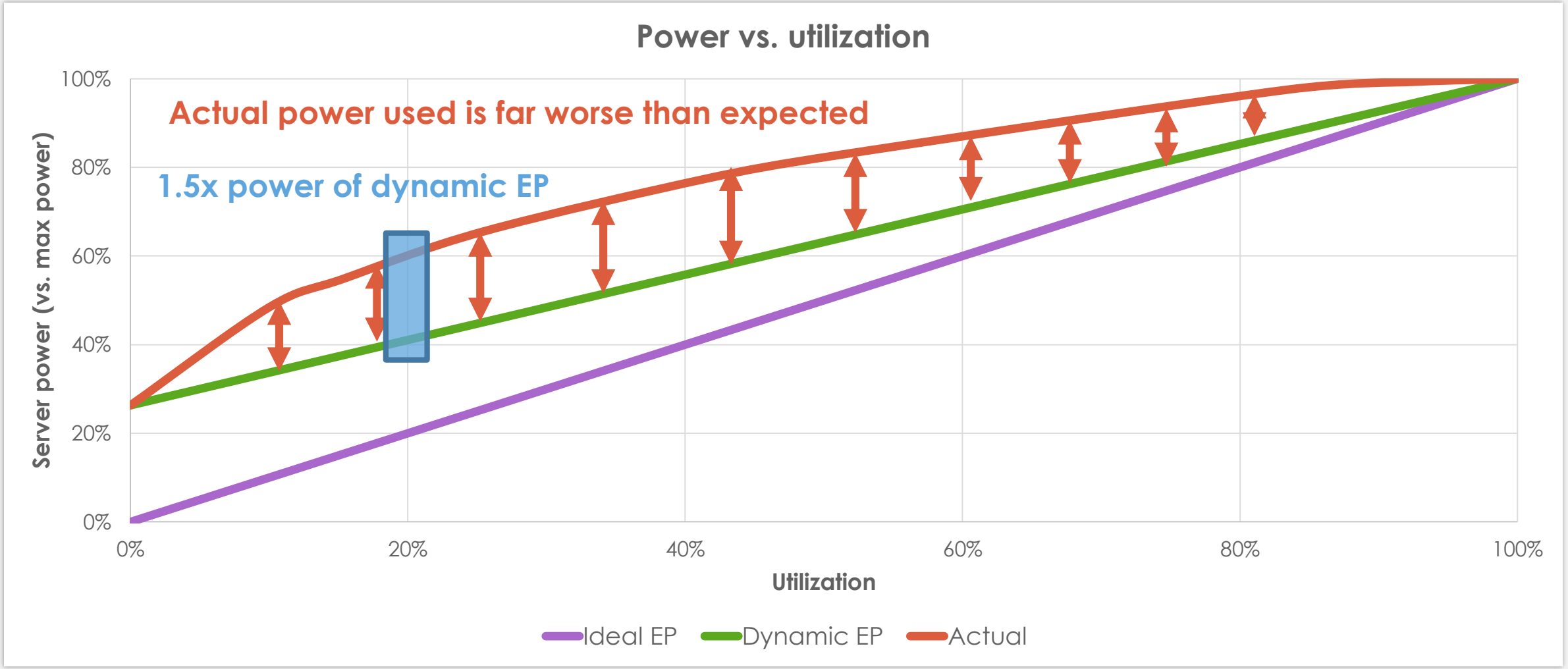
Poor energy efficiency at low utilizations



Poor energy efficiency at low utilizations



Poor energy efficiency at low utilizations



“Common wisdoms” regarding efficiency

- Stuck with low server utilization and poor energy efficiency

- **Claim 1**: hard to improve energy efficiency
  - Power management techniques cause latency violations
- **Claim 2**: hard to increase utilization
  - Co-locating workloads also causes latency violations

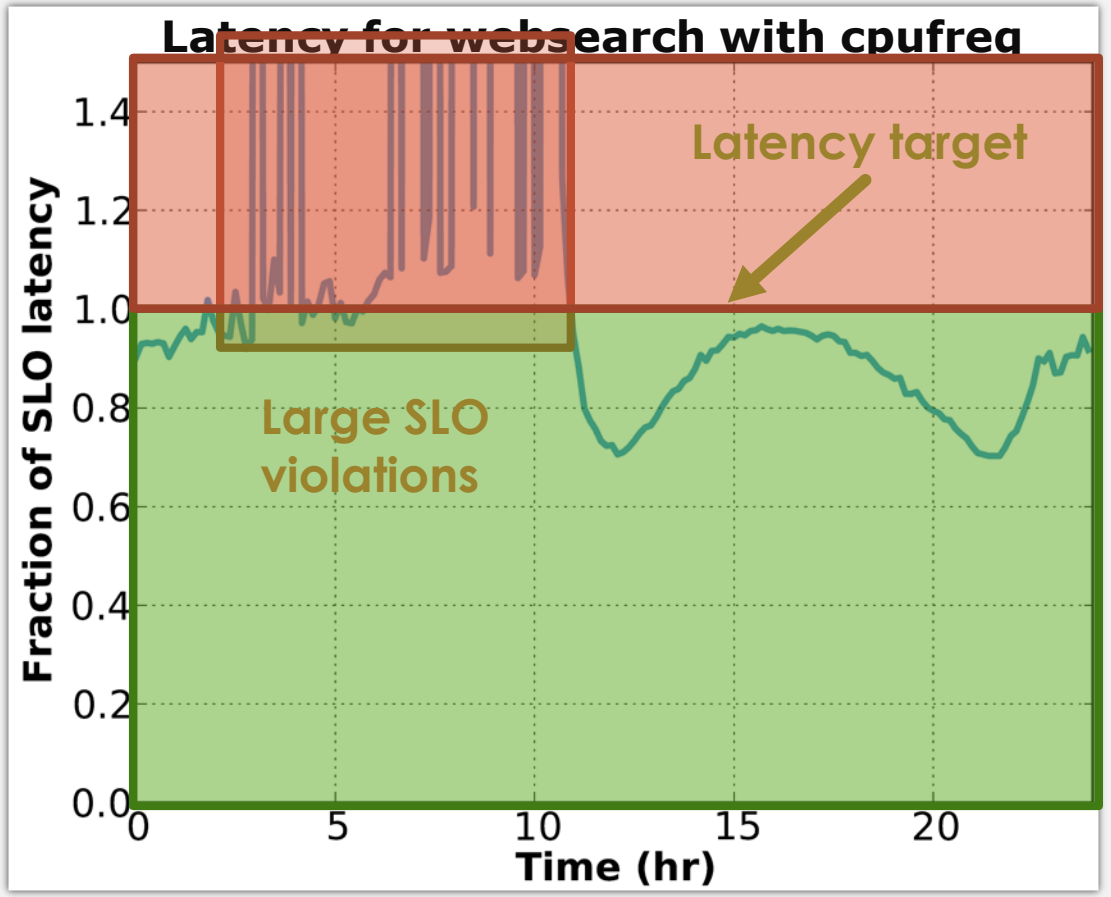
Claim 1: hard to improve energy efficiency

- Many proposed approaches for batch/real-time workloads do not work for latency-critical workloads

- Batch: system idle modes [PowerNap ASPLOS'09, Blink ASPLOS'11]
  - Not enough system idleness, even at low loads
  - Creating idleness with batching violates SLO [Meisner ISCA '11]
- Batch/real-time: power scaling [Isci MICRO'06, Pillai SOSP'01]
  - Mismatch between needs of real-time/batch and latency-critical

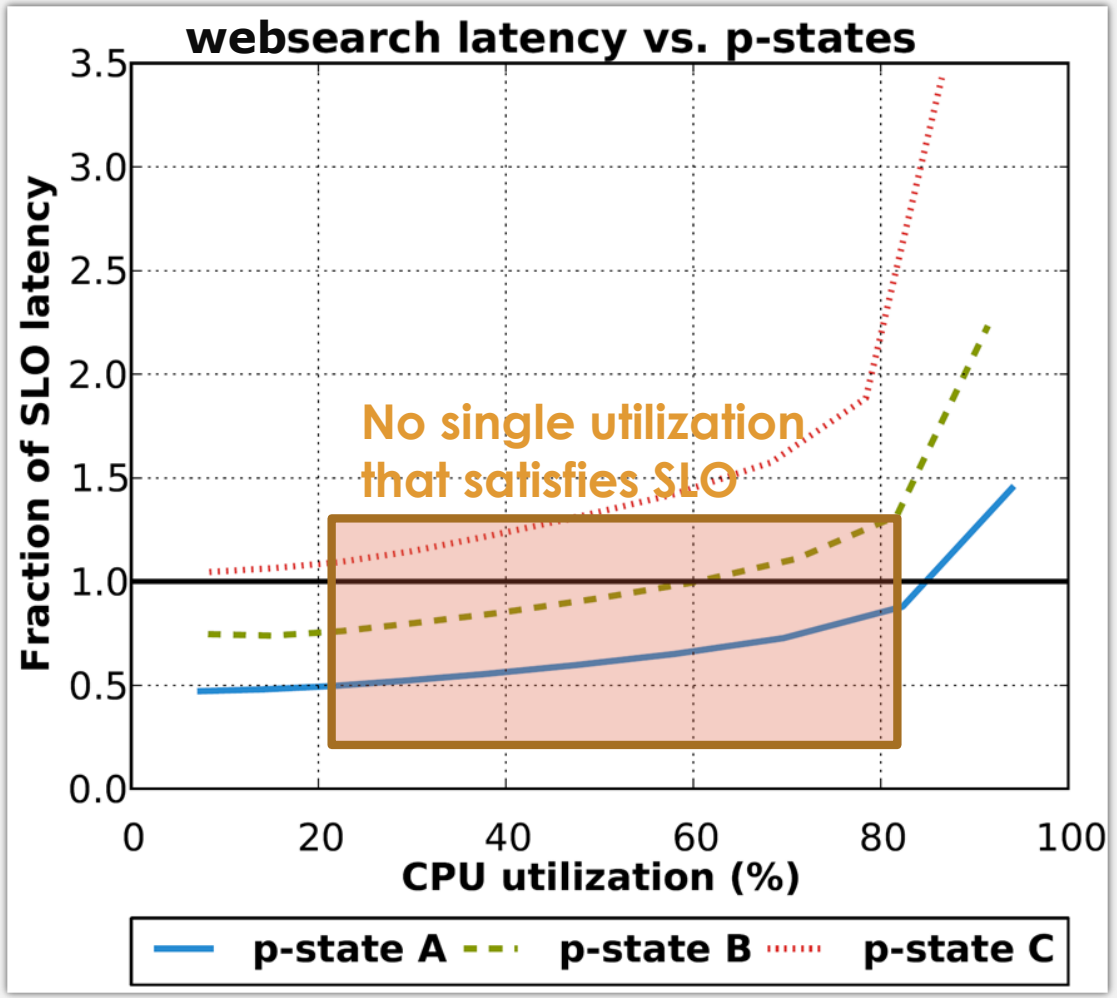
Power scaling is not suitable

- Cpufreq power governor:
  - Uses CPU utilization to determine p-state
  - Keeps utilization at 20-95%
- Run Google websearch with cpufreq power governor and measure latency

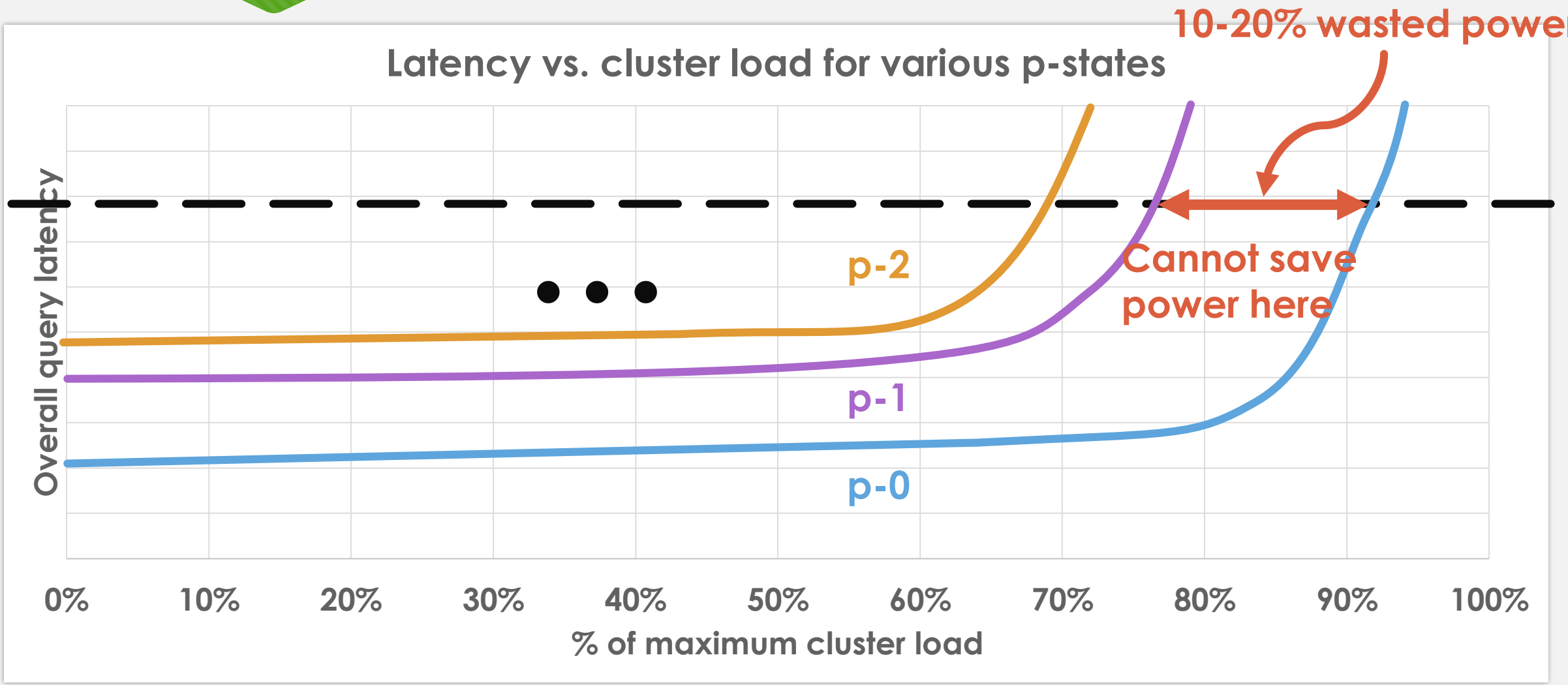


Why all cpufreq-like schemes won't work

- CPU utilization is a poor proxy for workload latency
- In the most extreme case: even a CPU utilization of 10% still leads to SLO violation



p-states are not fine grained enough

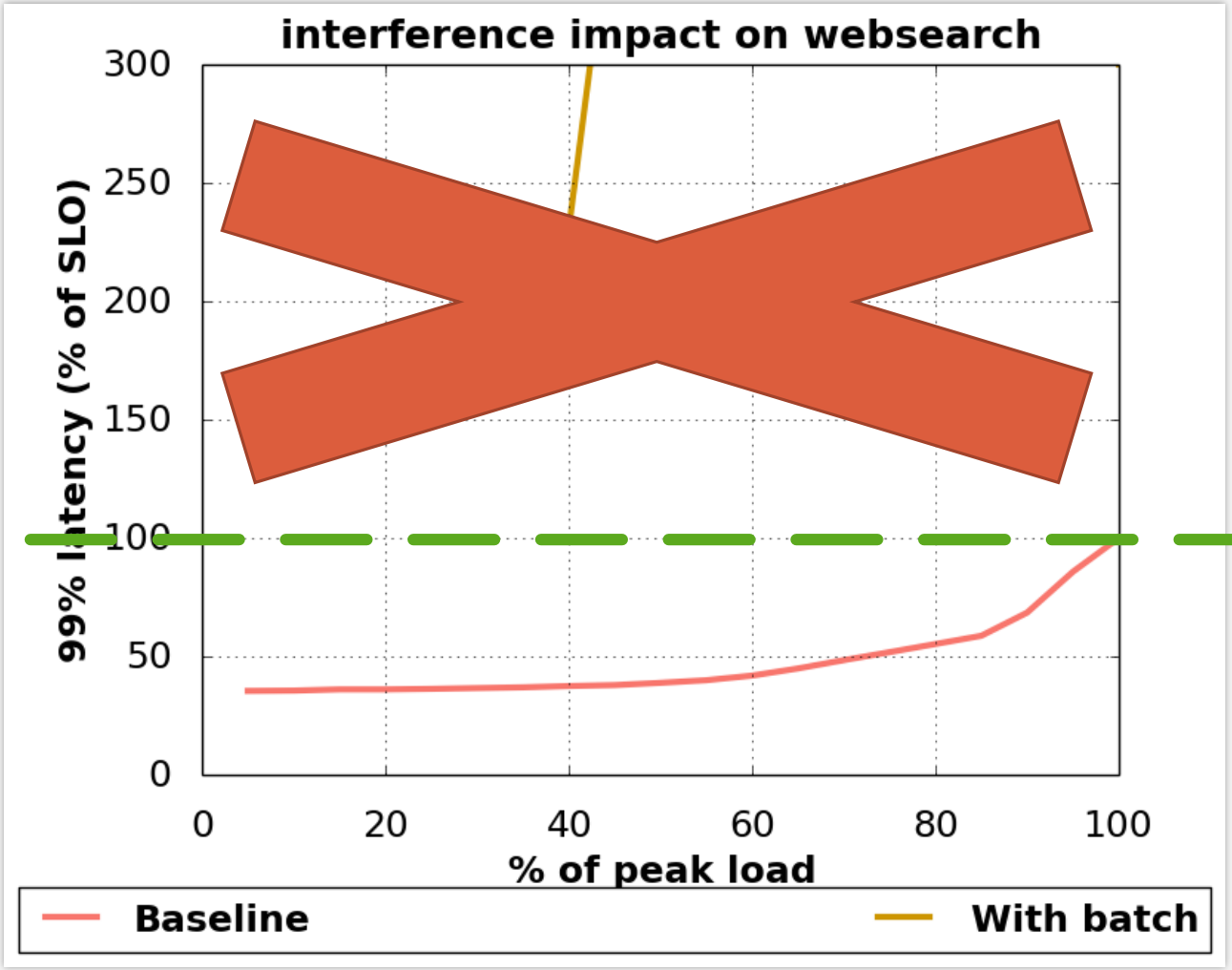


Claim 2: hard to increase utilization

- **Proposal**: during periods of low utilization, fill in spare capacity with extra work (oversubscription)
  - Works for batch workloads

- Unfortunately, latency-critical workloads do not mix well with other workloads
  - Interference on shared resources can cause SLO latency violations

Interference impact on Google websearch



SLO latency

Cannot co-locate workload at any load!

