**Parallel Data Laboratory**
Carnegie Mellon University

# *Pacemaker*

***USENIX OSDI 2020***

## Avoiding HeART attacks in storage clusters with disk-adaptive redundancy

***20 min version***

**Saurabh Kadekodi**, Francisco Maturana, Suhas Jayaram Subramanya, Juncheng Yang, K. V. Rashmi, Greg Ganger

# Today's storage clusters

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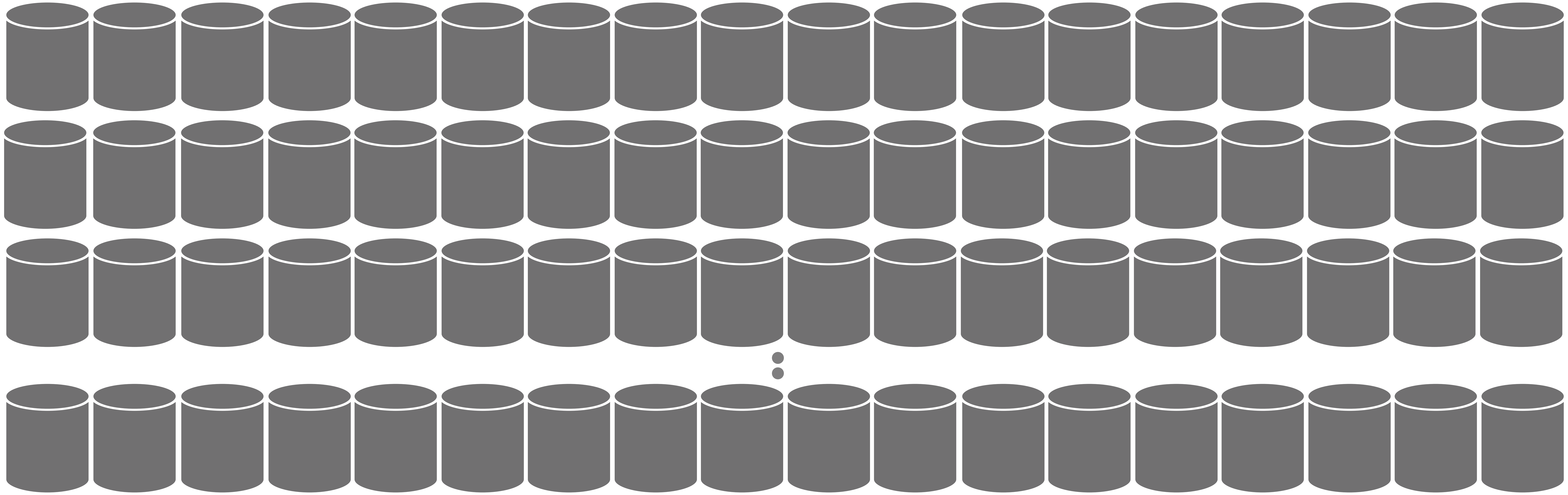
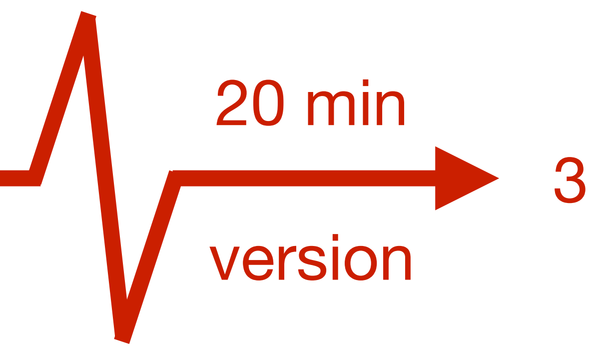
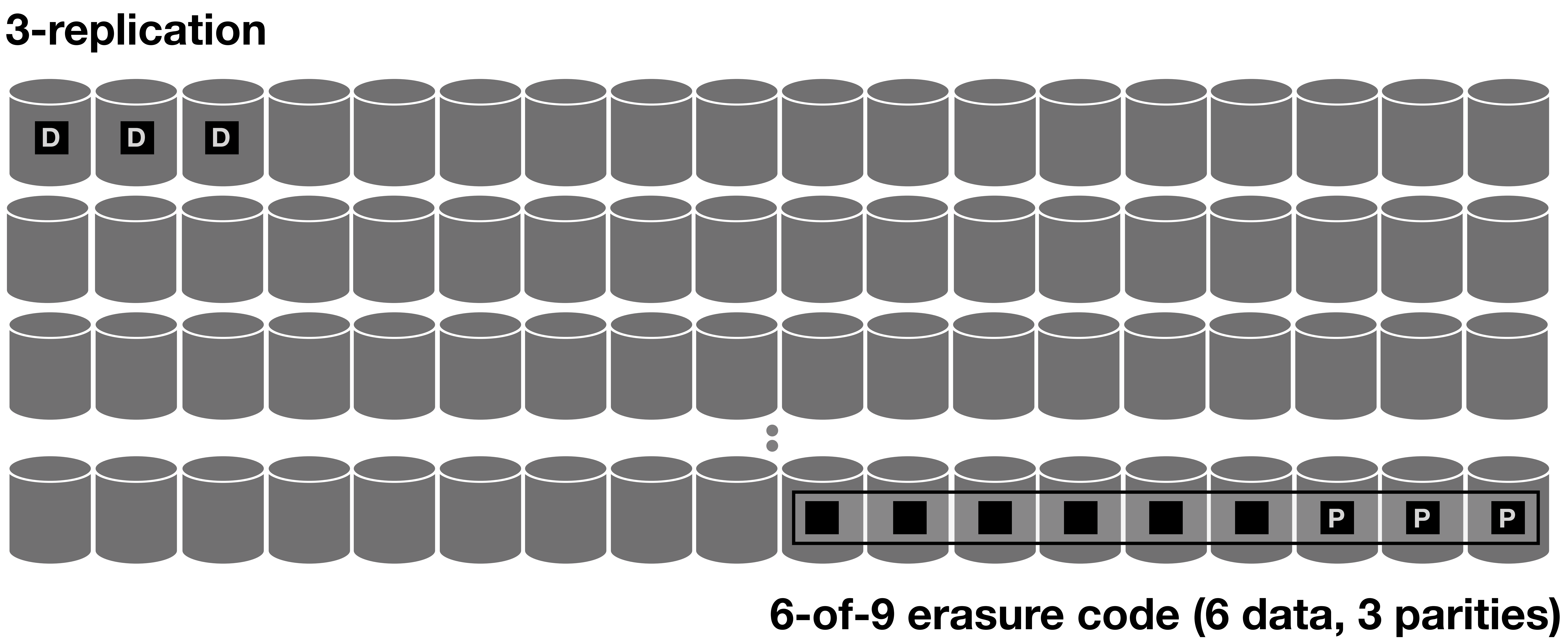


- Thousands to millions of disks in primary storage tier
- Failures common in today's cluster storage systems
  - Disk failures measured as **annualized failure rates (AFR)**
  - AFR = expected % of failures in a year

# Data redundancy for fault tolerance



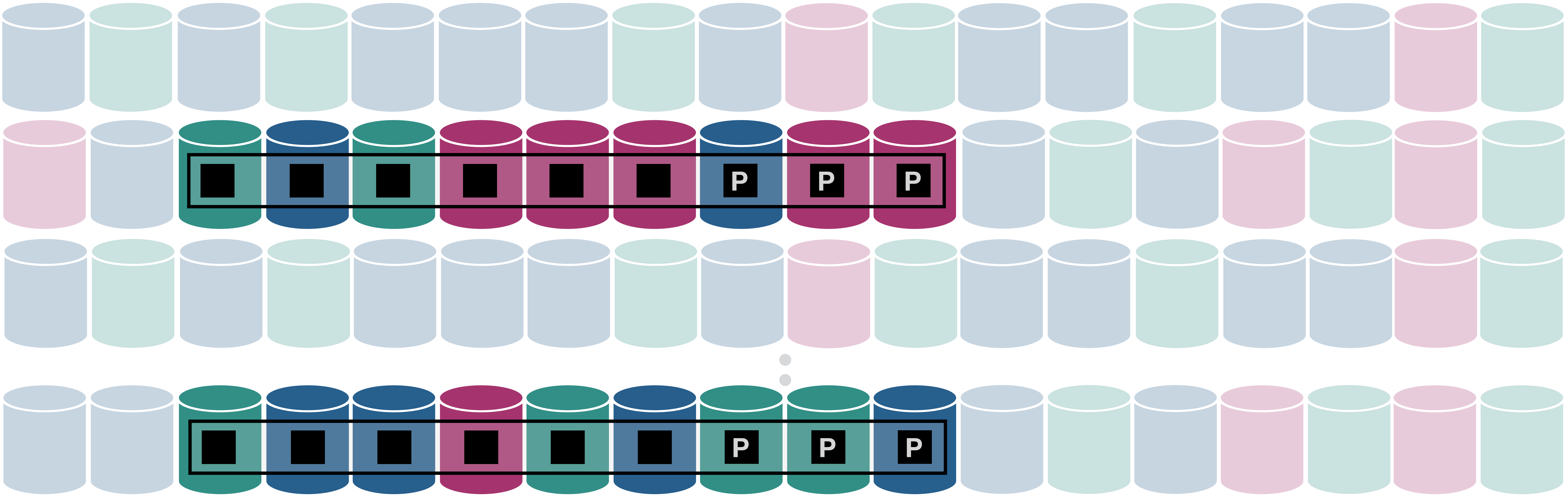

- Data redundancy is used to protect against data loss
- Multiple redundancy scheme may be used in the entire fleet

Redundancy scheme unaware of AFR differences among disks

# Reality: different disks fail differently








- Single storage cluster may have multiple makes/models
- Result: stripes (or replicas) may provide different reliability

