ColumnKeeper: Efficient Solutions to the ColumnDisturb Vulnerability in DRAM-based Systems

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Executive Summary

Problem: DRAM chips are **vulnerable** to **ColumnDisturb**, a new, **column-based** read disturbance phenomenon.
Naively mitigating ColumnDisturb incurs **significant overheads**.
Goal: Design mechanisms that **mitigate ColumnDisturb bitflips** with **low performance, energy** and **area** overheads
Key Idea: Track row activations **at subarray granularity.**
Iteratively **refresh all rows.**
ColumnKeeper-D (Deterministic): Uses **separate** activation counters for **odd** and **even bitlines** of each subarray and issues a preventive refresh when **either** counter reaches a **predetermined threshold**
ColumnKeeper-P (Probabilistic): **Probabilistically** issues refreshes to one row in **three consecutive subarrays** upon a row activation in the middle subarray
Evaluation

- ColumnKeeper **mitigates ColumnDisturb** bitflips with **low overheads** at **current (1M)** and "**near-future**" **(128K)** thresholds
- ColumnKeeper **can mitigate** ColumnDisturb bitflips with **low overheads** even **at low thresholds (16K)** with **changes to DRAM microarchitecture**

Outline

Background

Motivation

ColumnKeeper-D (Deterministic)

ColumnKeeper-P (Probabilistic)