Want to have our cake and eat it too

- "Common wisdom" suggests that low latency and high energy efficiency and utilization are incompatible

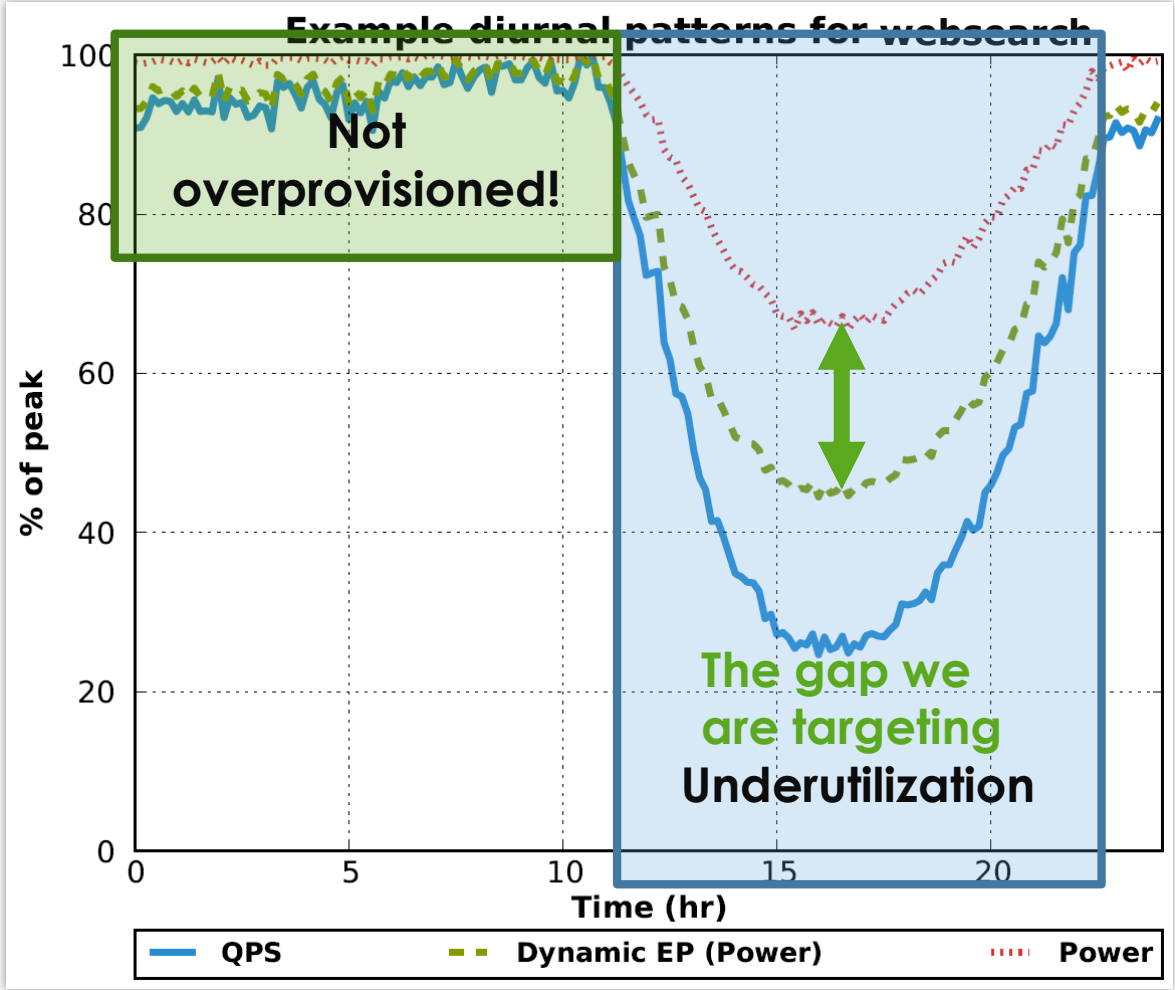
- Show that this is not the case, one step at a time
  - PEGASUS: energy efficiency
  - Heracles: high utilization

PEGASUS

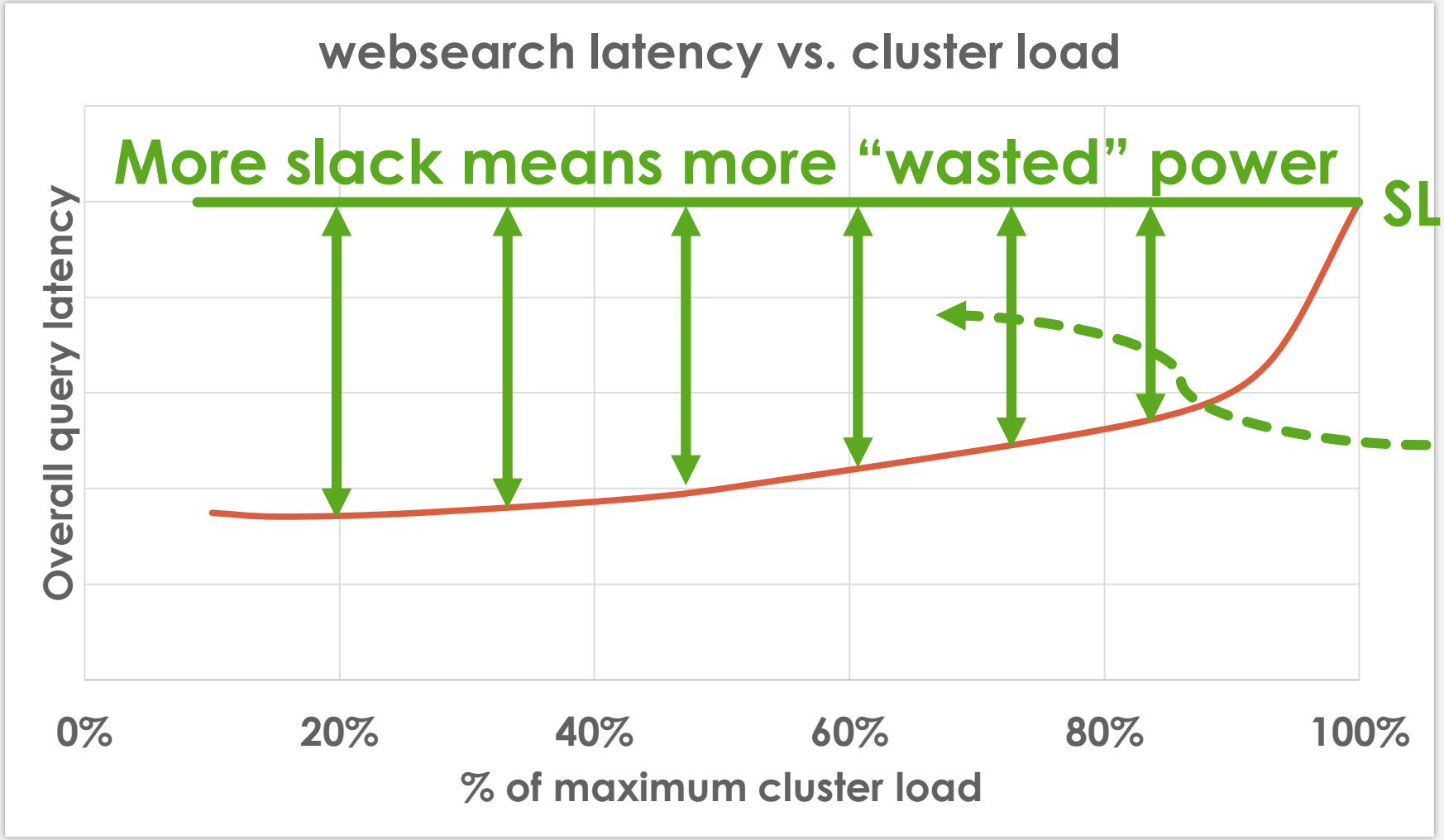
Reconciling low latency with energy efficiency

Opportunities for better energy efficiency

- Diurnal variation in cluster load and power for search across a 24 hour period
- Cluster not fully utilized half the time
- Gap between measured power and EP curves represent potential savings



The extra power is hiding in the latency



Too much latency slack is harmful

- **Beating the end-to-end SLO is no better than meeting it**
  - The end-user only cares if the web page takes a long time to load
  - If the page loads in 0.25sec vs. 0.50sec, user does not notice

- **Better target: keep the latency the same at all utilizations (iso-latency)**

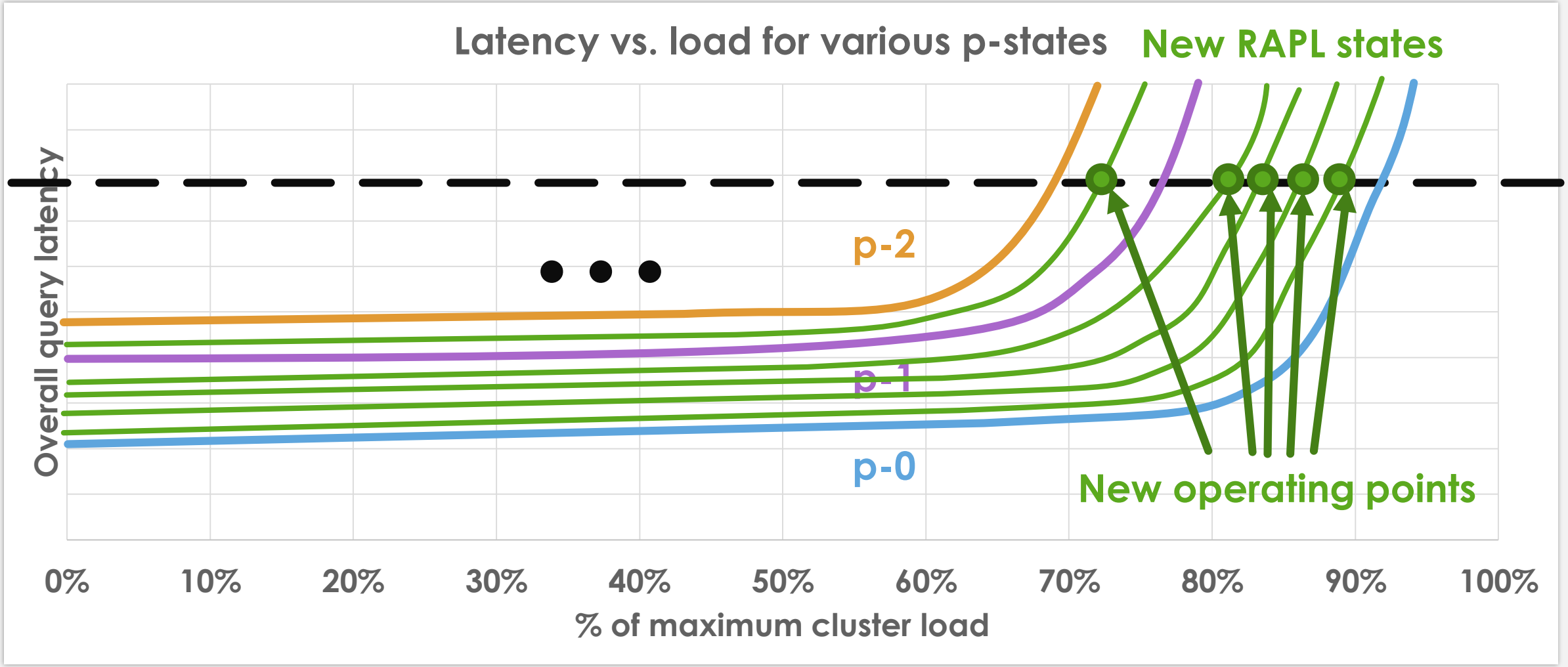
Iso-latency power management

- **Idea:** Trade end-to-end latency slack for power savings
- Use power management mechanisms to keep the workload performing just well enough to avoid SLO violations
  - **Need end-to-end latency feedback from workload**
    - Most OLDI workloads have ways of measuring this ✓
  - **Need fine-grained power management mechanisms**
    - ???

RAPL: a fine-grained mechanism

- RAPL: **R**unning **A**verage **P**ower **L**imit
- **Fine-grained**: power limit increments as small as 0.125W
- **Fast**: <1ms delay to apply new limit
- **Effective**: Dynamic Voltage Frequency Scaling (DVFS) behind the scenes to meet the power limit
  - More fine-grained than p-states
  - Can even modulate between multiples of base clock frequencies