**Same redundancy is either insufficient or overly wasteful**

# How much do failure rates vary?

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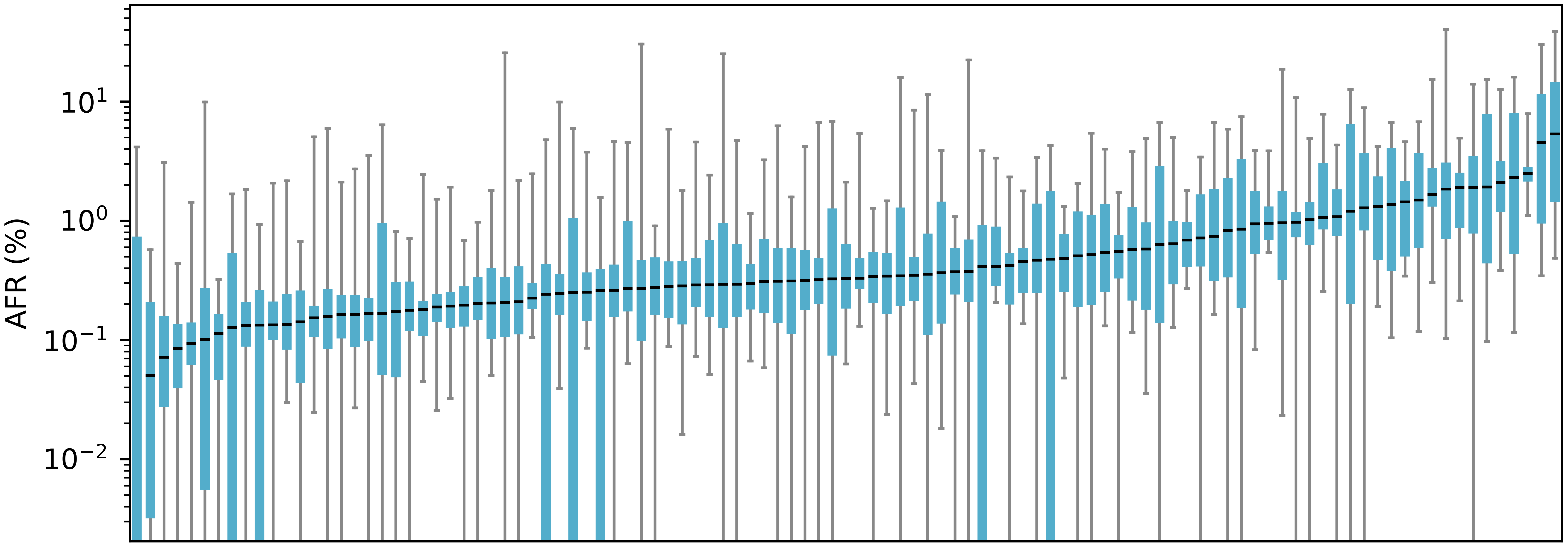
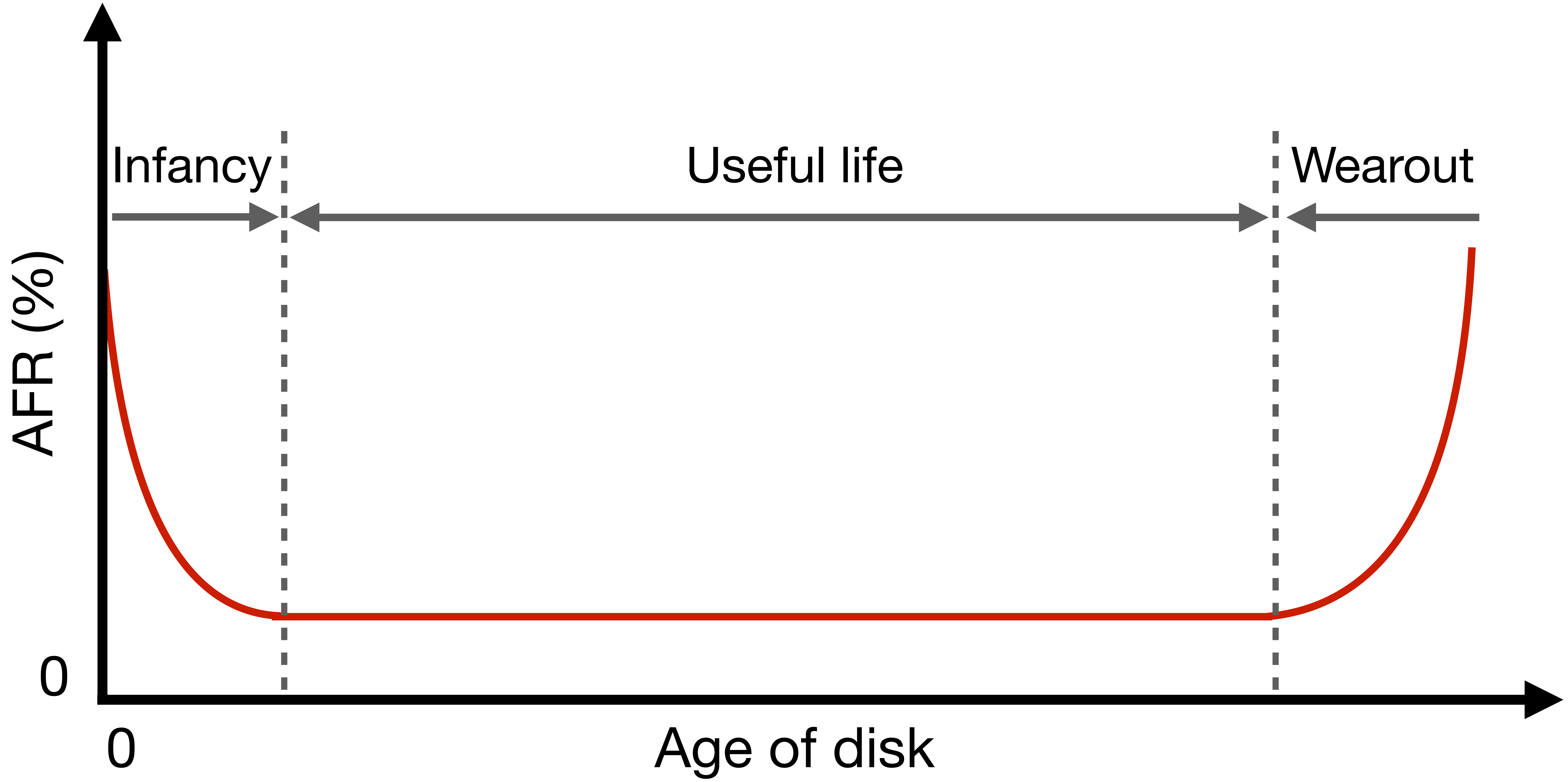



- Totally over 5.3 million HDDs, across over 60 makes/models
- Deployed in production environments at NetApp, Google, Backblaze
- Each box represents a make/model with at least 10000 HDDs