Evaluation

Conclusion

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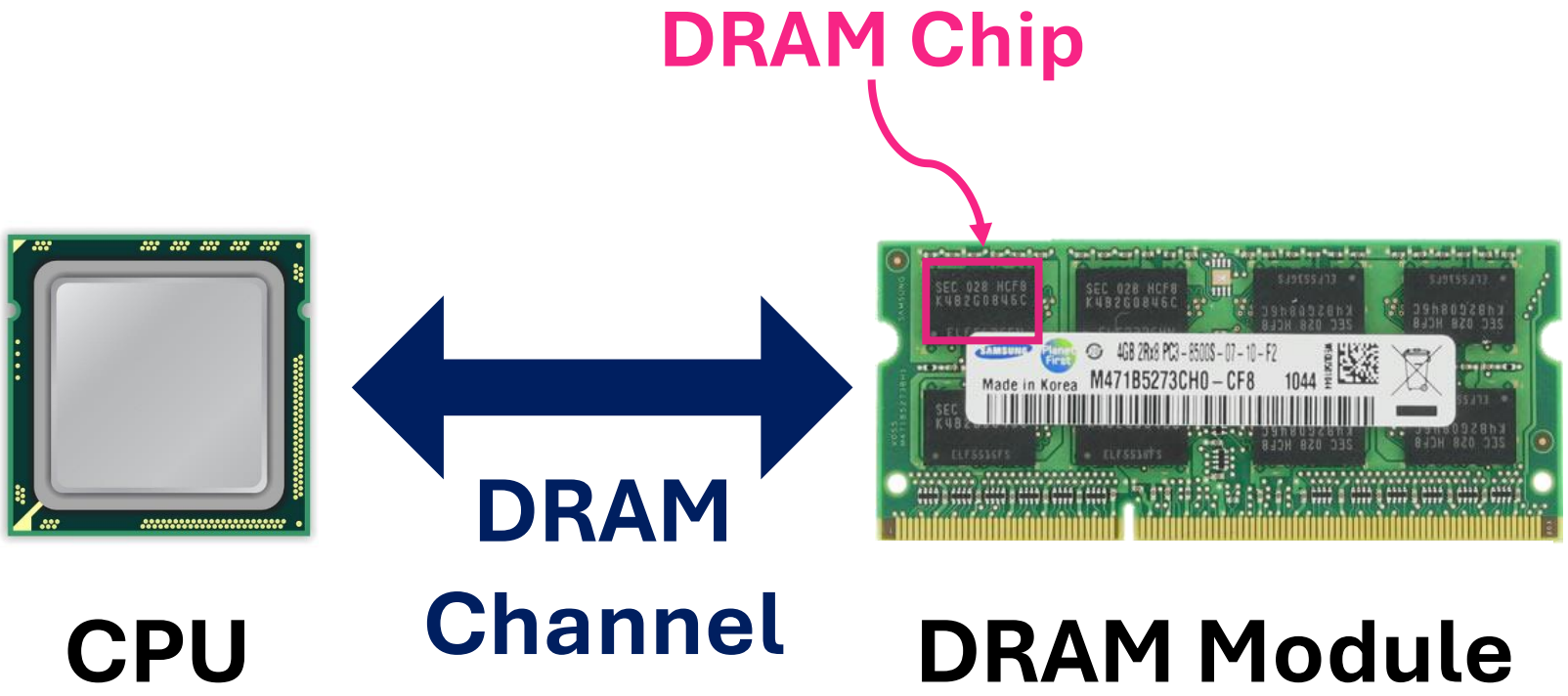
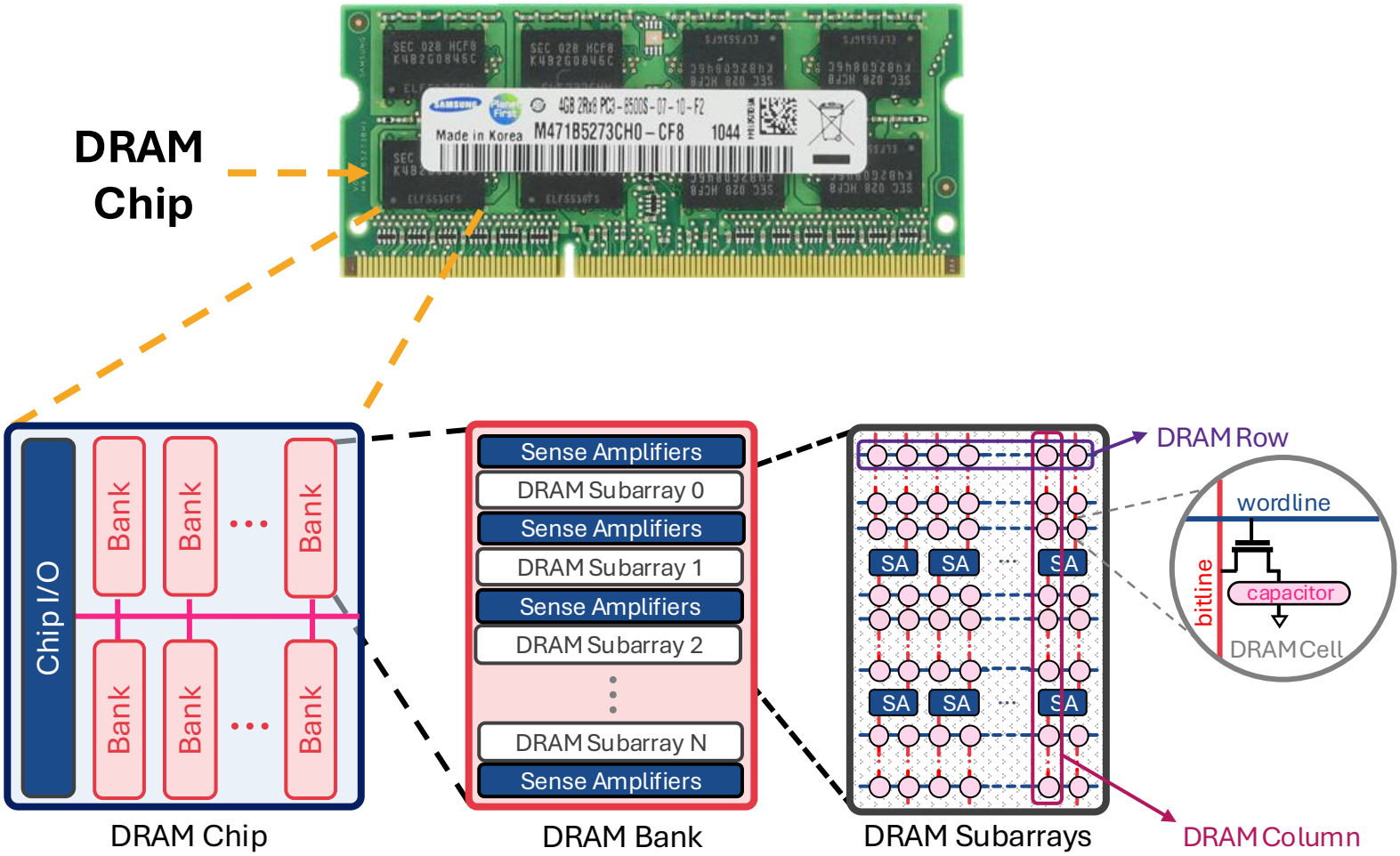
DRAM Organization