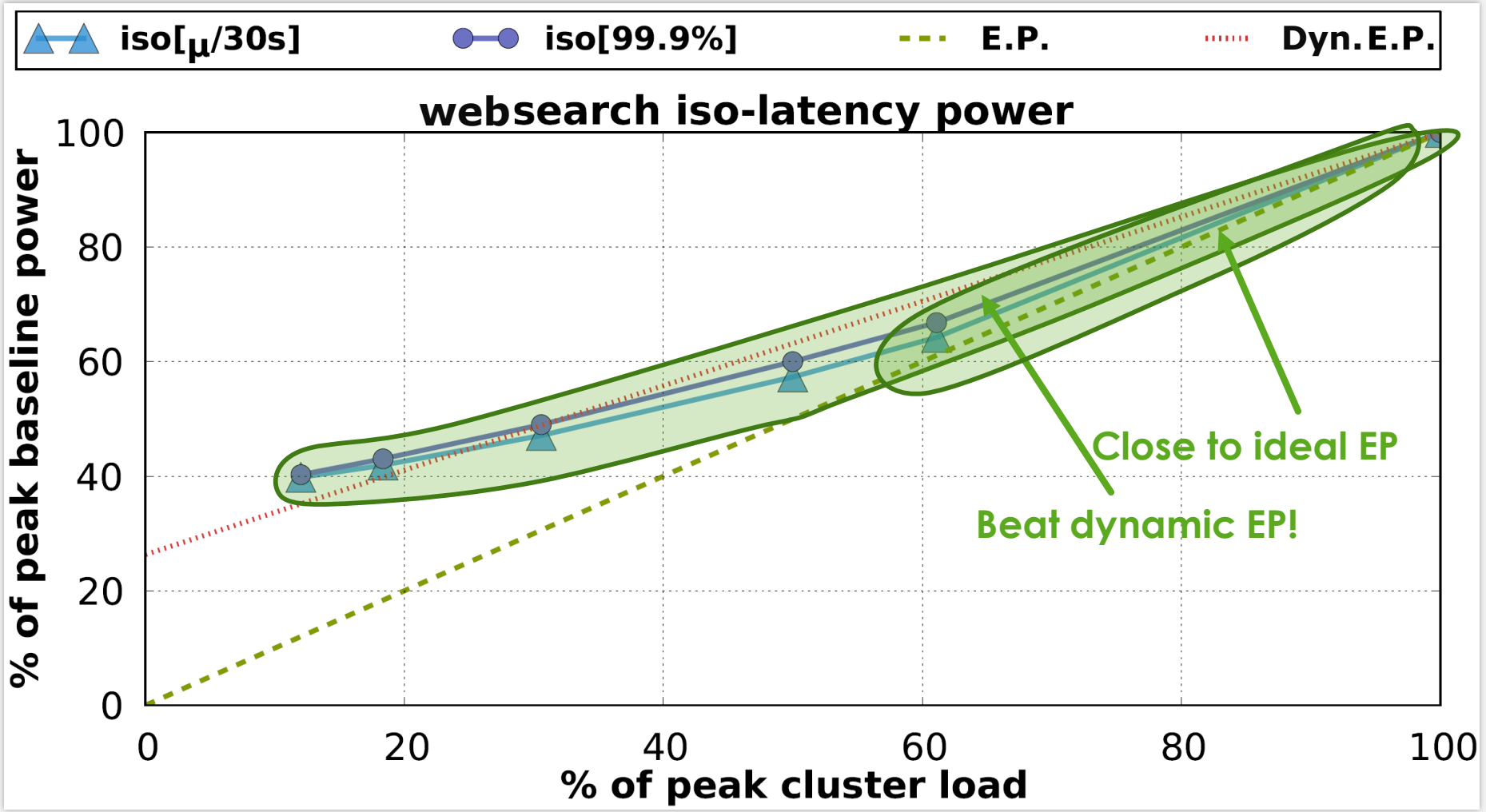
Advantages of fine-grain control



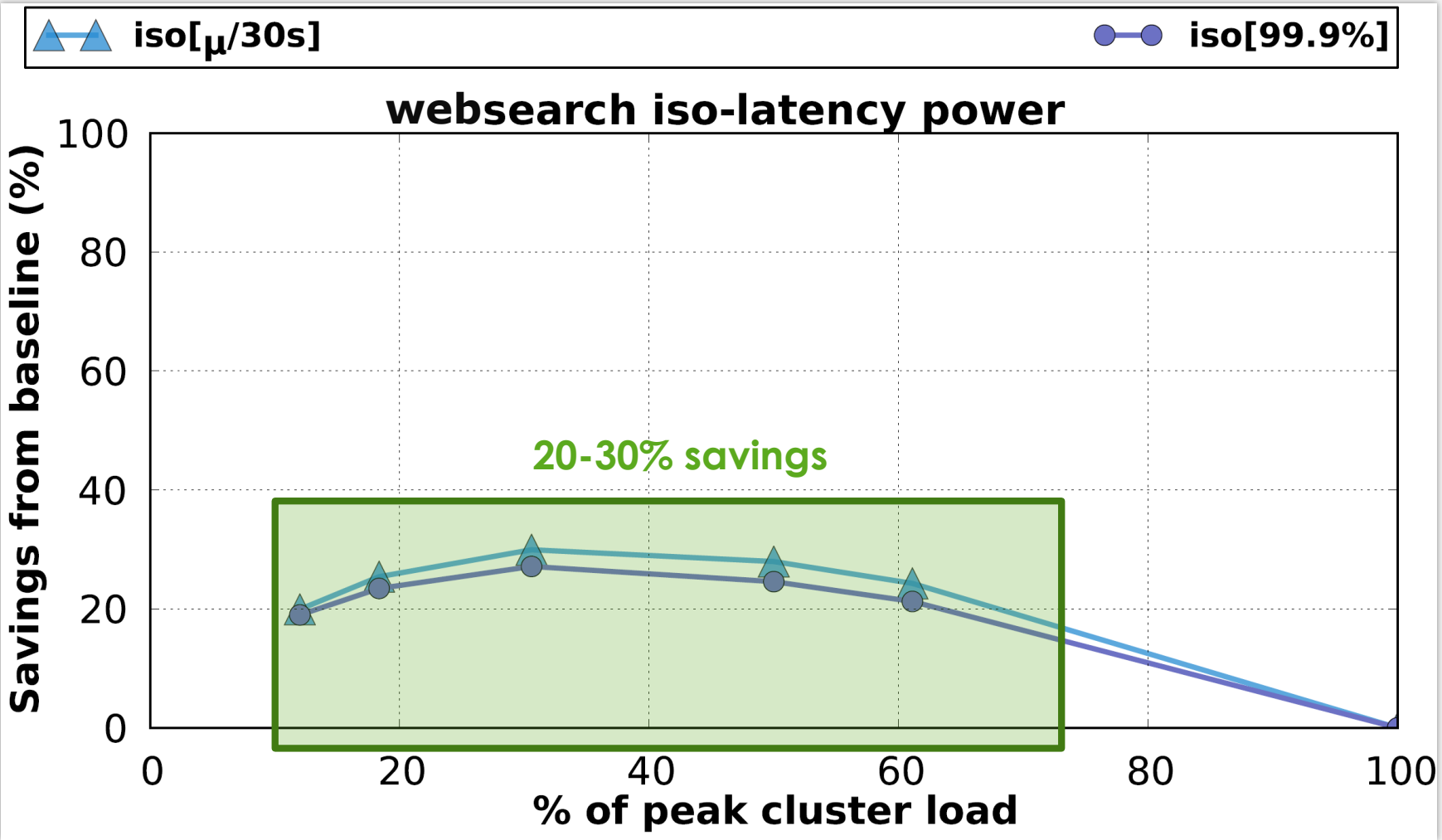
Evaluation of iso-latency potential

- Use static oracle to find lowest power that satisfies SLO
- Do this for several Google workloads
  - **websearch**: Google websearch
  - **memkeyval**: In-memory key-value store
- Measure **total system power** before and after iso-latency
- Do this for varying strictness of end-to-end SLOs
  - 30sec moving average, 99.9%-ile latency

Iso-latency potential: power

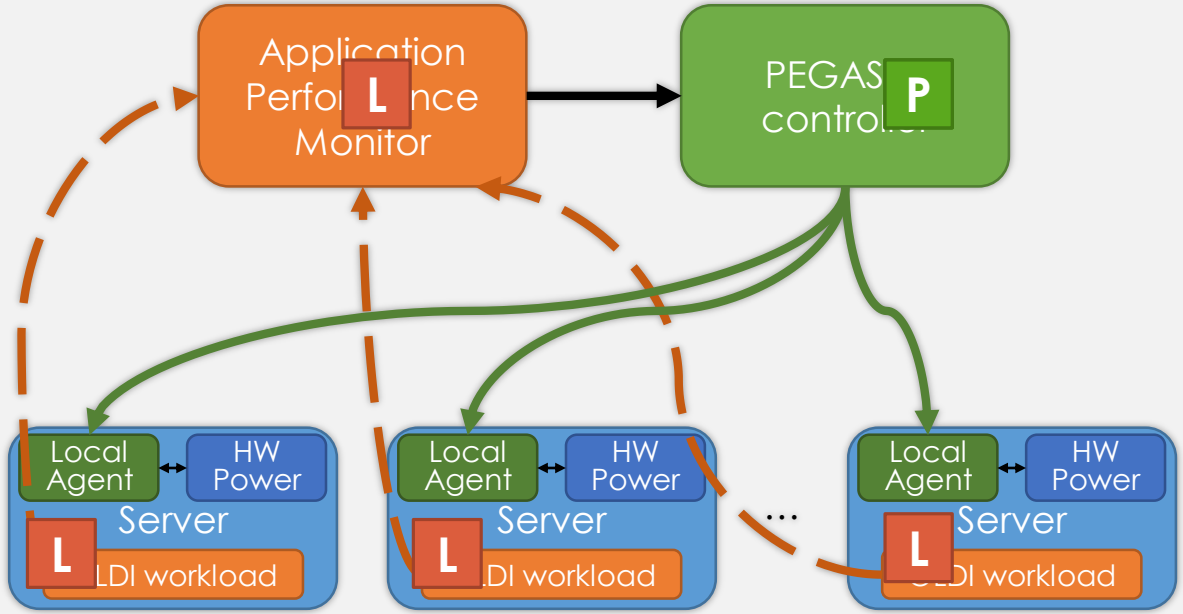


Iso-latency potential: power savings



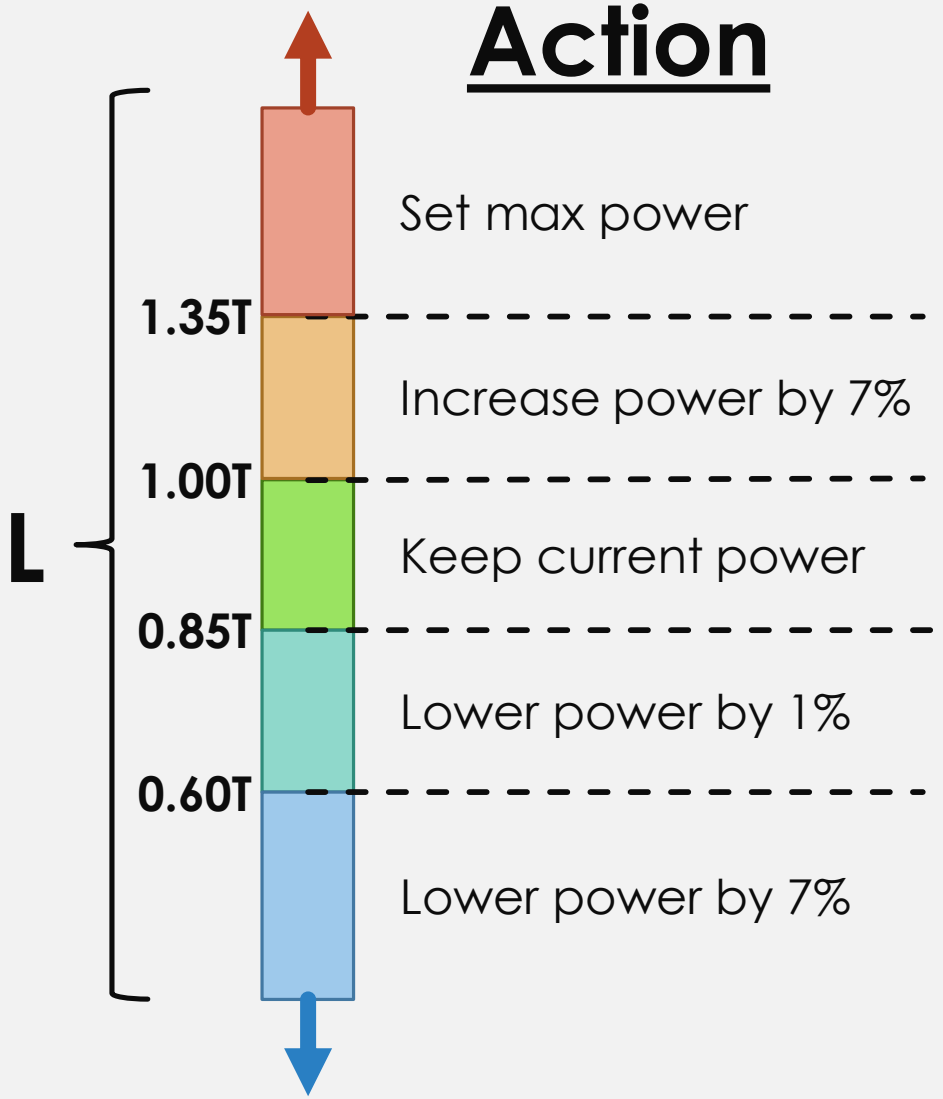
PEGASUS description

- Real-time dynamic controller for **iso-latency**
- Use RAPL as knob for power
- Measures latency slack and sets **uniform** power limit across all servers
- Power is set by workload specific policy
- ~500 lines of code



Example PEGASUS policy for websearch

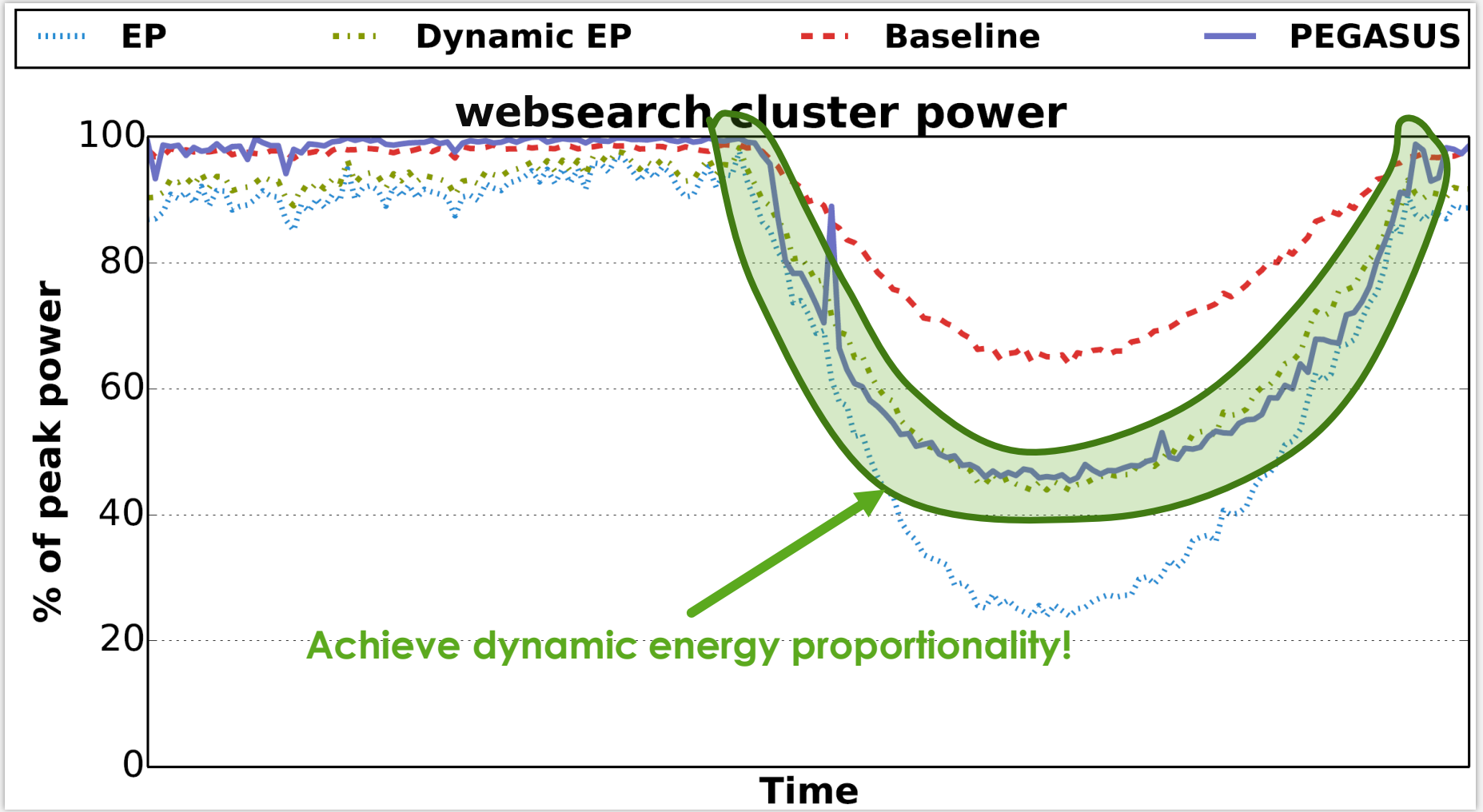
- **L** = Measured instant latency
- **T** = SLO target
- Use instant latency for quick corrections
- Violating SLO latency triggers fail-safe
- Constants determined through empirical optimization



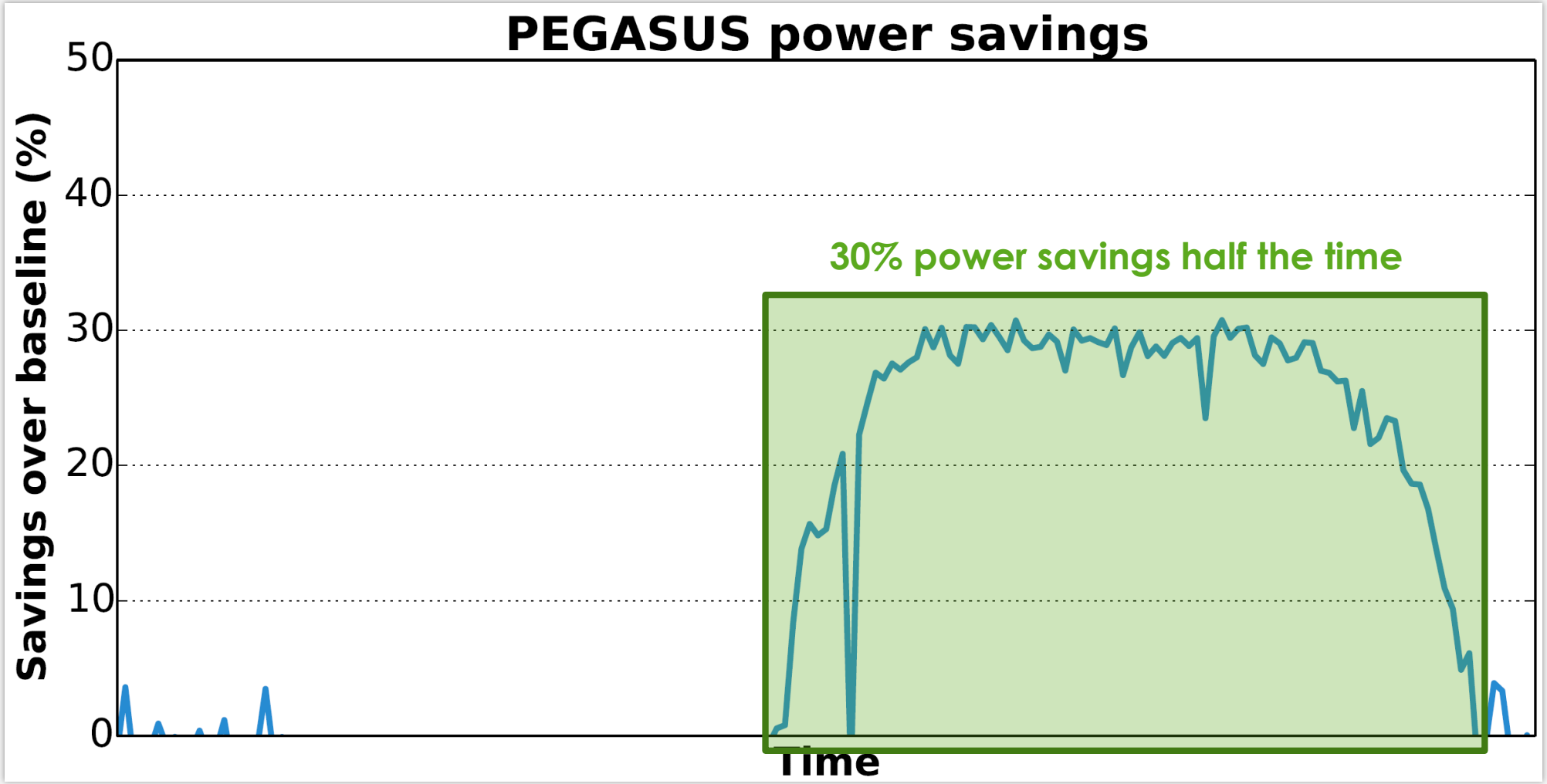
PEGASUS evaluation methodology

- Workload parameters
  - **SLO metric**: 30 second average latency [μ/30s]
  - Traffic pattern and user queries derived from anonymized search logs
  - Index derived from production search index
- Evaluate on several cluster sizes
  - **Small**: tens of machines, use full 24hr trace
  - **Production**: thousands of machines, use 12hr portion
- Measure full cluster power and SLO latency