**Over 10x difference in failure rates across makes/models**

# The disk hazard (bathtub) curve



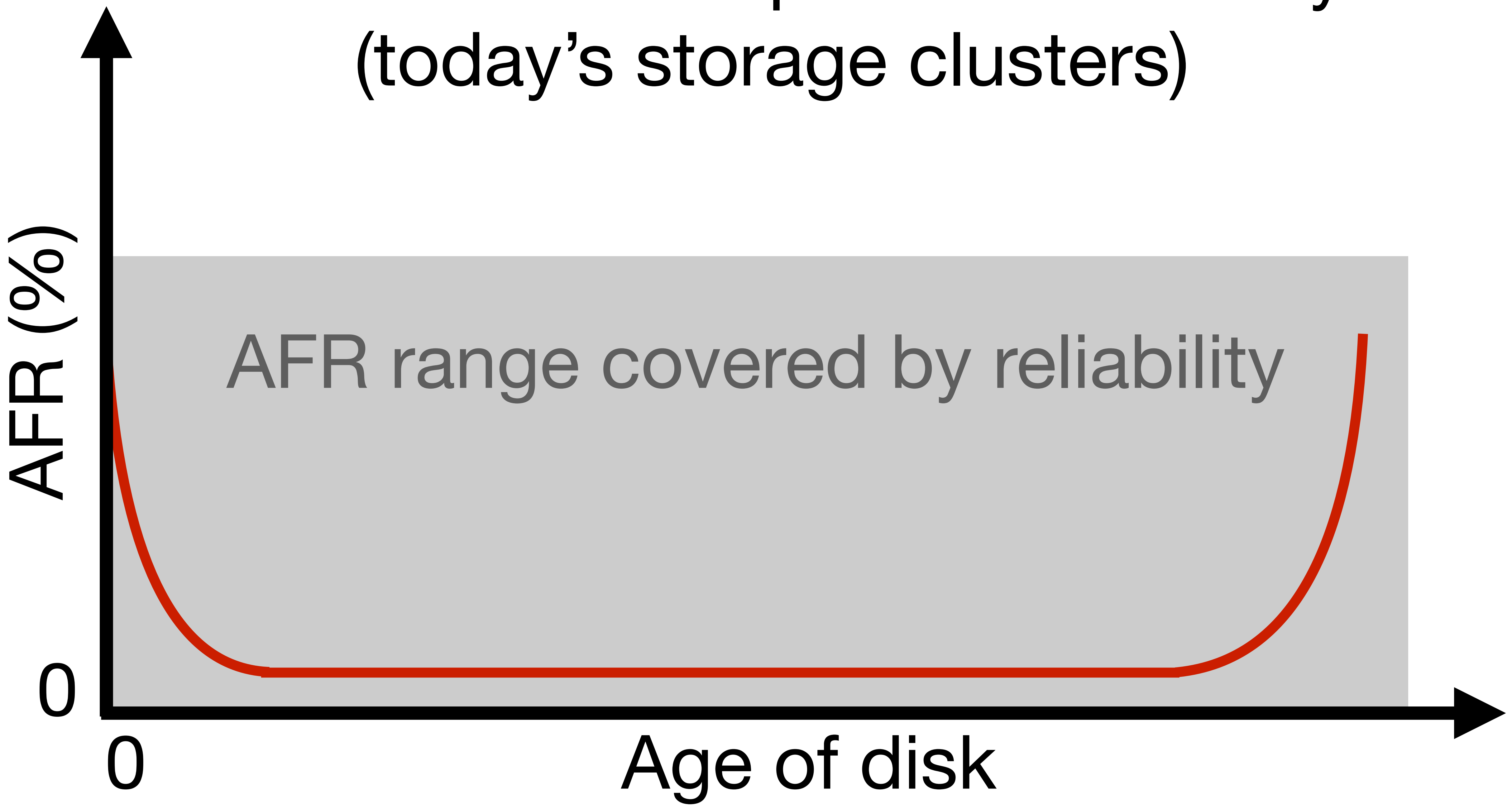



Failure rate varies over a disk's lifetime

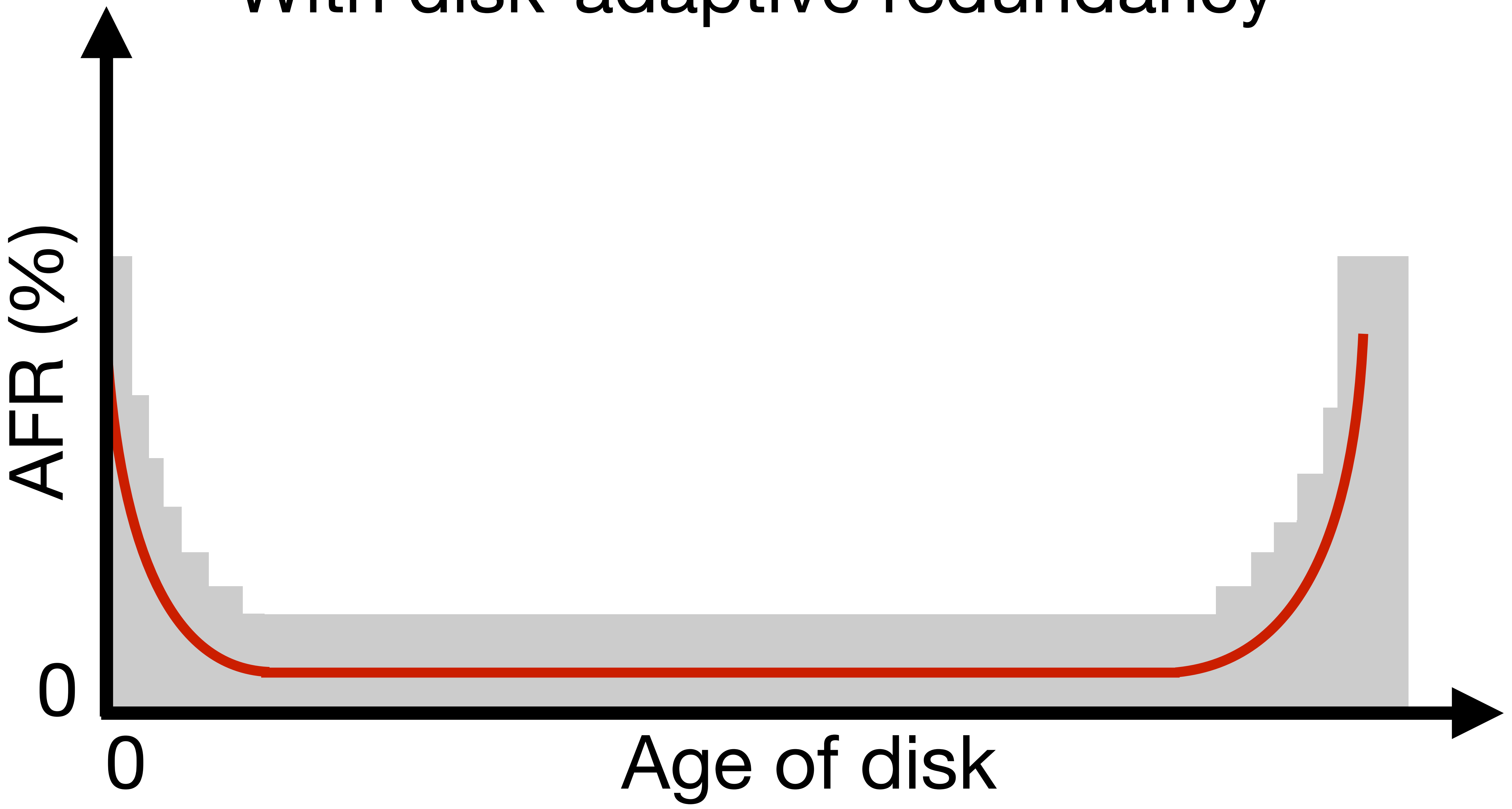
# Tailoring data redundancy to disk failure rate



Without disk-adaptive redundancy
(today's storage clusters)




With disk-adaptive redundancy




**Lower AFR ⟶ Lower redundancy ⟶ Lower storage cost**

# Disk-adaptive redundancy promises huge savings

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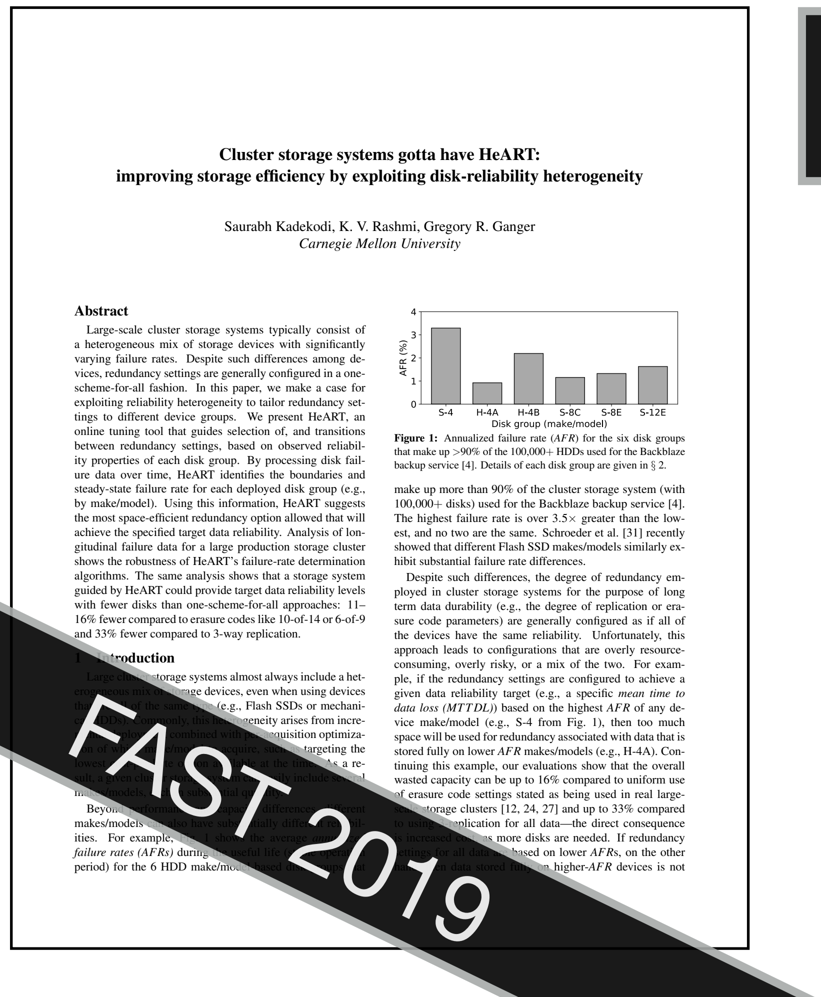
- First proposed as the **He**terogeneity **A**ware **R**edundancy **T**uner (HeART)
  - Published in USENIX FAST 2019
- HeART simulated disk-adaptive redundancy in storage cluster with over 100K HDDs
- Promised substantial storage space-savings over one-scheme-fits-all approaches:
  - Up to **33% lesser space compared to 3-way replication**
  - **11—16% lesser space compared to popular erasure codes**: 6-of-9 and 10-of-14
- In modern storage clusters >10% space-savings ⟶ tens of thousands of fewer disks



Cluster storage systems gotta have HeART: improving storage efficiency by exploiting disk-reliability heterogeneity