DRAM Organization



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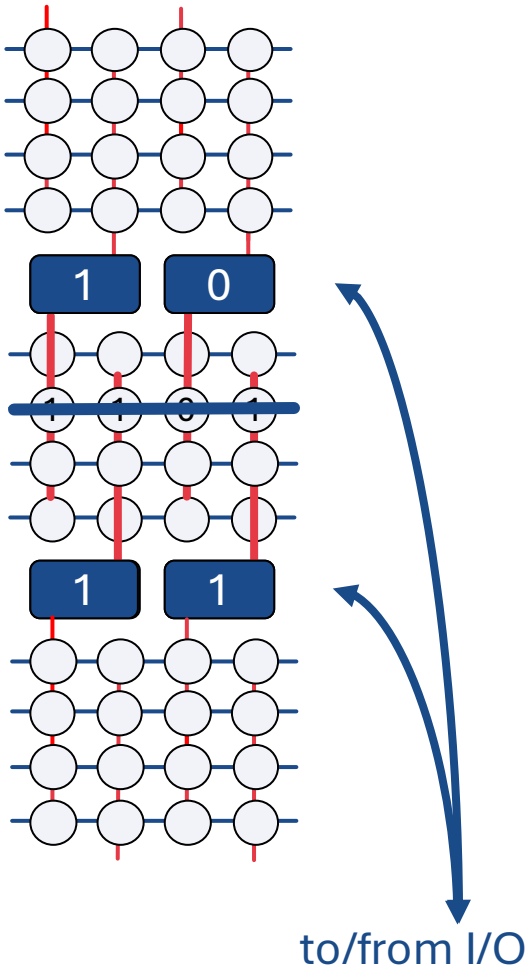


1 **ACTIVATE**: Fetch the row into the **sense amplifiers**

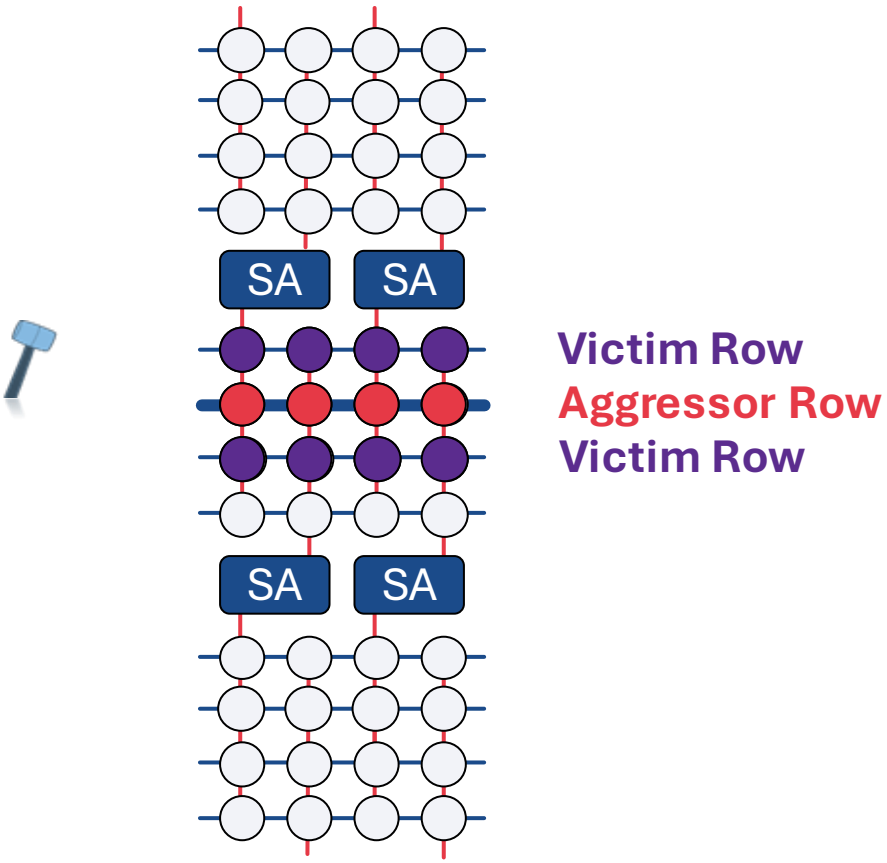
2 **READ/WRITE:** Retrieve or update data