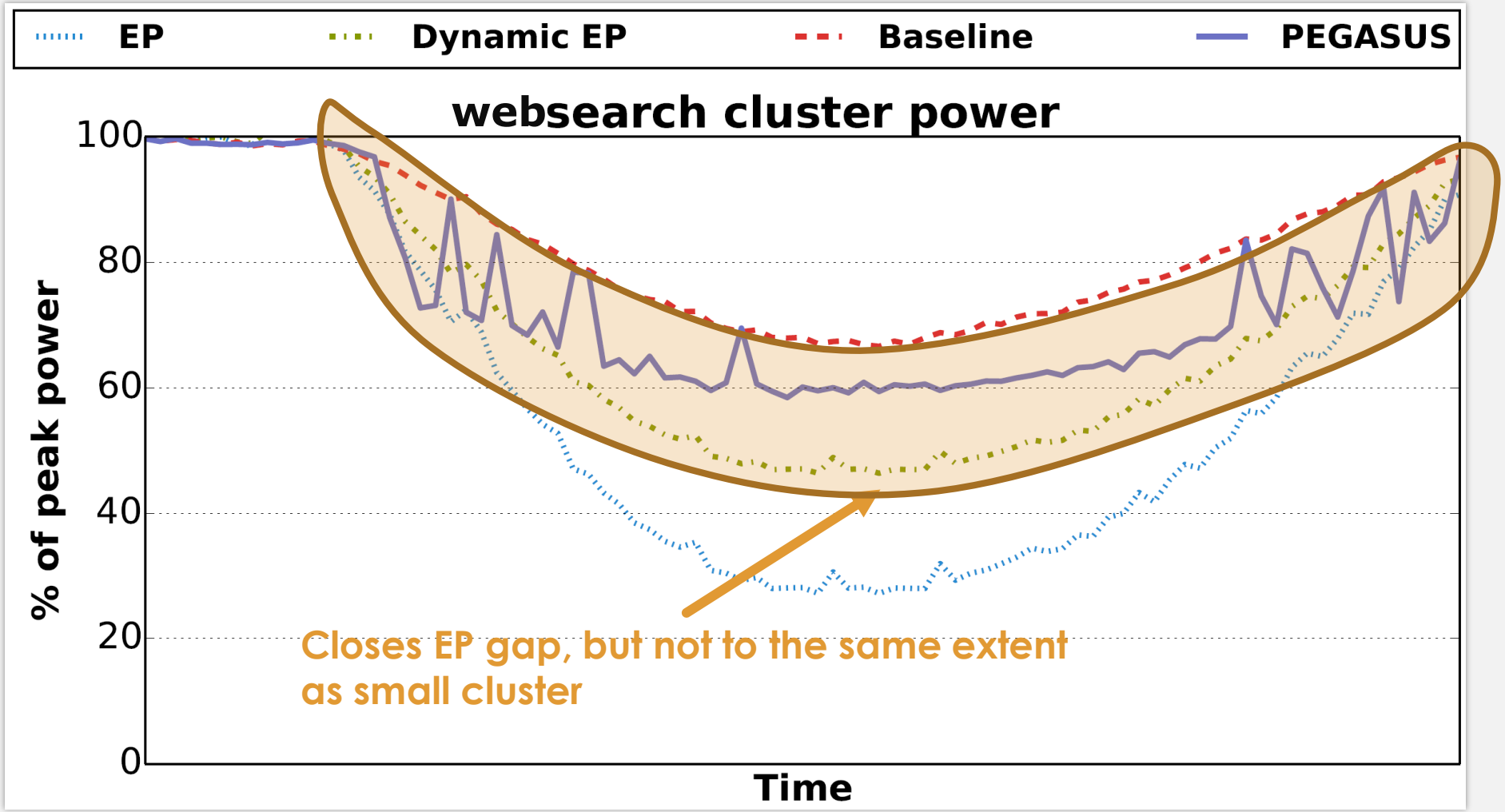
Small cluster results: power over time



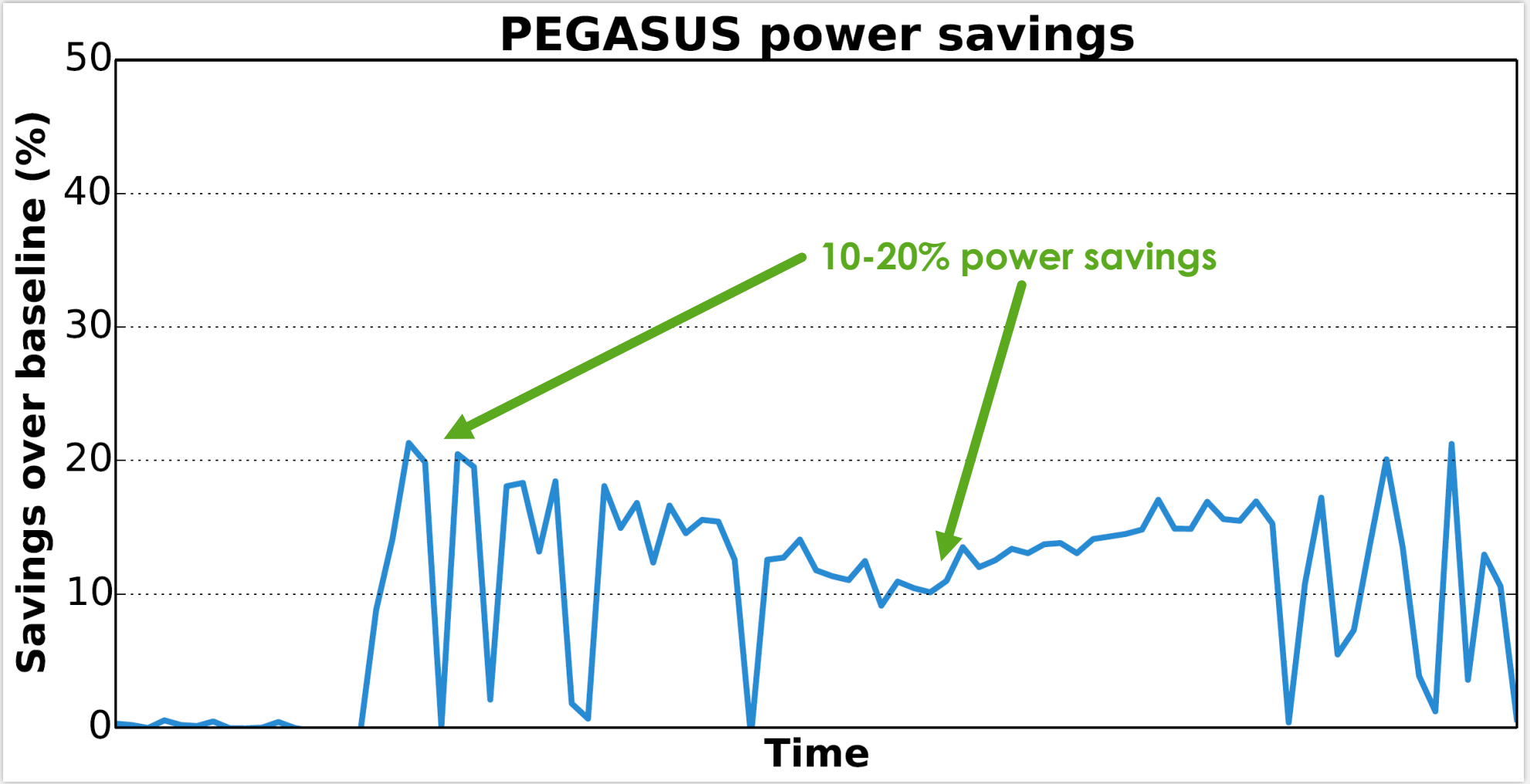
Small cluster results: power comparison



Production cluster results: power over time



Production cluster results: power comparison

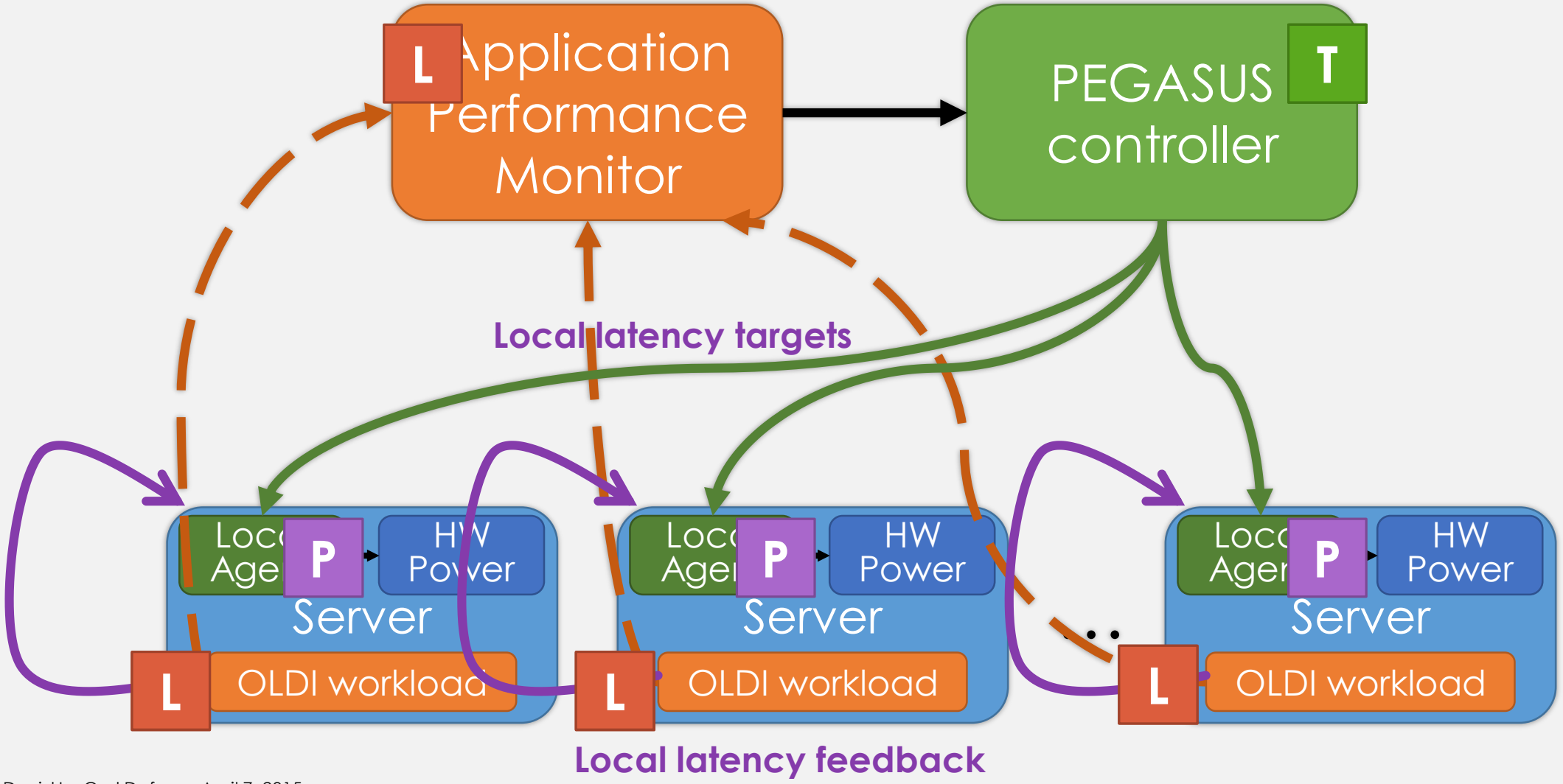


Improving PEGASUS scalability

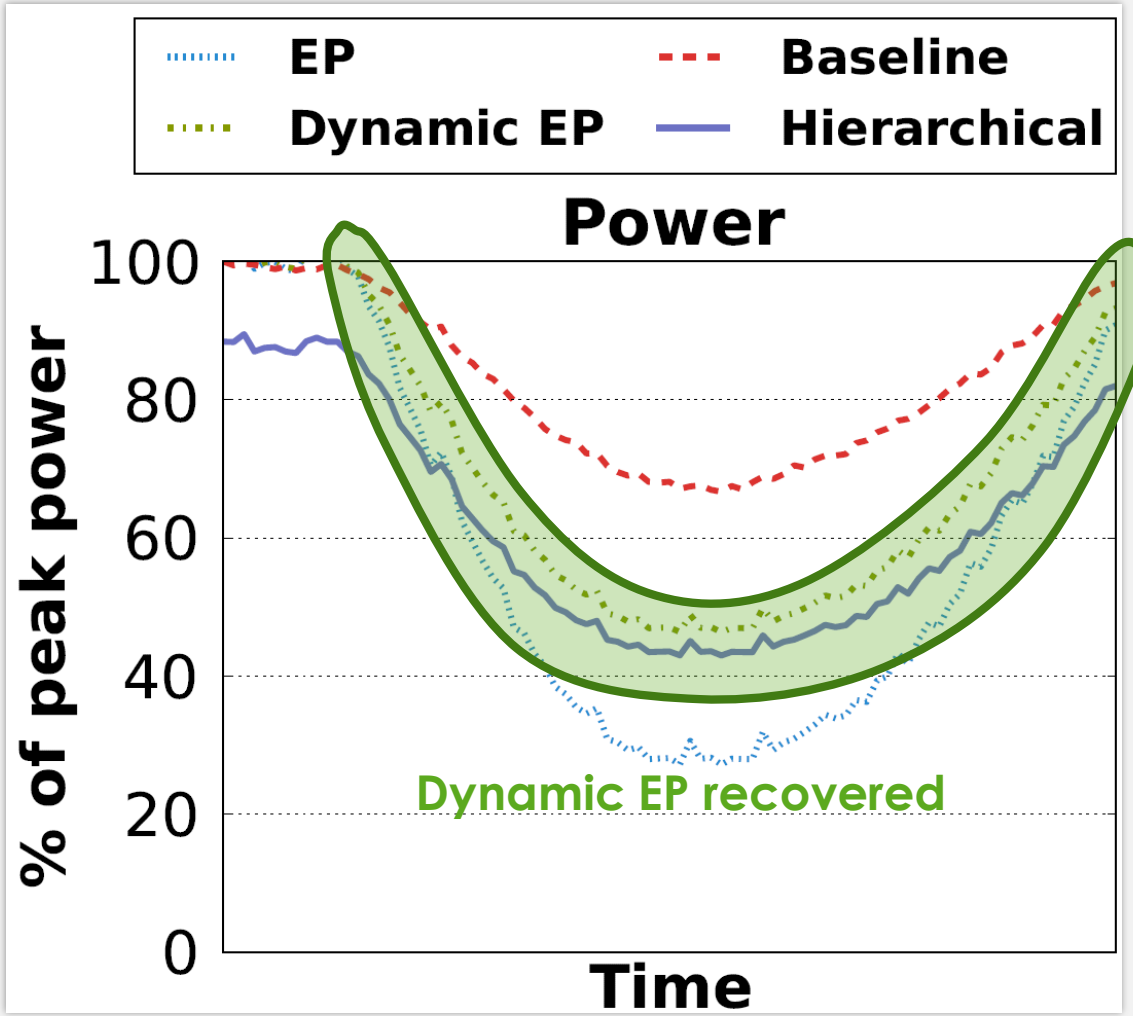
- Production cluster sees **"tail at scale"** for server utilization
  - At peak load, 0.2% nodes at 100% load while 50% nodes at <85% load
  - Caused by popular queries hitting a few shards
  - **Issue:** Hot nodes set lower bound on power limits for everyone