Saurabh Kadekodi, K. V. Rashmi, Gregory R. Ganger
Carnegie Mellon University

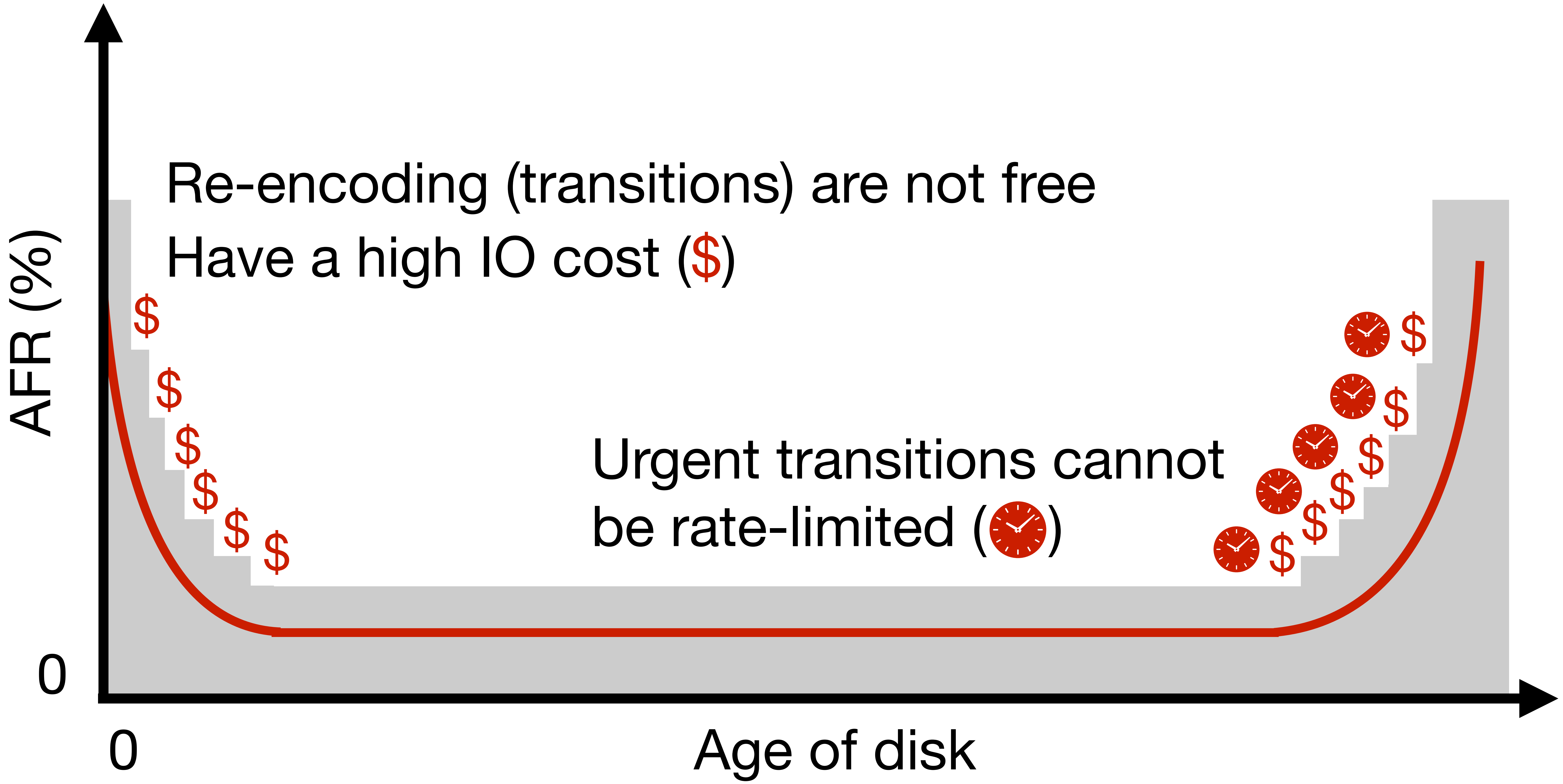
Abstract



**Disk-adaptive redundancy can substantially reduce storage and energy costs**

# Existing solutions suffer from transition overload



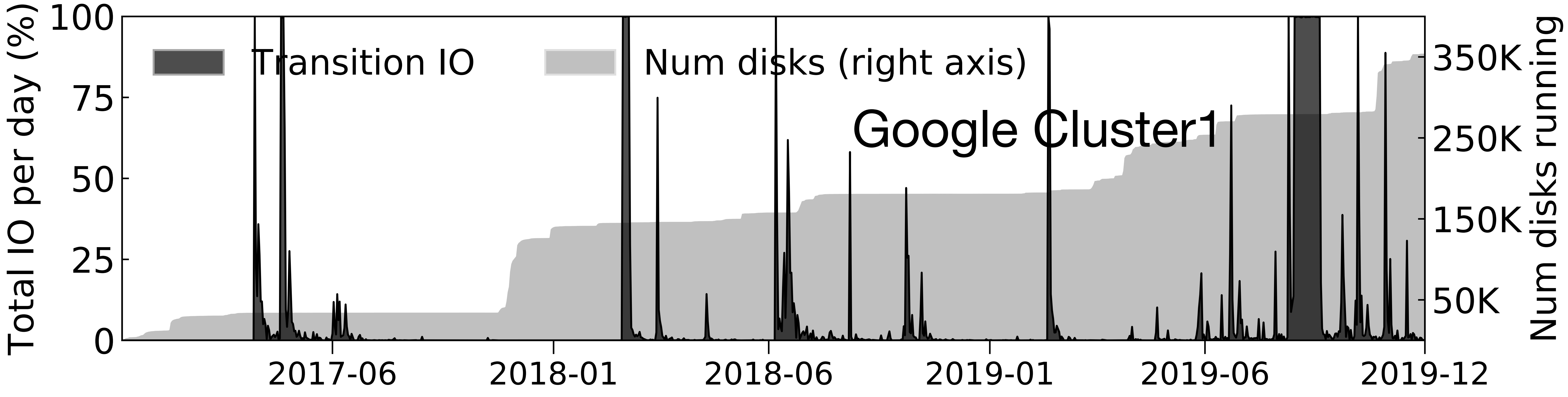


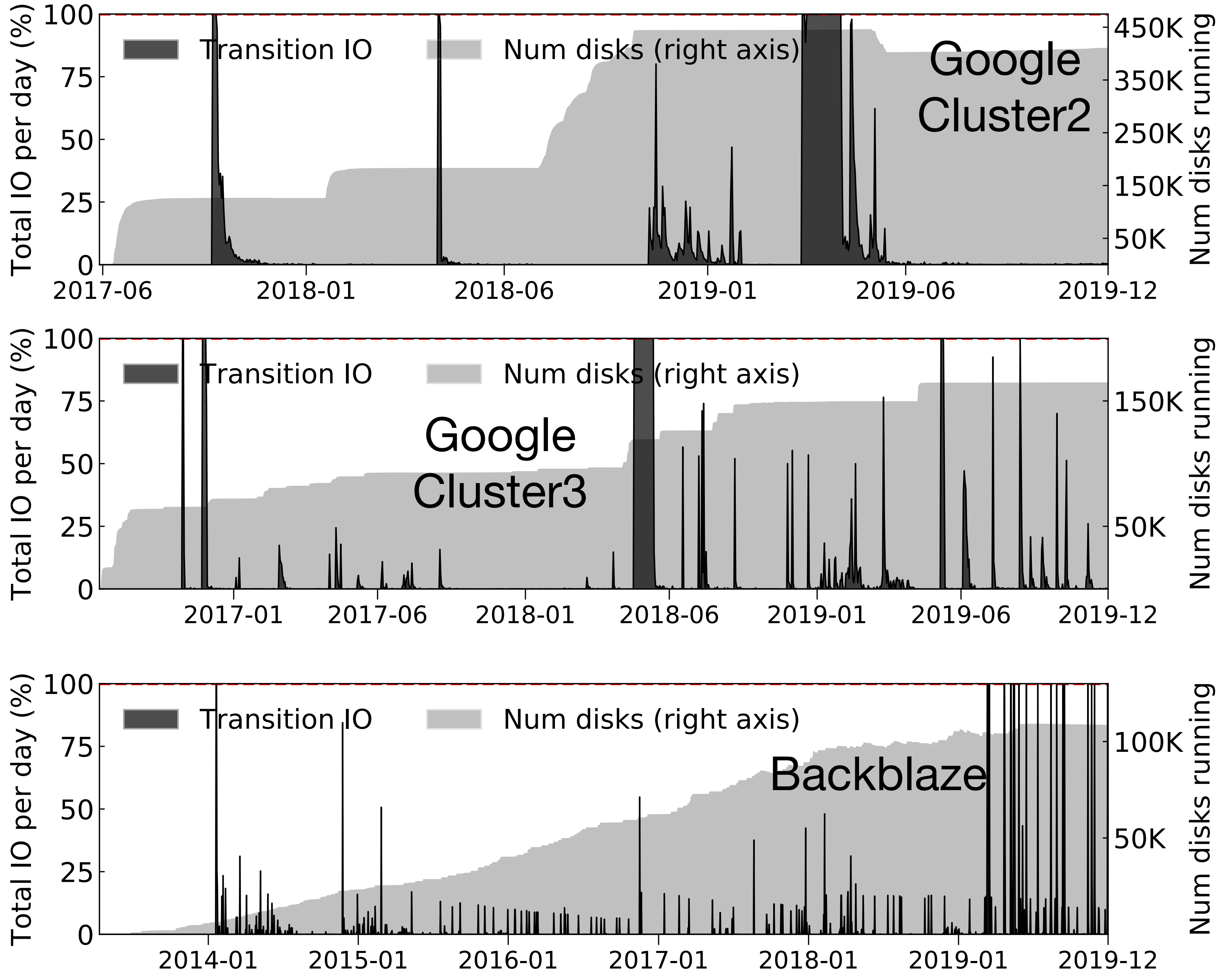

High IO cost and urgent transitions cause **transition overload**

# Transition overload is a show-stopper



- Existing disk-adaptive redundancy simulated on clusters

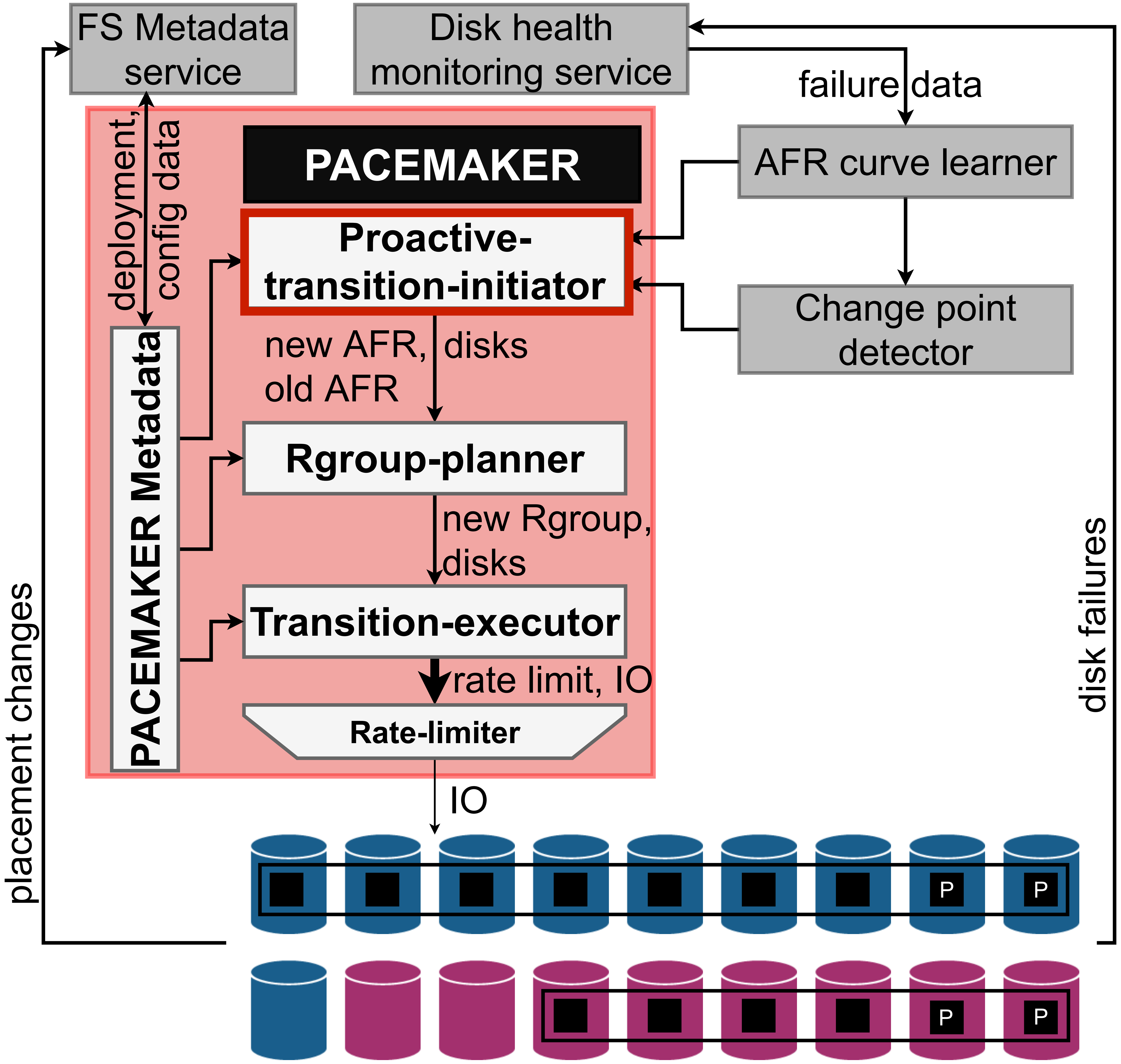



- Weeks of 100% cluster IO bandwidth spent in transitions
  - caused by costly transitions