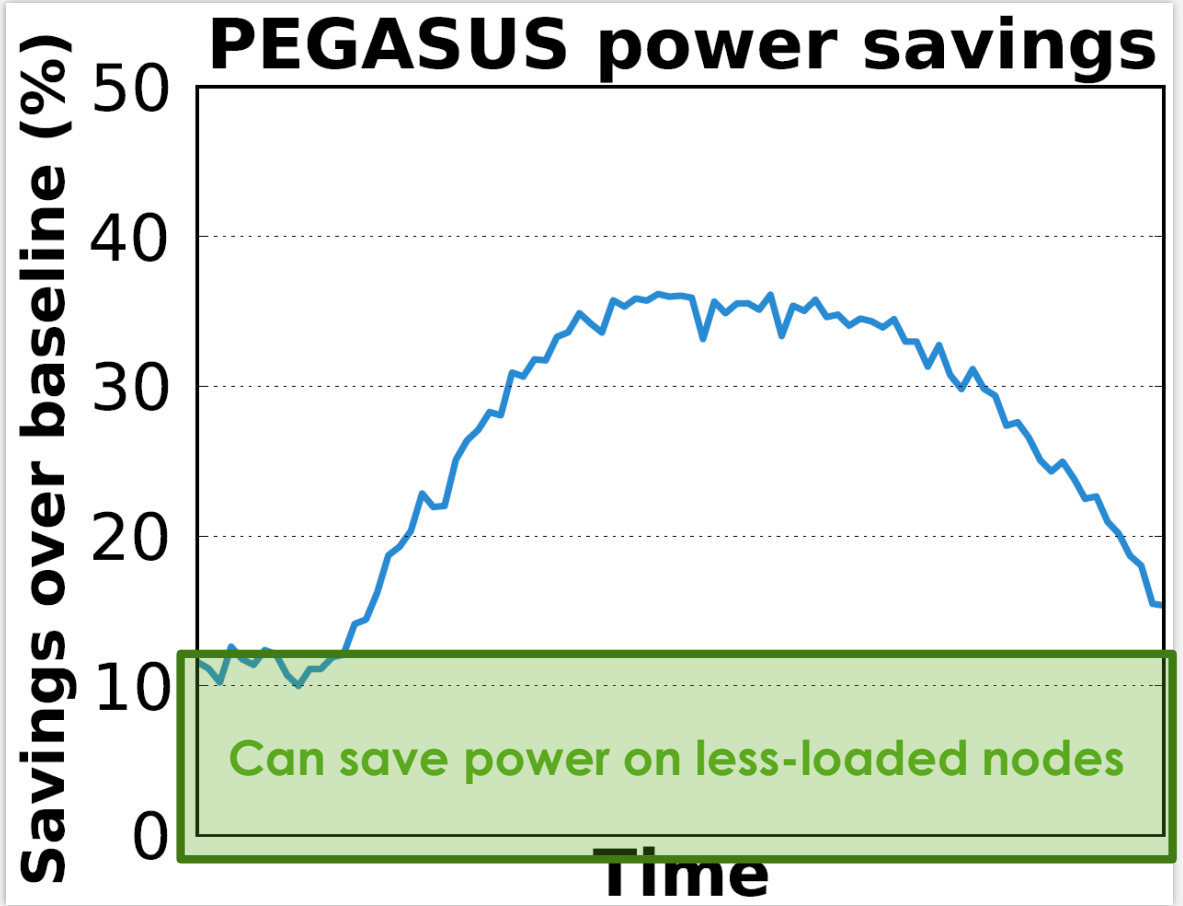
- **Idea**: hierarchical control
  - **Global:** sets latency targets instead of power limits
  - **Local:** decides amount of power needed to meet target latency

Hierarchical PEGASUS design



Estimated hierarchical PEGASUS results





PEGASUS summary

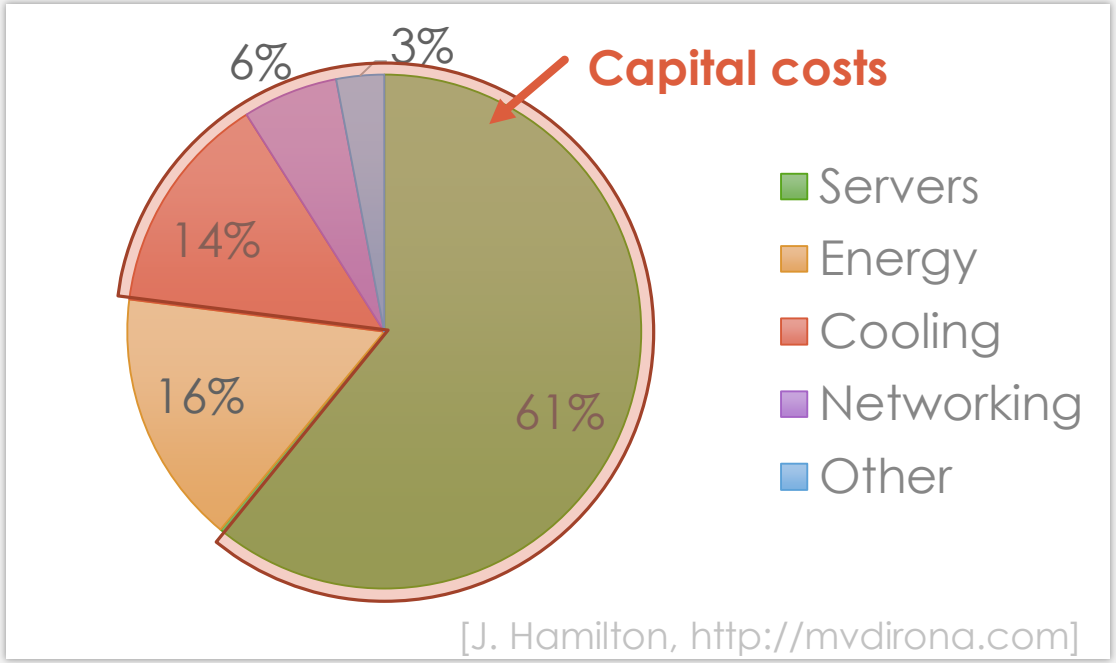
- Halfway there to fully energy proportional systems
- **Iso-latency:** Use SLO metrics and fine-grained power control
  - Save up to 30% power
  - Meet/exceed energy proportionality targets
- PEGASUS achieves **iso-latency** benefits
  - Up to 20% savings on production cluster
  - Be aware of tail at scale effects

Heracles

Reconciling low latency with high utilization

The need for resource efficiency

- Energy efficiency is good but resource efficiency is better
  - Vast majority of costs are non-energy costs

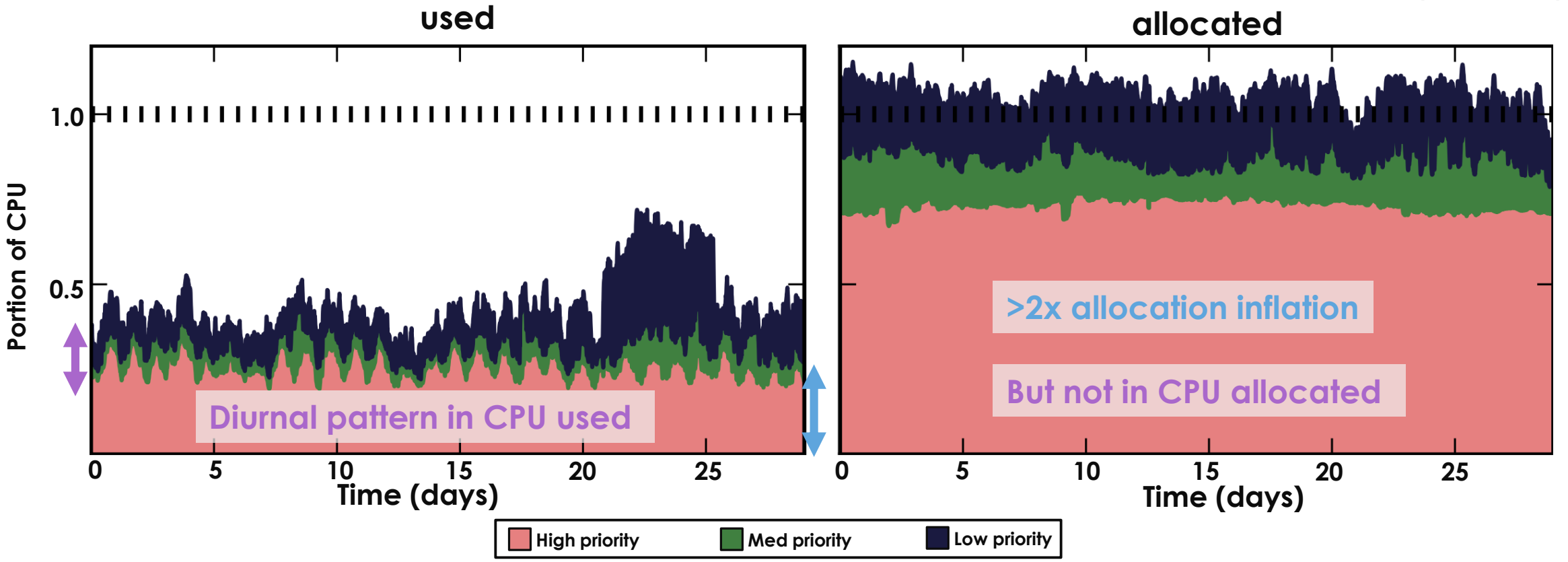


  - Increases capability of existing hardware

Underutilization even with cluster management

Study of utilization on 12,000 node Google cluster

[Reiss SOCC '12]

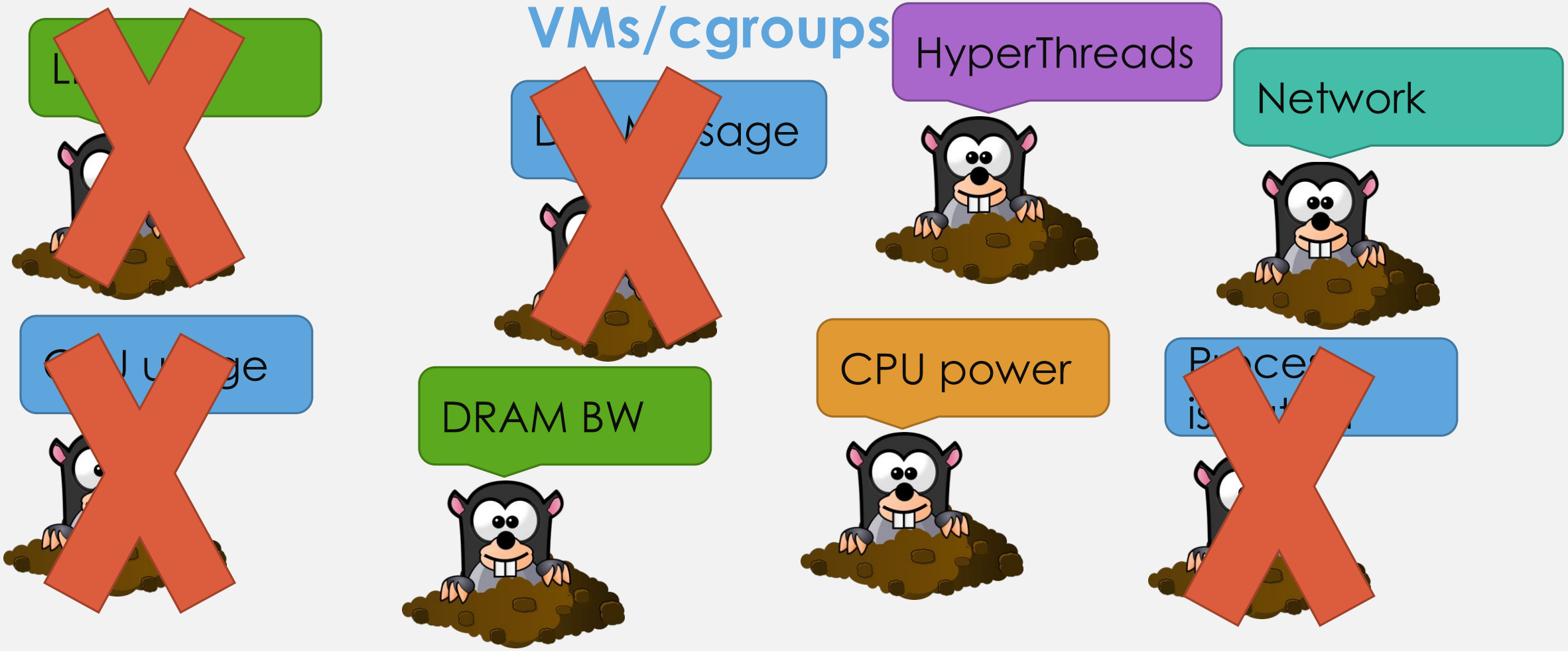


Underutilization is a structural problem

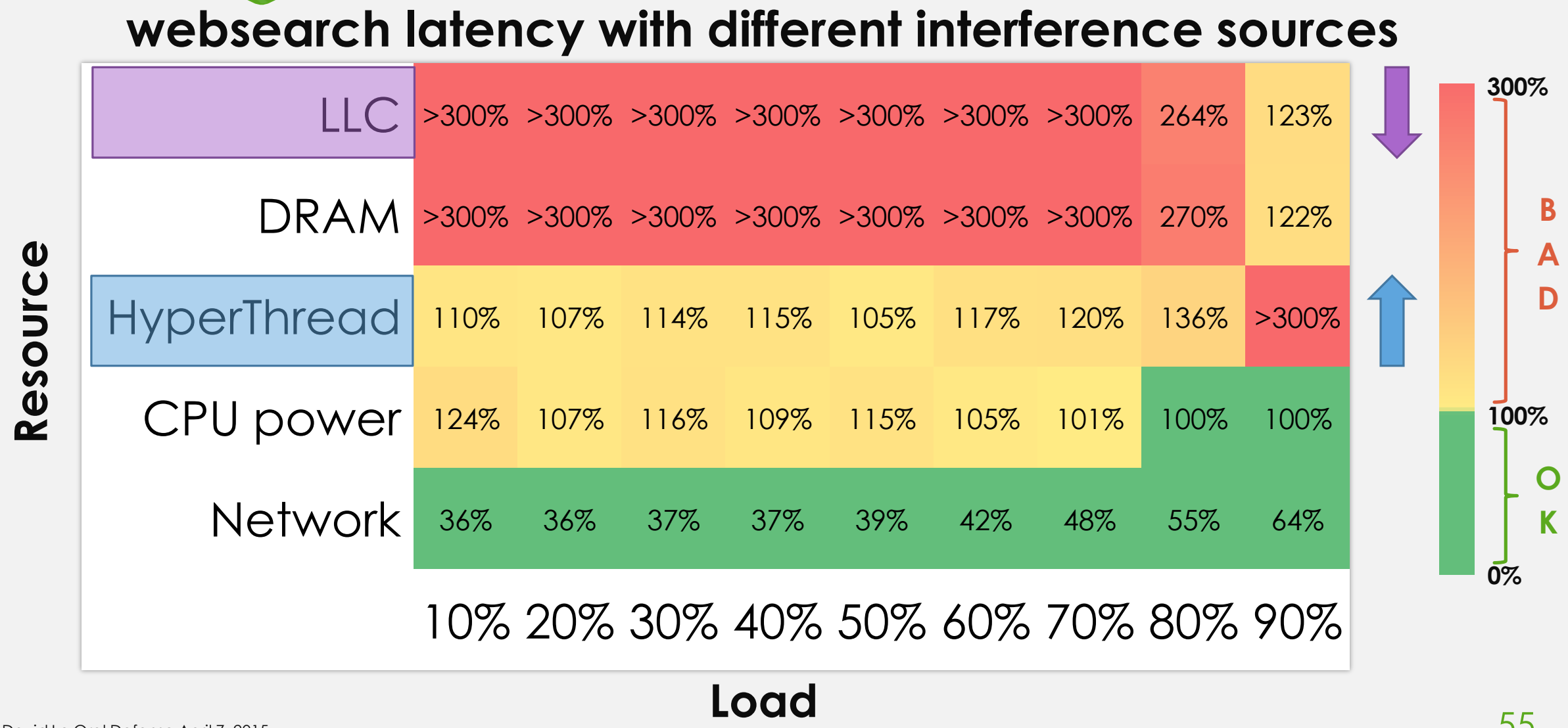
- Effectively an infinite supply of low priority batch jobs
  - Analytics, machine learning, etc.
- High priority jobs are allocated 2x the resources actually used

- Reasons for overprovisioning:
  - Diurnal user traffic
  - Planning for high traffic events
  - Avoid interference from other workloads

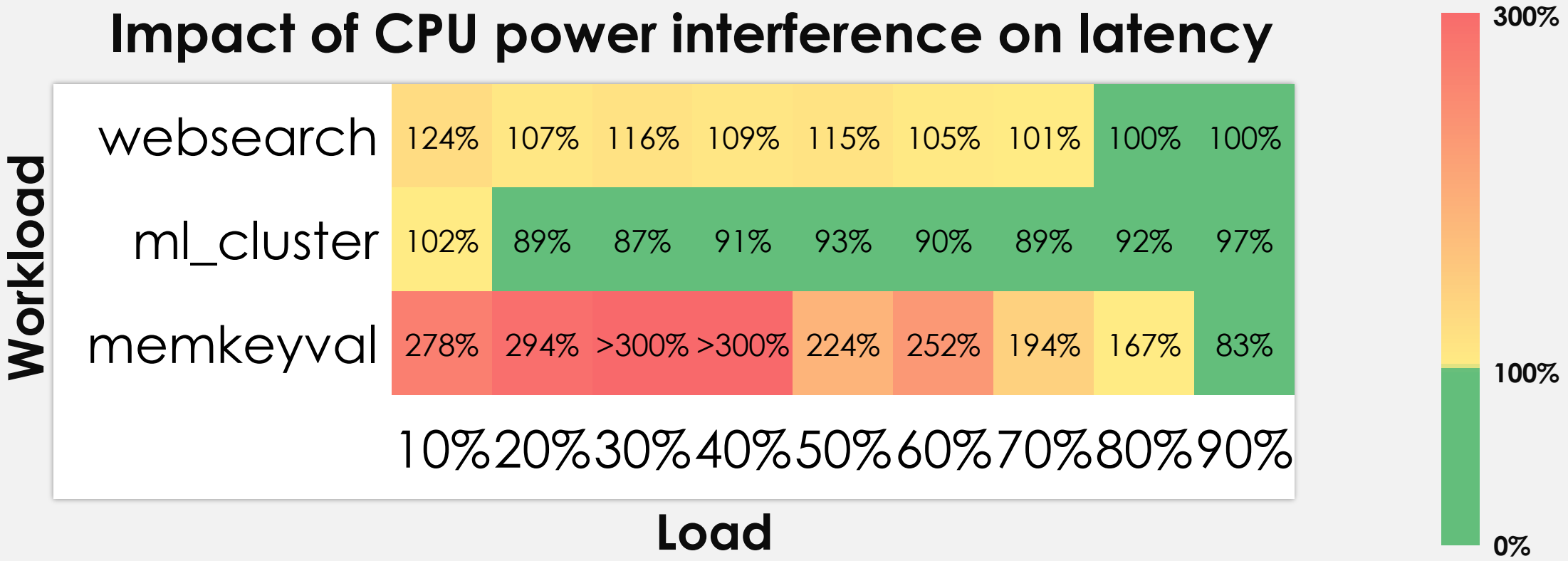
Lots of sources of interference



Interference is different based on resource



And is different based on workload

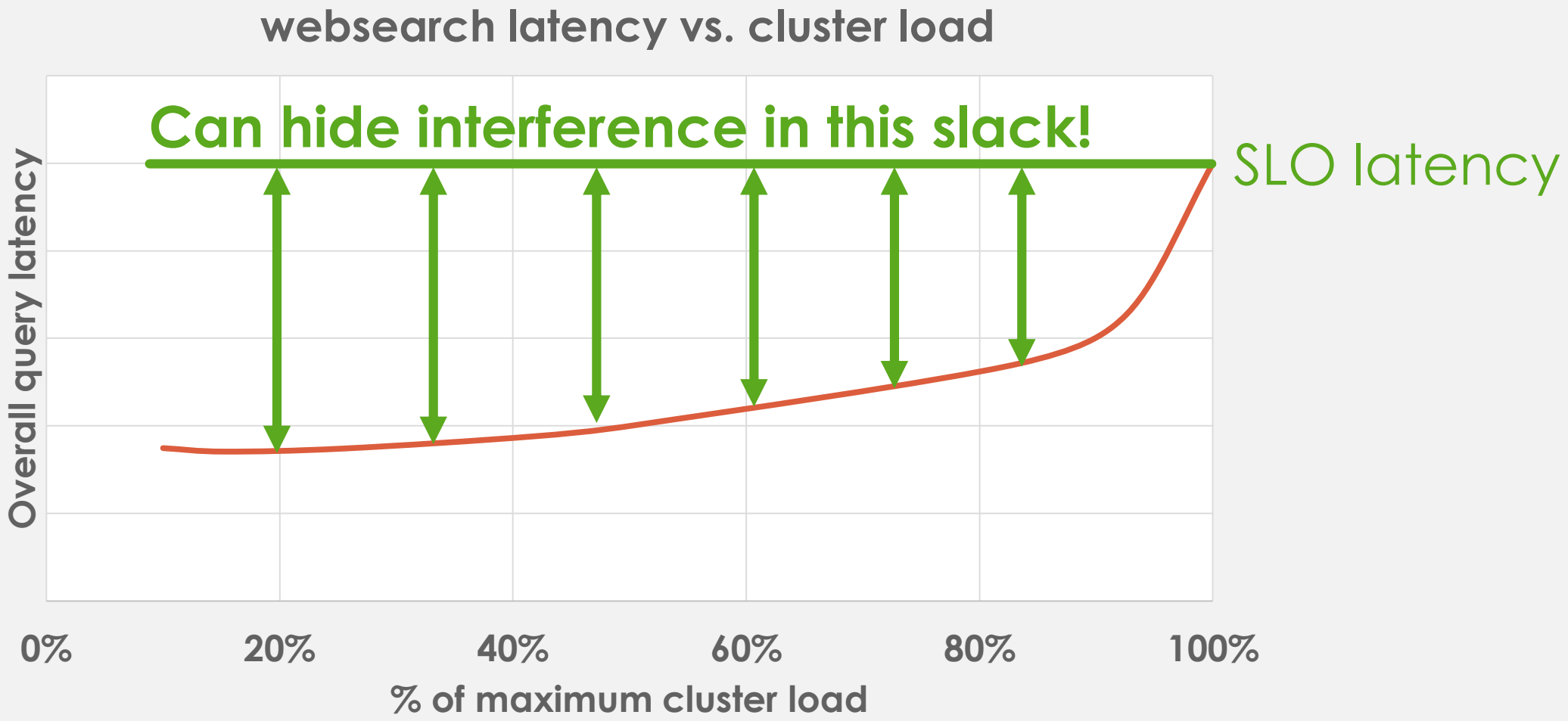


Need dynamic control scheme!

Heracles in a nutshell

- Oversubscription by co-locating a **Best Effort (BE)** job with a **Latency Critical (LC)** job, such as OLDI workloads
- Uses hardware and software knobs to mitigate interference
- Uses latency information from the application to adjust knobs
- Runs locally on each node, complements cluster manager

Use iso-latency to tolerate some interference



Knobs to mitigate interference

- **CPU (HT/L1/L2)**: isolate different workloads to different cores
- **LLC**: hardware cache partitioning
- **DRAM BW**: software monitoring and scheduling
  - Intuition: each core can only issue so many requests/sec
- **Network**: rate limiting in Linux kernel with HTBs
- **CPU power**: per-core DVFS

But how should the knobs be set?

- This looks like an optimization problem
  - **Objective**: maximize utilization
  - **Constraints**: preserve SLO of latency critical application

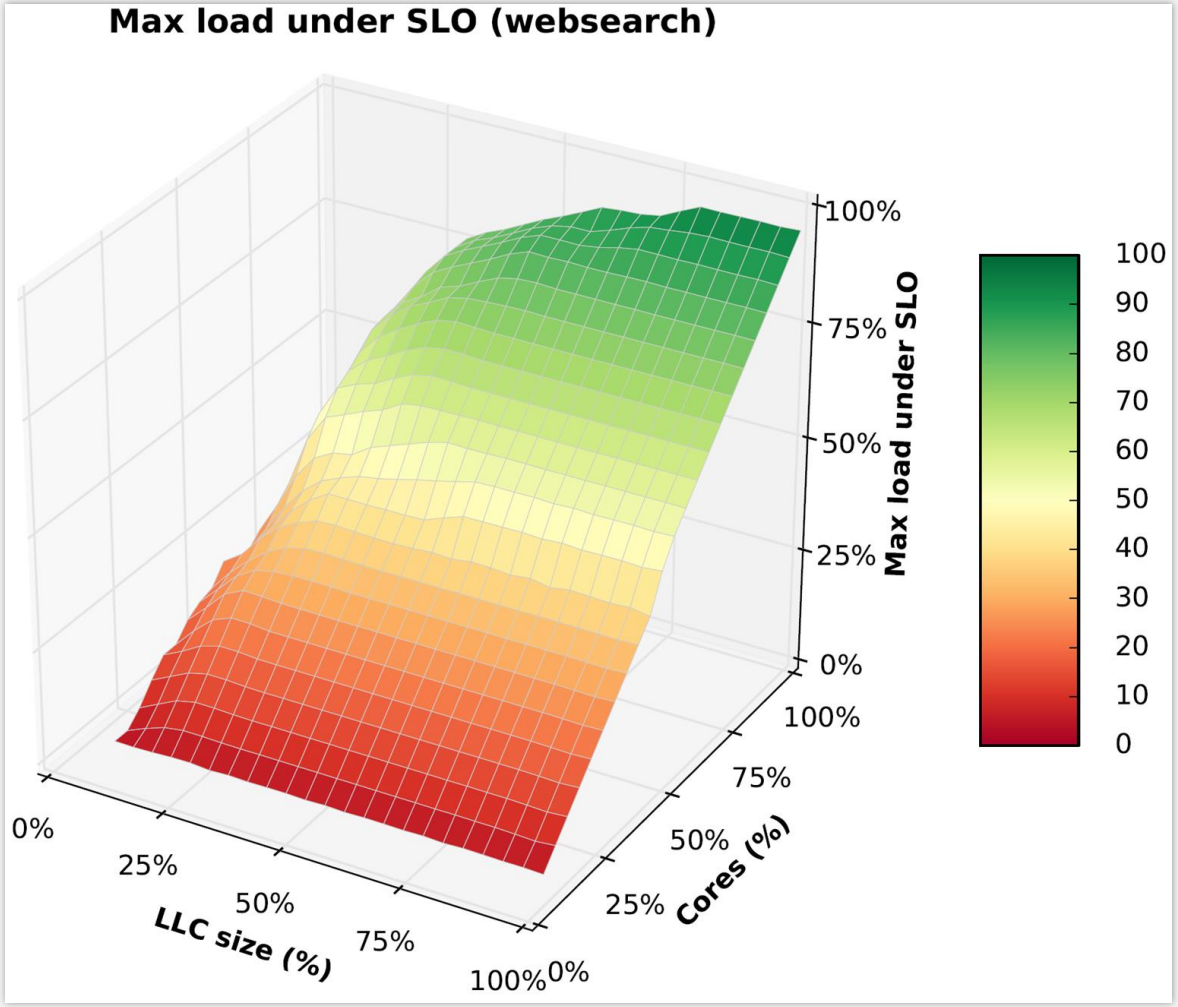
- **Challenge: 5-dimensional formulation!**

Decoupling interference sources

- **Observation**: latency violations occur when a shared resource is extremely loaded
  - High demand for resource causes significant contention
  - LC workload is unable to obtain its required allocation

- **Insight:** assume independent interference under 2 conditions
  - LC workload is not starved for any resource
  - Each resource has enough slack to absorb bursts

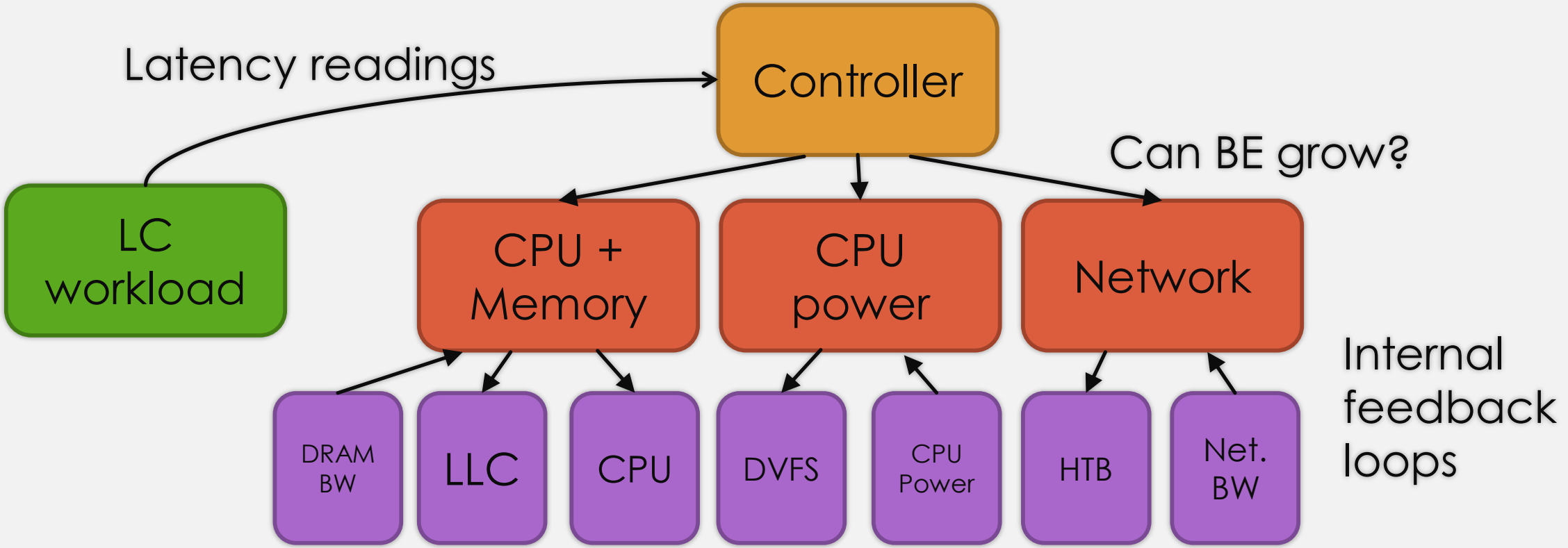
Gradient descent find optimal allocation



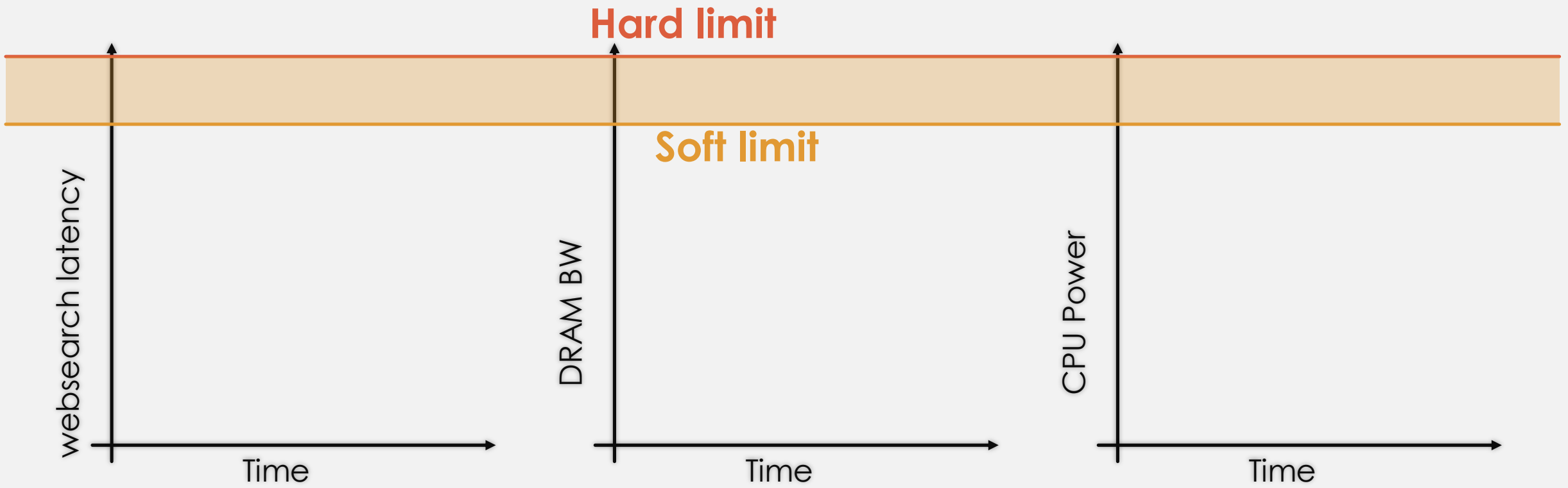
- Performance as a function of resources is convex for benchmarked workloads
- Use of gradient descent is guaranteed to produce optimality

Heracles: shared resource manager

- **Goal**: meet SLO, keep BE from saturating shared resource
- Runs on each machine, ~1k lines of code