  - in addition to too many disks transitioning together

# Pacemaker built to overcome transition overload






3 questions guide Pacemaker's approach:

1. When should disks transition?

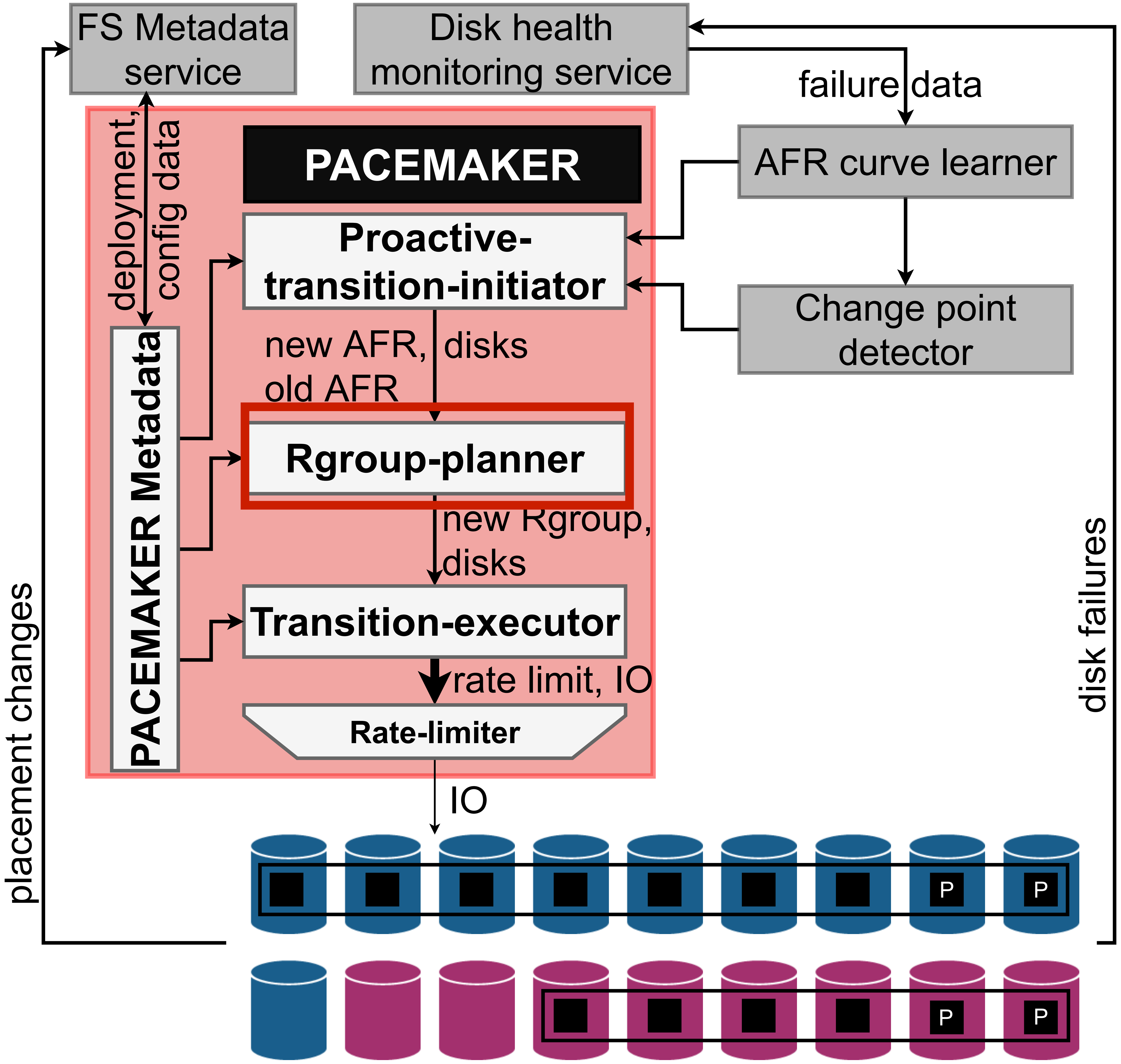
   Issue proactive transitions that can be safely rate-limited

2. Which scheme should disks transition to?

3. How should the disks transition?

# Pacemaker built to overcome transition overload



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Most space-efficient scheme with constraints on IO

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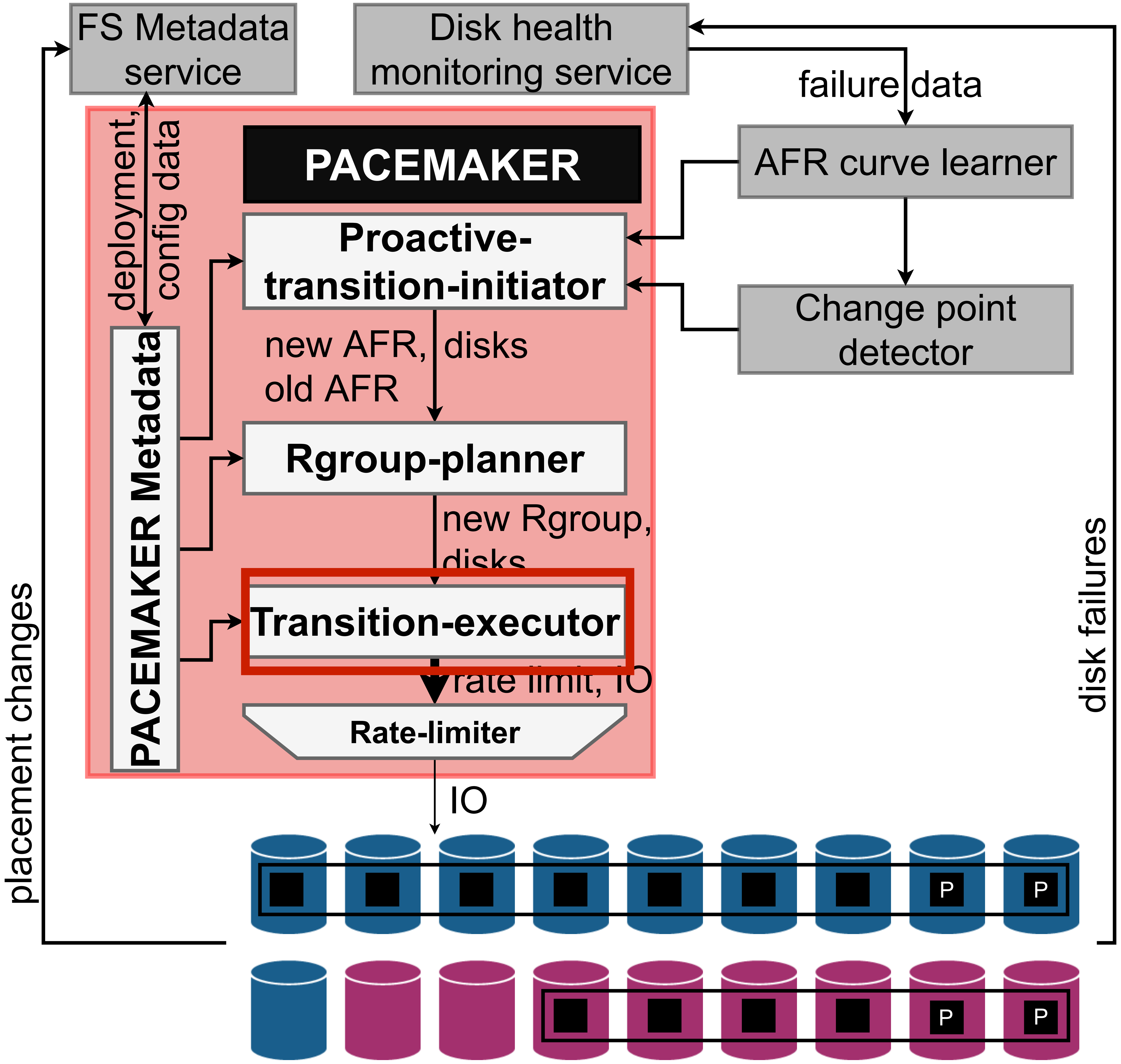