Example Heracles run



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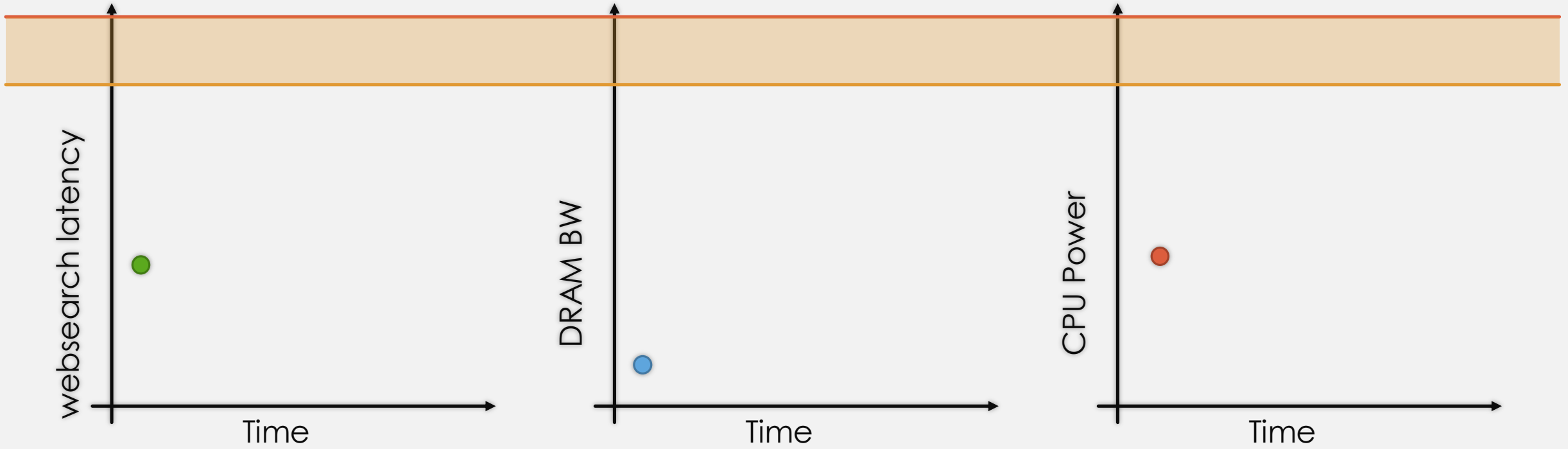
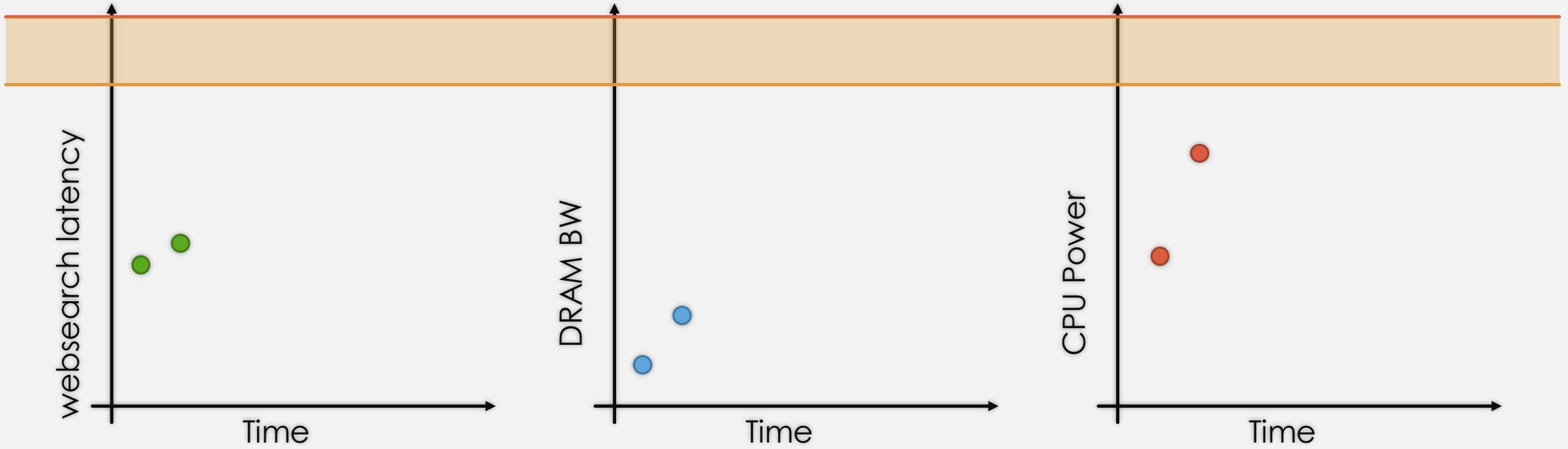


Core Allocation

Example Heracles run



Core Allocation

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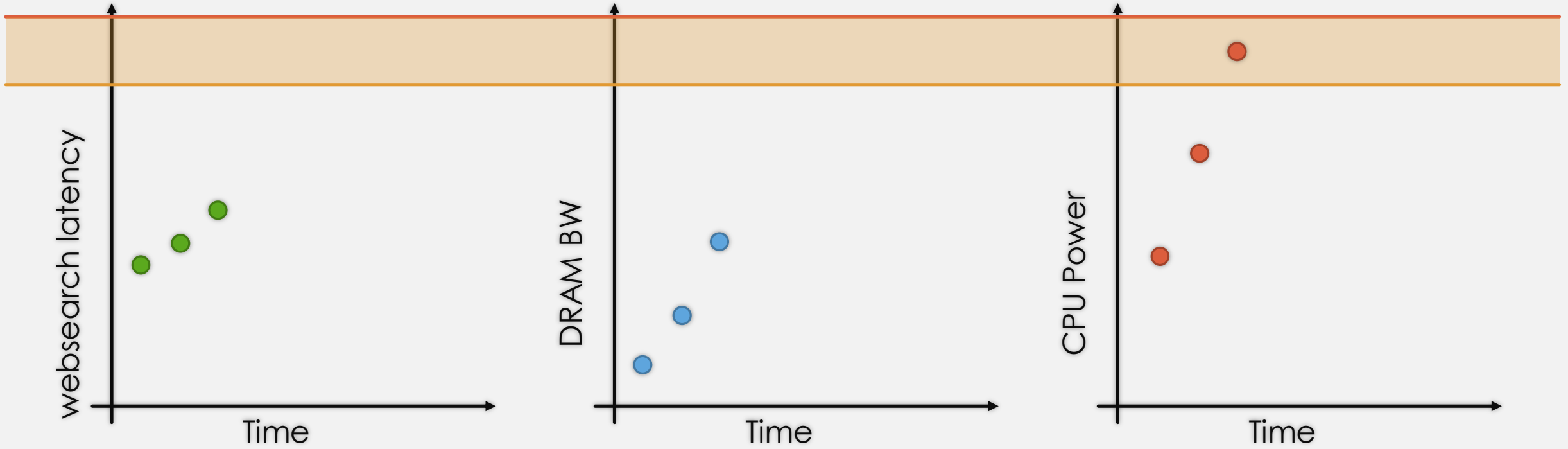
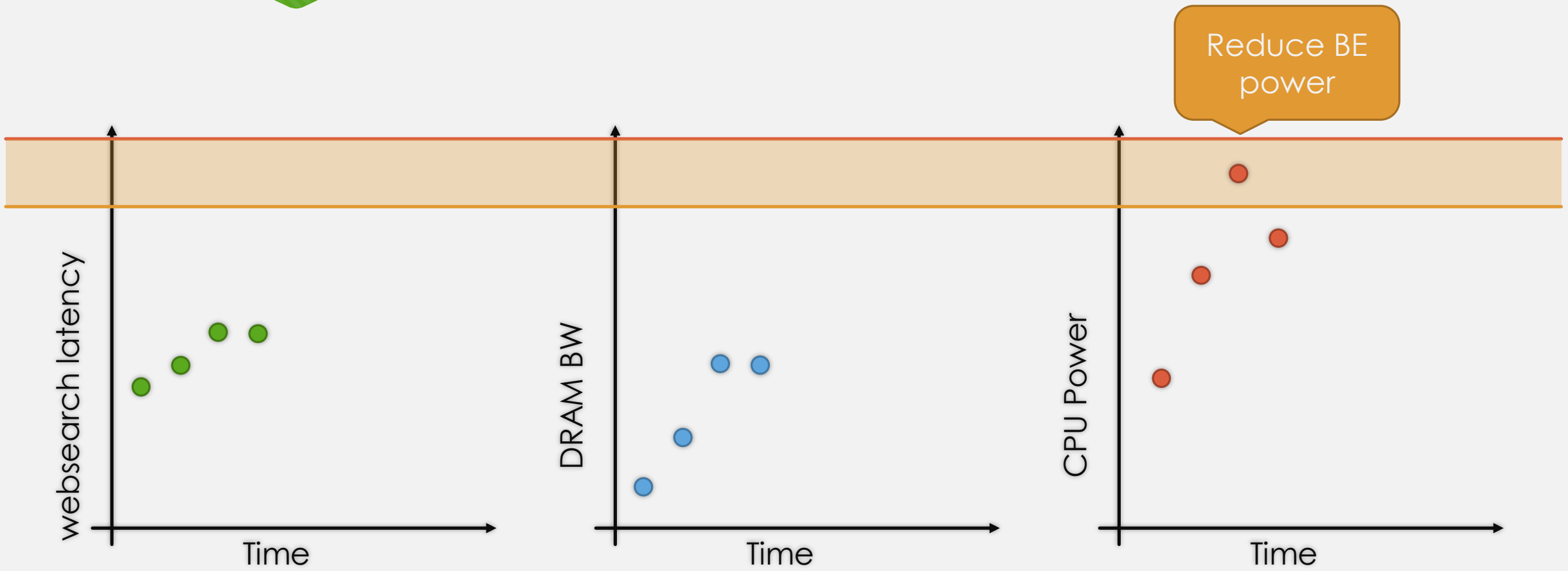


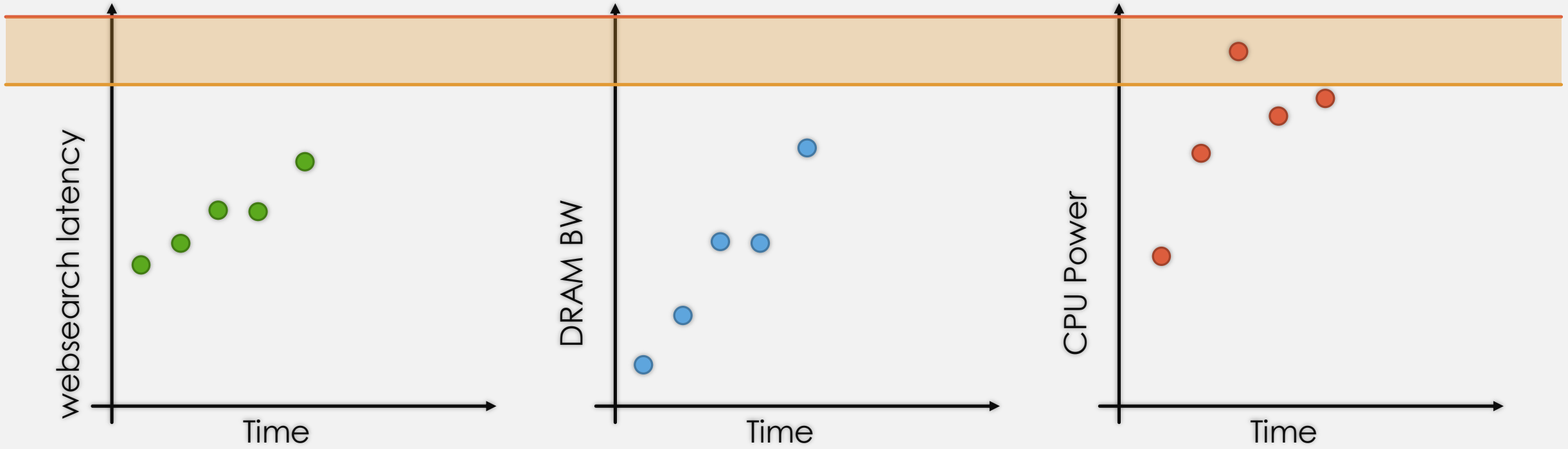
Core Allocation

Example Heracles run



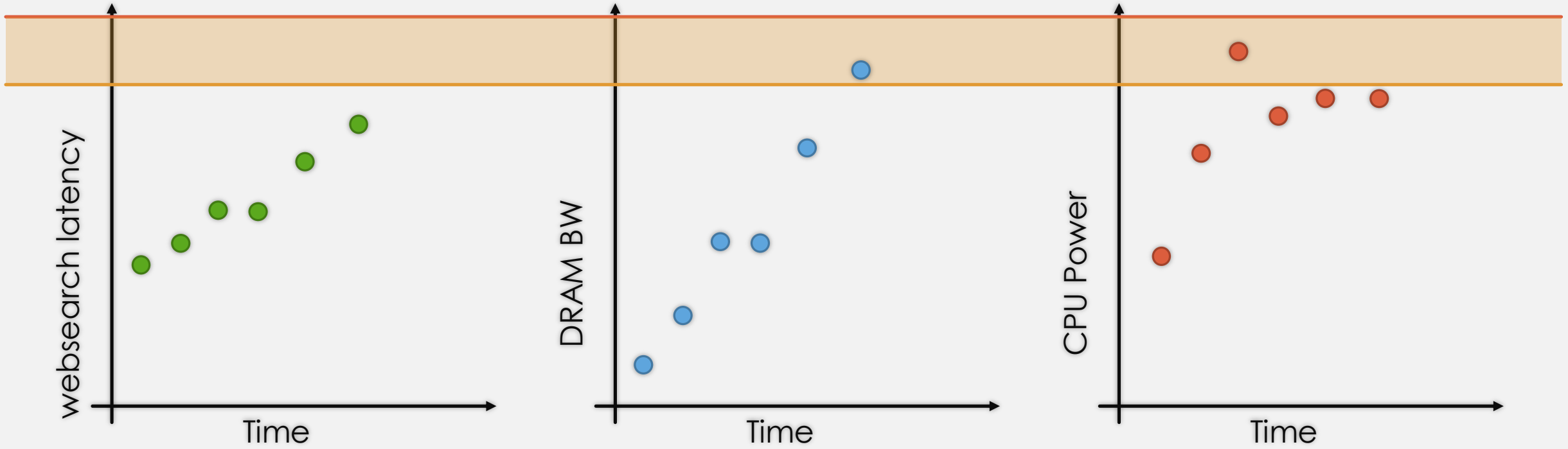
Core Allocation

Example Heracles run

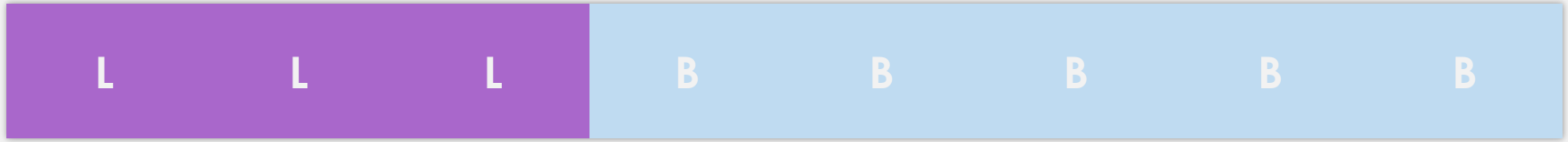


Core Allocation

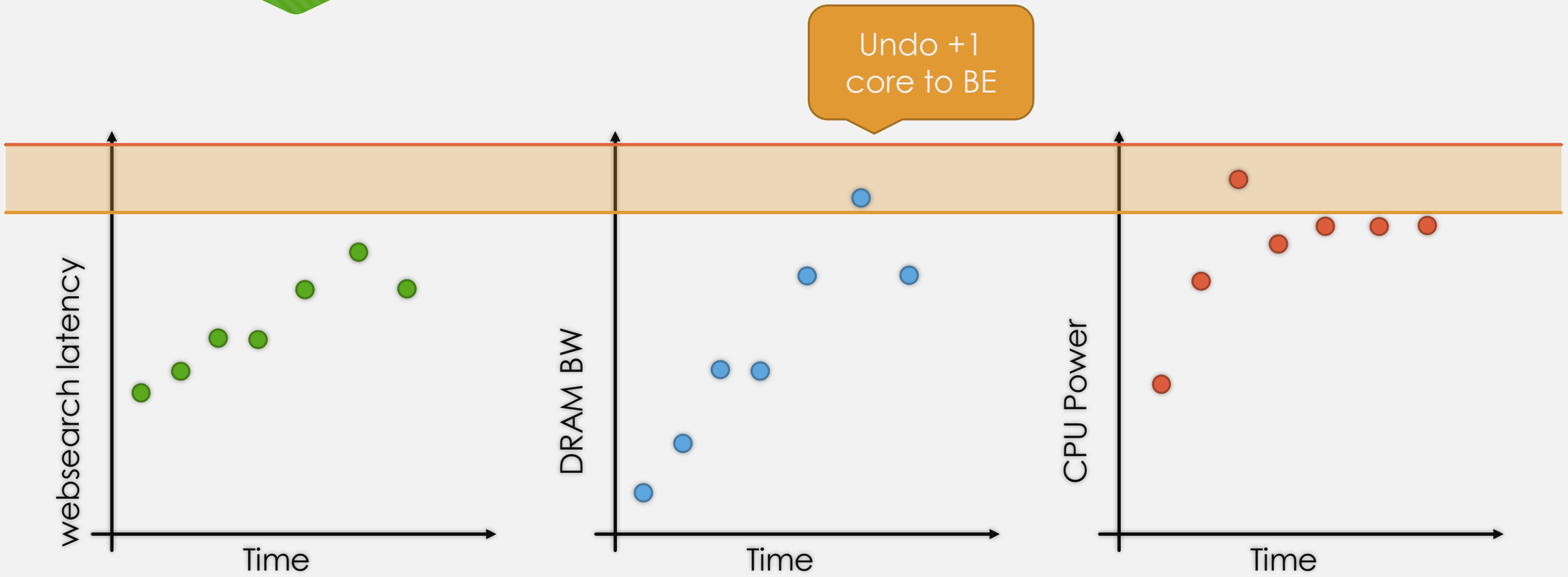
Example Heracles run



Core Allocation



Example Heracles run



Core Allocation

Latency Critical OLDI workloads

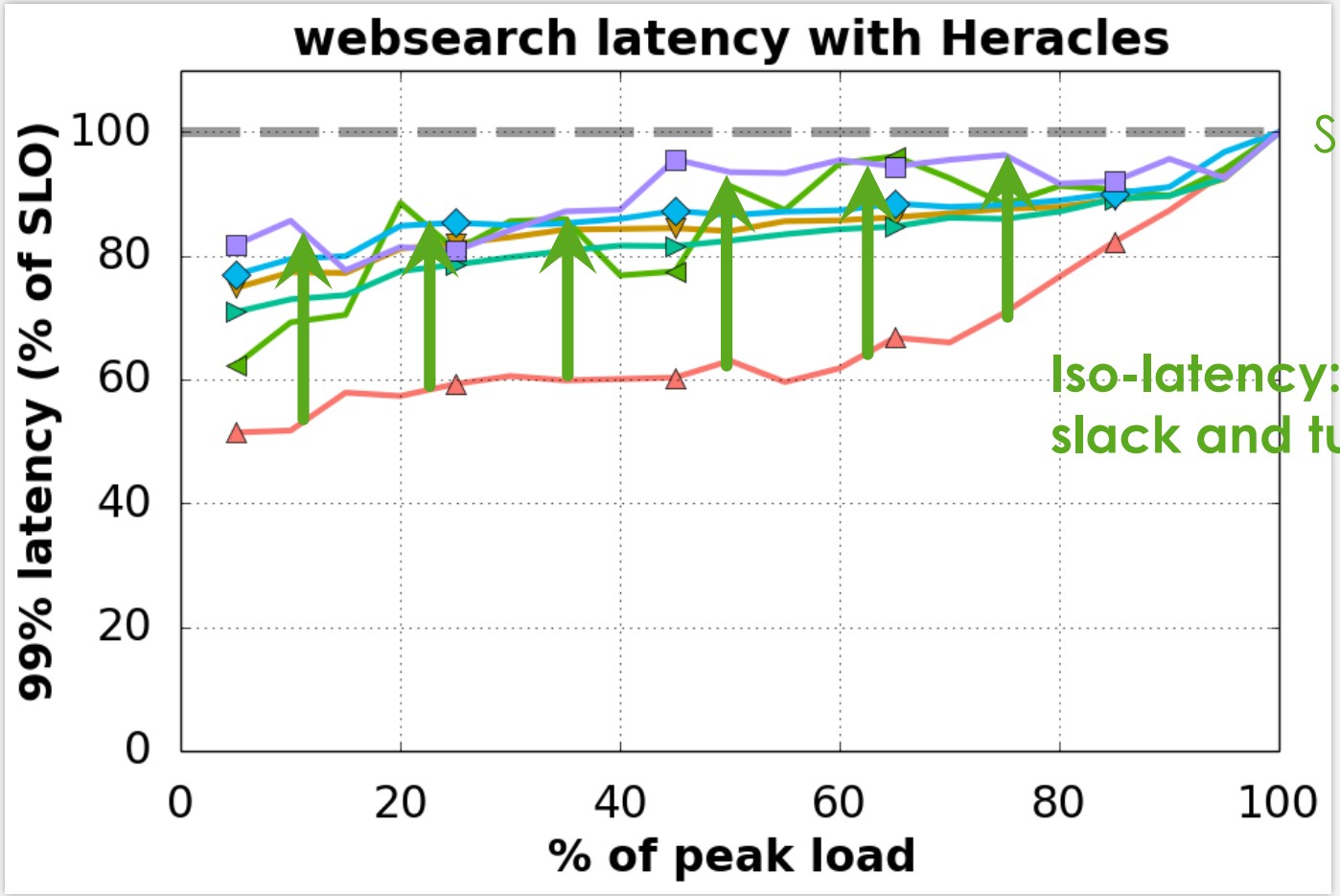
- **websearch**
  - Leaf node, document retrieval/scoring
  - 99%-ile latency SLO of tens of milliseconds
- **ml_cluster**
  - Machine learning for text clustering
  - 95%-ile latency SLO of tens of milliseconds
- **memkeyval**
  - In-memory key-value store
  - 99%-ile latency SLO of hundreds of microseconds

Best Effort jobs

- **stream-LLC**: LLC antagonist
- **stream-DRAM**: DRAM BW antagonist
- **cpu_pwr**: CPU power antagonist
- **brain**: deep learning (LLC, DRAM, CPU, CPU power)
- **streetview**: image stitching (DRAM BW)

Run Heracles on real hardware, measure latency and utilization

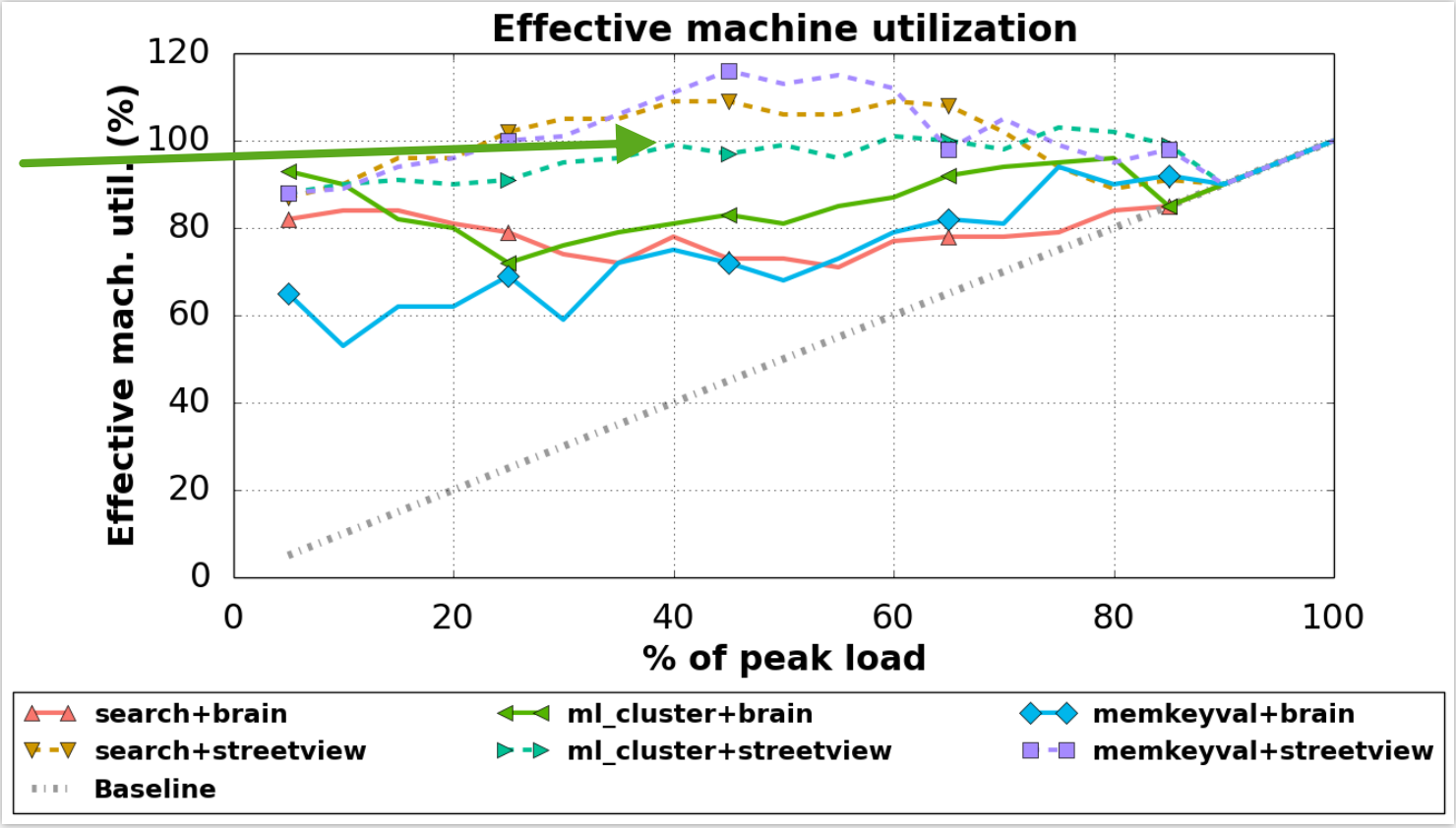
Latency validation: do no harm



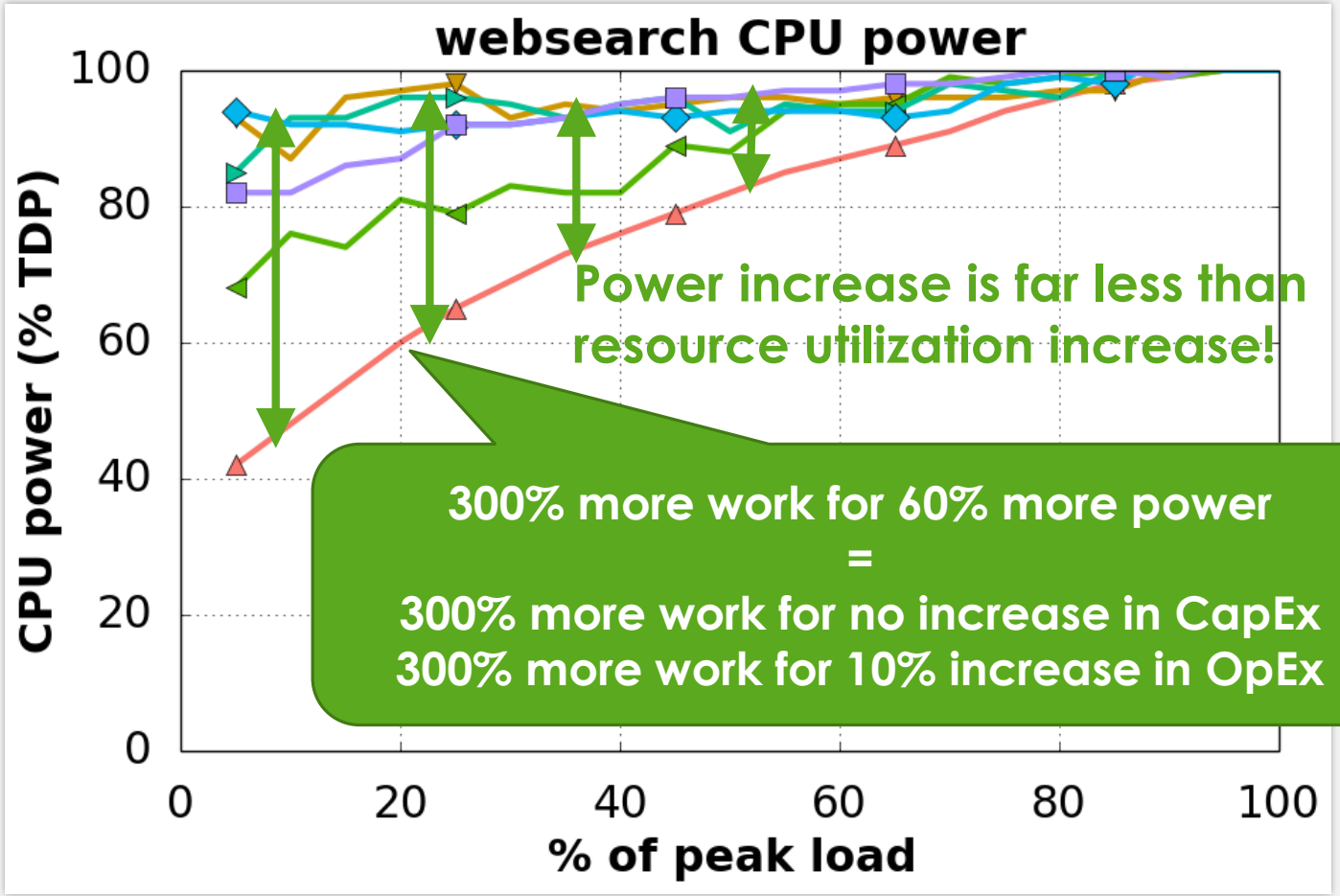
Putting it together: resource efficiency

Effective Machine Utilization = (LC load) + (% BE throughput)

Better than 100% is due to better binpacking

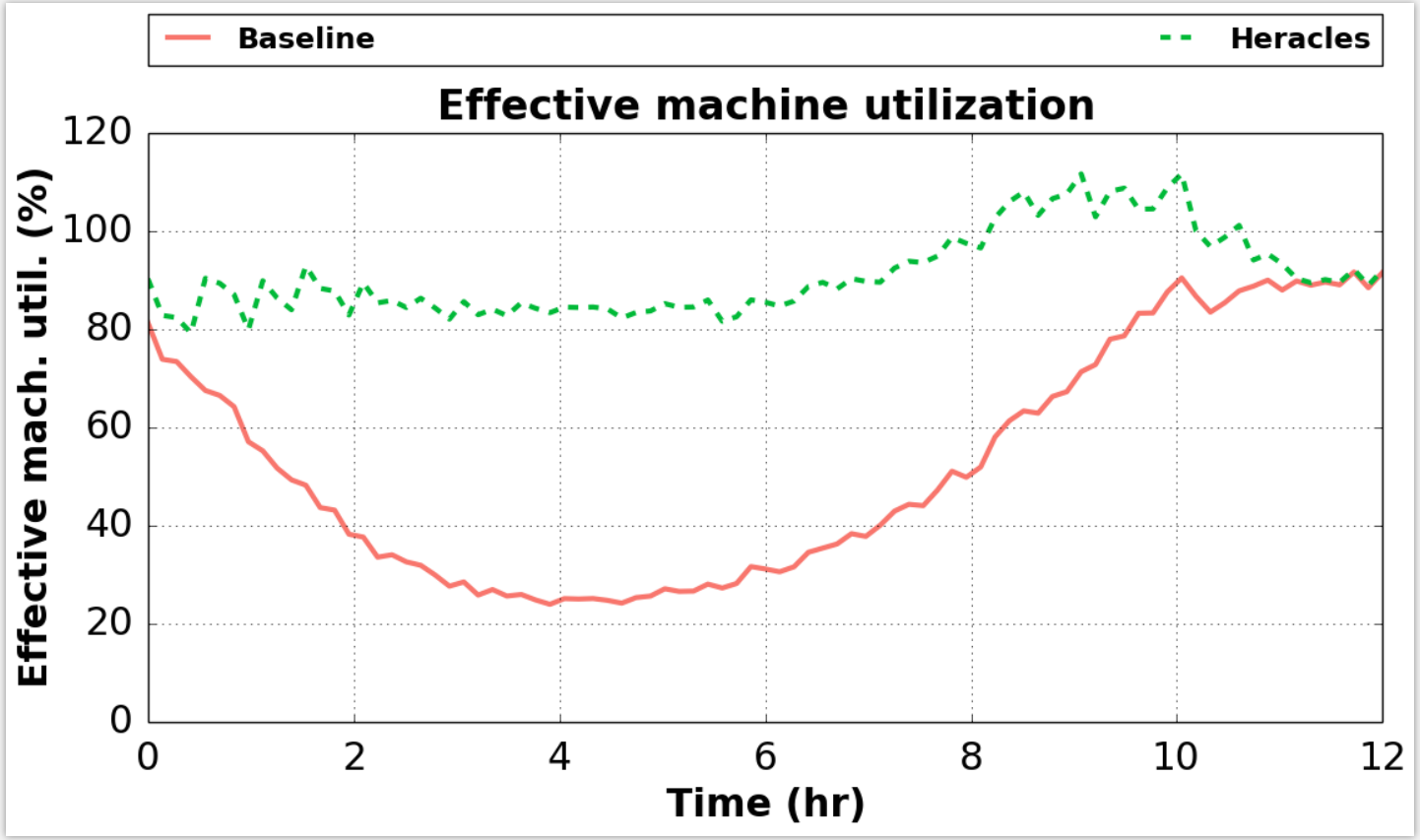


Bonus: energy efficiency too!



Minicluster results

- Use load trace for off-peak hours on websearch minicluster



Related work

- Interference-aware cluster management
  - Paragon [ASPLOS'13], Quasar [ASPLOS'14], BubbleUp [MICRO'11], BubbleFlux [MICRO'12], CPI2 [Eurosys'13]
  - **Complementary, as Heracles enables more co-location opportunities**

- Hardware/software partitioning mechanisms
  - Cache: Vantage [ISCA'11], Ubik [ASPLOS'14], UCP [MICRO'06]
  - Iyer et al [SIGMETRICS'07], memory hierarchy QoS
  - **Lots of individual mechanisms available, Heracles puts them together**

Heracles summary

- Increasing utilization is key to improving datacenter efficiency
- Lots of knobs to control lots of sources of interference
  - Need coordinated policy to find optimal settings
- Heracles significantly increases utilization
  - Achieves average of 90% utilization for Google workloads
  - Potential increase of >300% in cost efficiency

Contributions recap

- Autoturbo: improving energy efficiency
- OLDIsim: scale-out benchmark
- PEGASUS: improving energy efficiency
  - Achieves dynamic energy proportionality for latency-critical jobs
  - Saves up to 30% power during low loads
- Heracles: improving resource efficiency
  - Enables high utilization even in the face of tight SLO constraints
  - Achieves 90% utilization without causing latency violations

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Thanks for listening!

Fin.