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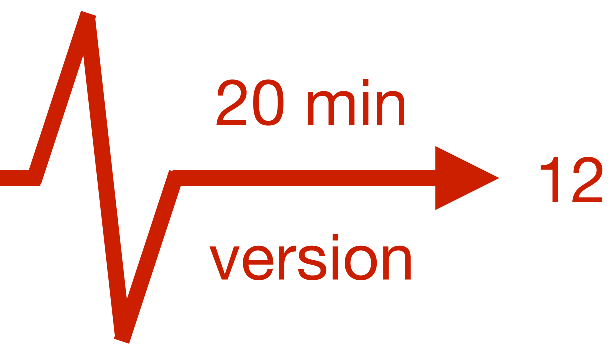
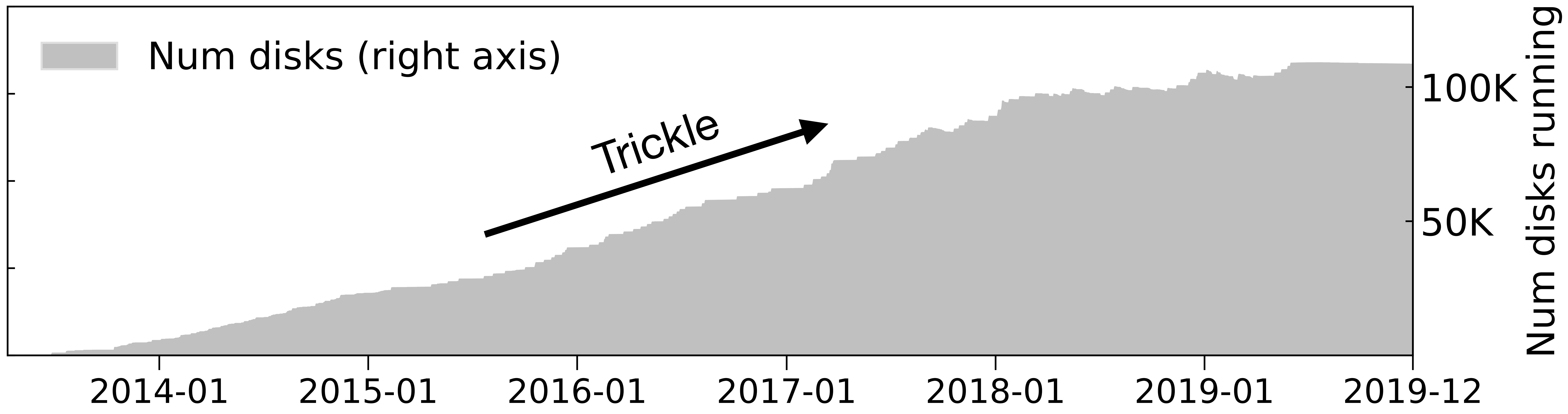
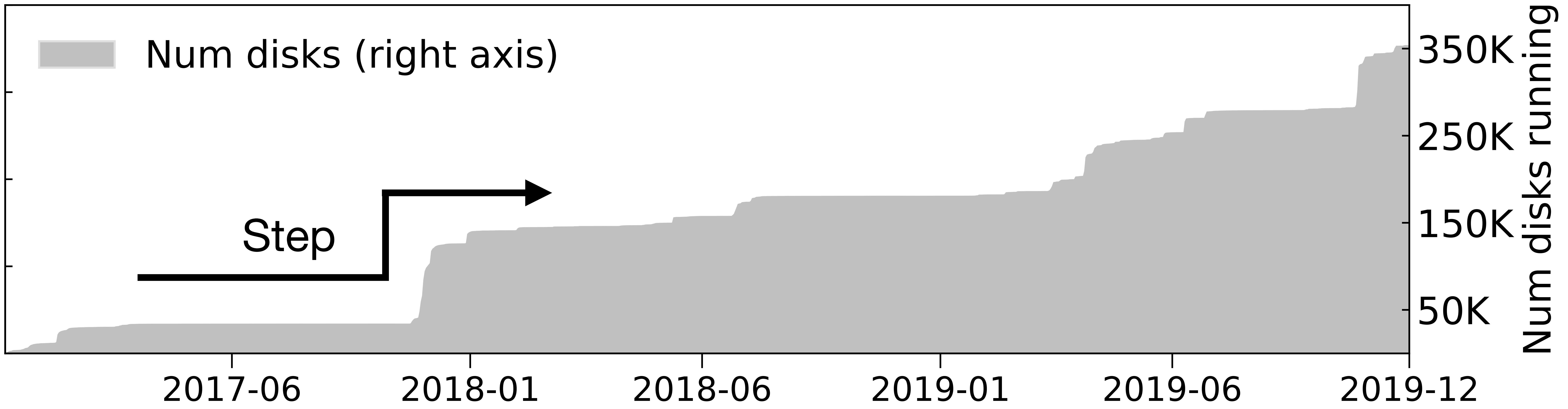
3. How should the disks transition?

New IO-efficient transitioning mechanisms

# Disk deployment patterns: **trickle** and **step**

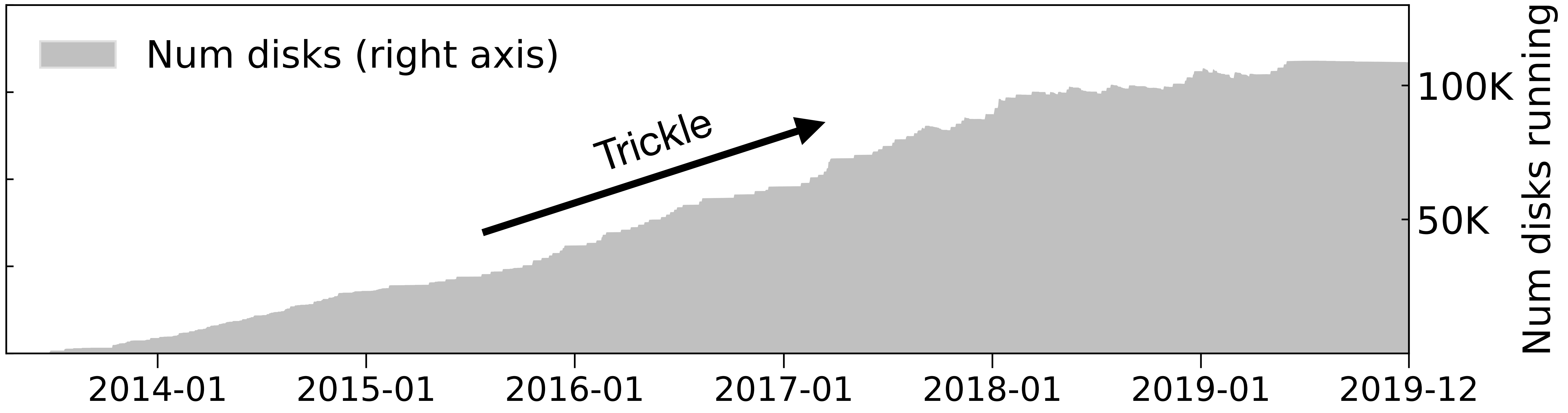


# Proactive transitions for trickle deployments






- Trickle-deployed disks are deployed in tens and hundreds every few days
- Thousands of disks are needed for statistically accurate AFR estimation
  - AFR rise for a given age can't be known until few thousand disks cross that age
- Pacemaker marks **first *C* disks are canary disks** (*C* = 3000)
  - Pacemaker learns the AFR curve from canaries
  - Redundancy not optimized for canary disks
- Remaining trickle-deployed disks can be proactively transitioned
  - AFR curve learned from canaries educates Pacemaker of age when AFR rises

# Proactive transitions for step deployments

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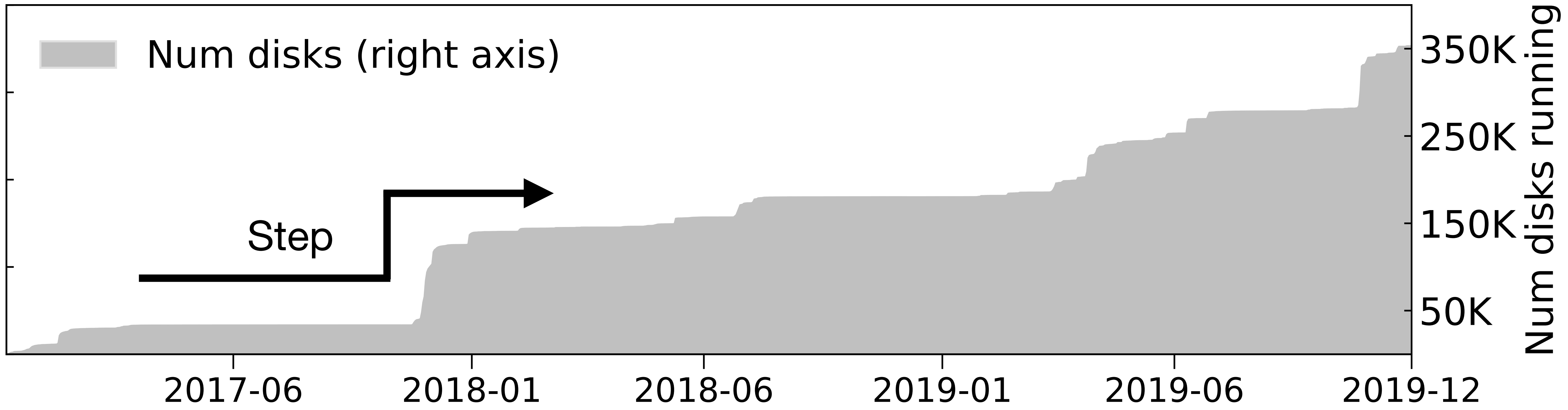
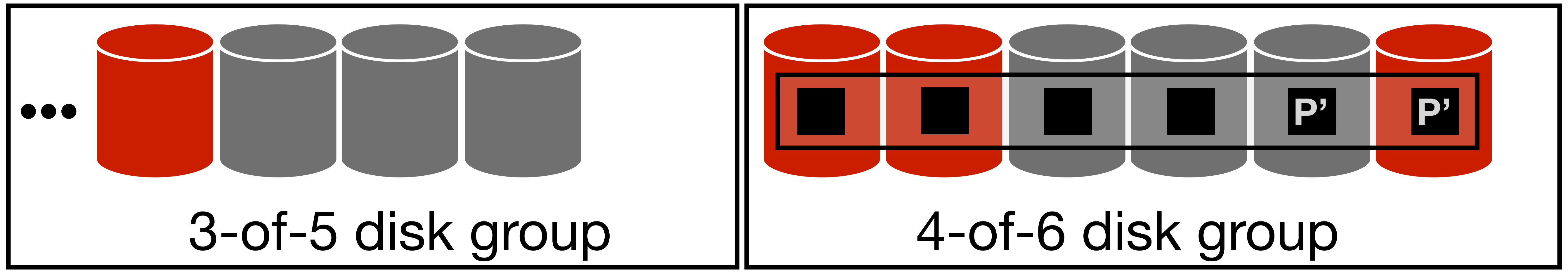



- Step-deployed disks deployed in several thousands over a few days
  - Canaries useless for step-deployed disks; almost all disks deployed together
  - Not optimizing for canaries implies not optimizing for most disks
- Step-deployed disks always provide high-confidence AFR estimate
  - Not true for trickle-deployed disks deployed a-few-at-a-time over long periods
- Pacemaker uses slowly rising AFR as an early-warning system
  - AFRs rise gradually towards wearout (refer paper)
- Early-warning triggers proactive transitions

# Traditional re-encoding (transitioning) is costly






Disk transition IO > $2 \times k_1 \times$ disk-capacity

- Need to re-encode (transition) $k_1$-of-$n_1$ to $k_2$-of-$n_2$
- Read rest of the data chunks of stripe ($k_1 \times$ disk-capacity)
- Write new stripe to new disk-group ($k_1 \times$ disk-capacity)
- Create new parities
- Delete old parities

# Transitioning by emptying disks

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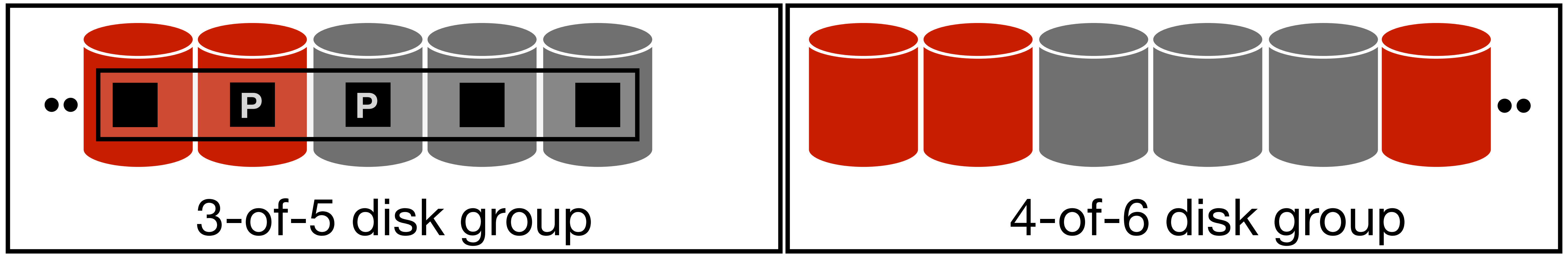
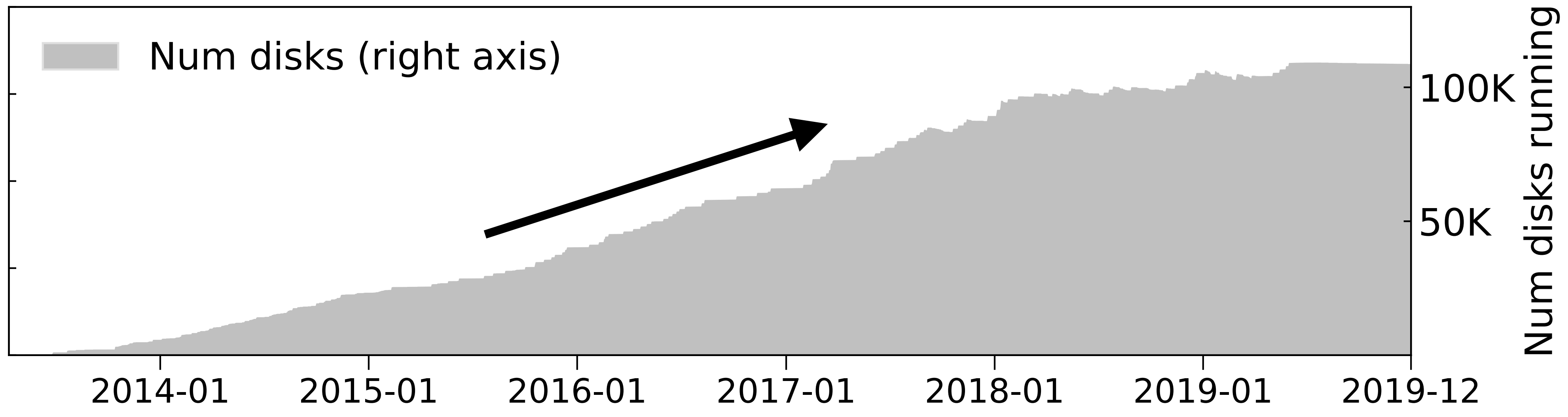


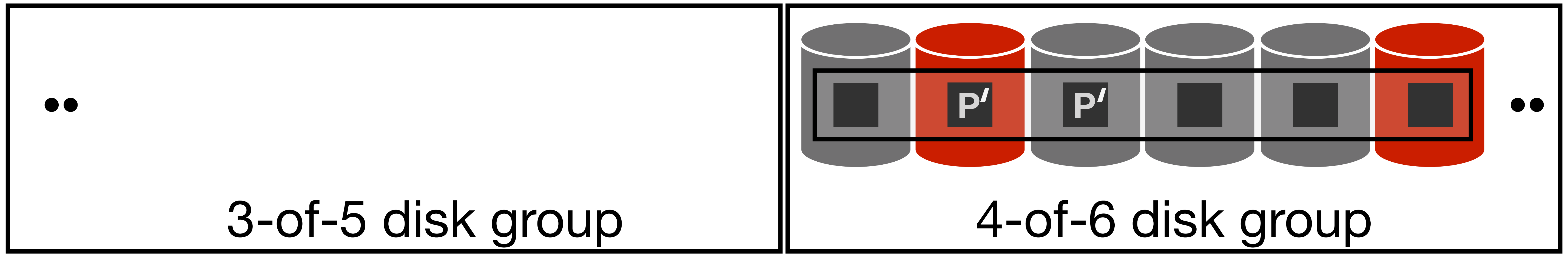



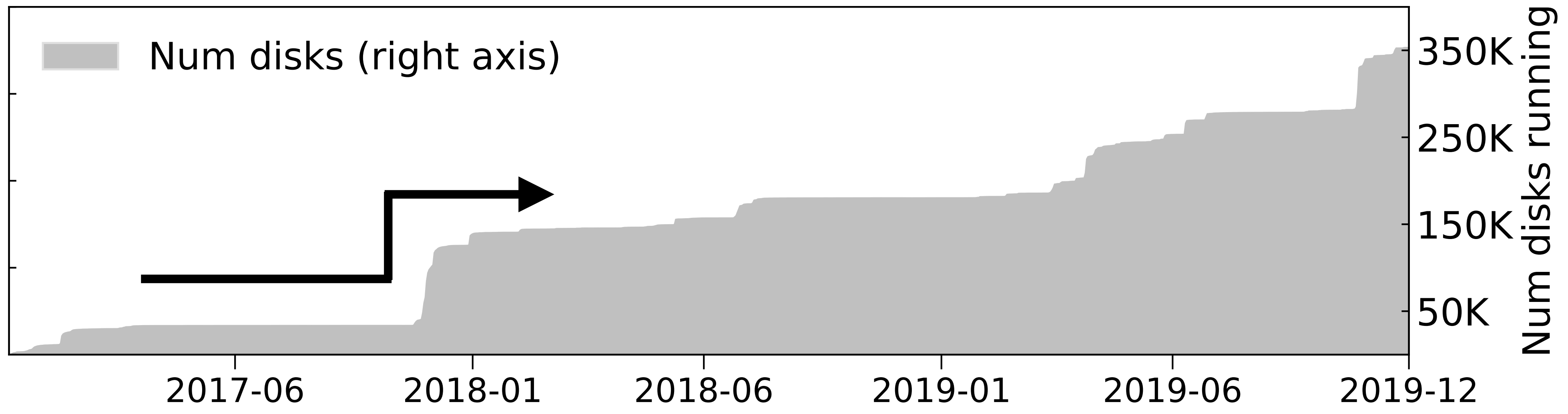

Disk transition IO = $2 \times$ disk-capacity
cheaper than traditional by $\approx k_1 \times$

- Move data in same disk-group **before transition** ($2 \times$ disk-capacity)
- Transition an empty disk
- No data on disk ⟶ no expensive re-encoding
- Apt when a few disks are transitioning at a time (trickle deployments)

# Transitioning by bulk parity re-calculation





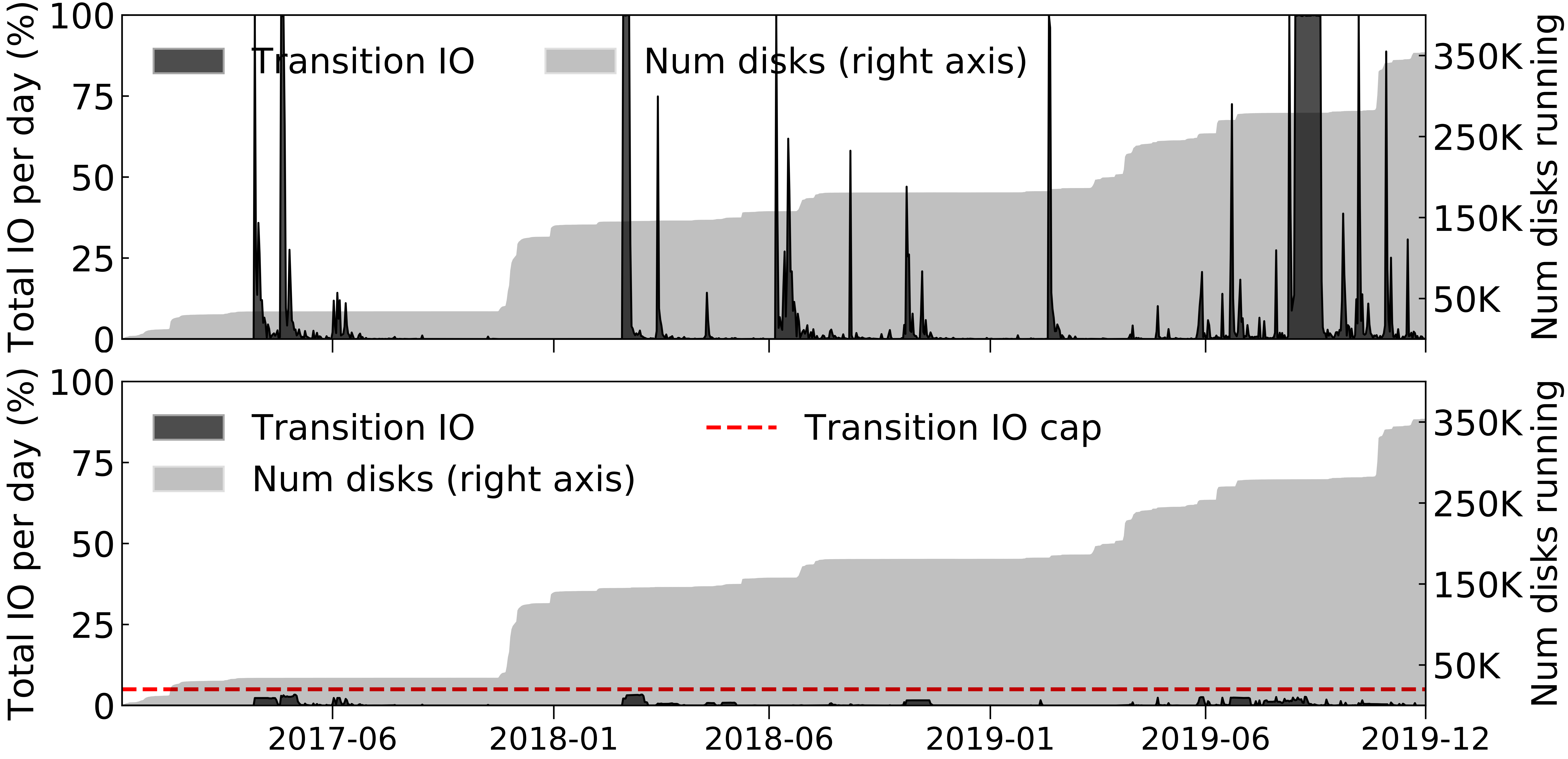

$$\text{Disk transition IO} = \left(1 + \frac{n_2 - k_2}{k_2}\right) \times \frac{k_1}{n_1} \times \text{disk-capacity}$$

cheaper by $\approx n_1 \times$

- Disks transition **without moving data**
- New parities calculated based on new scheme ($1 \times$ disk-capacity)
- New stripes formed (write only new parities)
- Apt for re-encoding large disk populations together (step deployments)

# Evaluation: Google Cluster1 (transition overload)

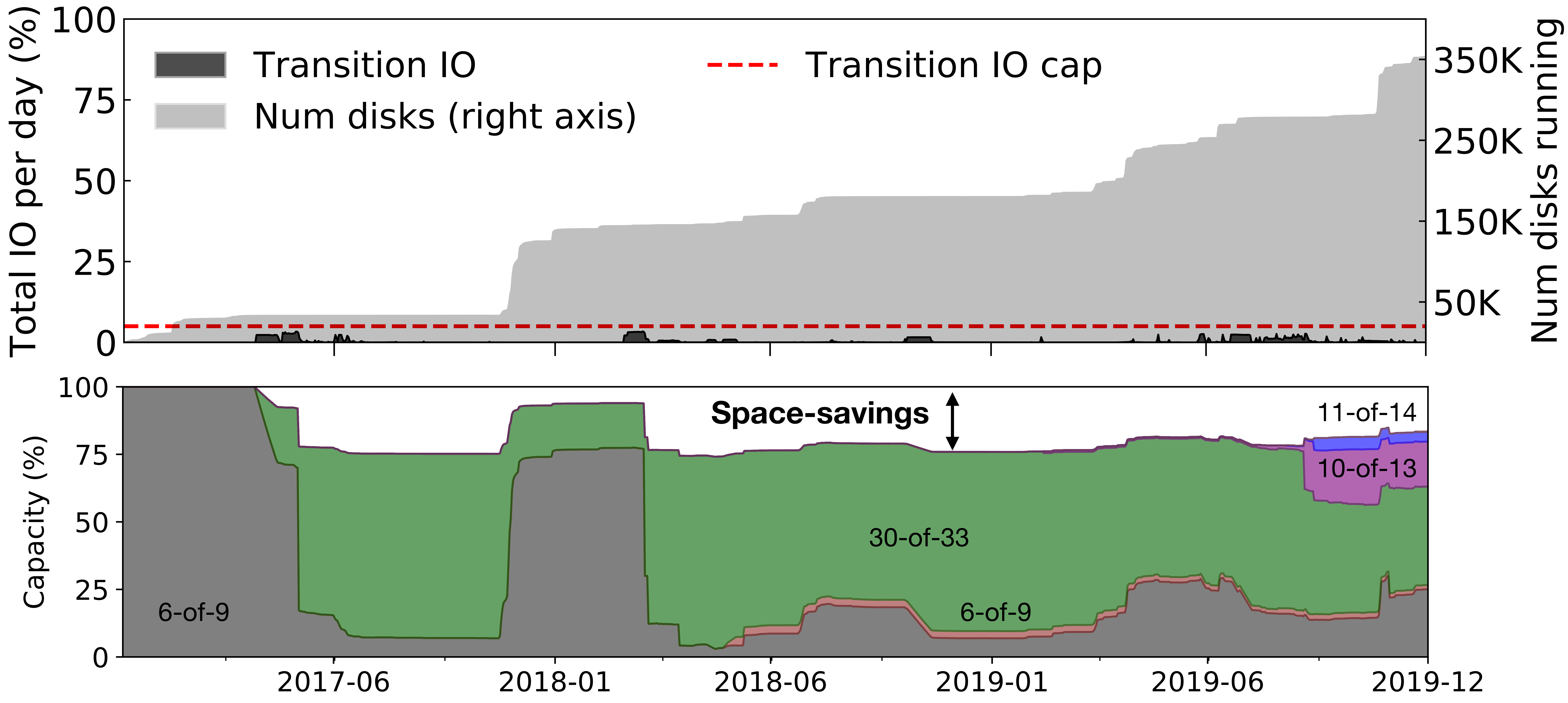





Avg. IO = 0.3%
Peak IO < 5%

# Evaluation: Google Cluster1 (space-savings)






Avg. space-savings = 14%
Peak space-savings = 25%

# Conclusion

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- Disk-adaptive redundancy systems suffer from transition overload
- Pacemaker is an IO-efficient disk-adaptive redundancy orchestrator
  - Only uses 0.2—0.4% cluster IO bandwidth on average for redundancy transitions
  - All transition IO activity is safely capped to <5% cluster IO bandwidth
  - Provides between 14—20% average space-savings; tens of thousands of fewer disks
- Pacemaker's design is informed by real-world disk failure analysis
  - 5.3 million disks spanning over 60 makes/models from Google, NetApp, Backblaze
  - Pacemaker's design is based on insights from this analysis (refer paper for details)
- Working prototype of Pacemaker-equipped HDFS (refer paper)
  - Prototype reuses existing HDFS machinery to enable disk-adaptive redundancy
  - Open sourced at: https://github.com/thesys-lab/pacemaker-hdfs
- Contact saukad@cs.cmu.edu for questions or feedback