3 **PRECHARGE**: Prepare the bank for a new ACTIVATE

DRAM Read Disturbance: RowHammer

Read disturbance in DRAM **breaks memory isolation**

Prominent example: **RowHammer**



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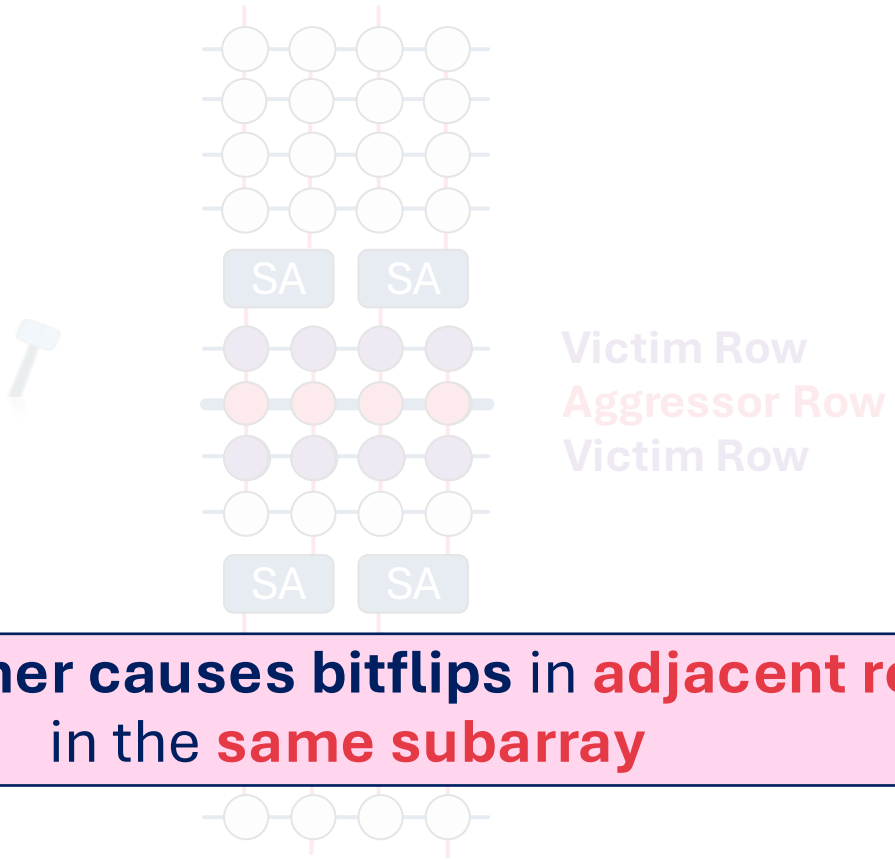
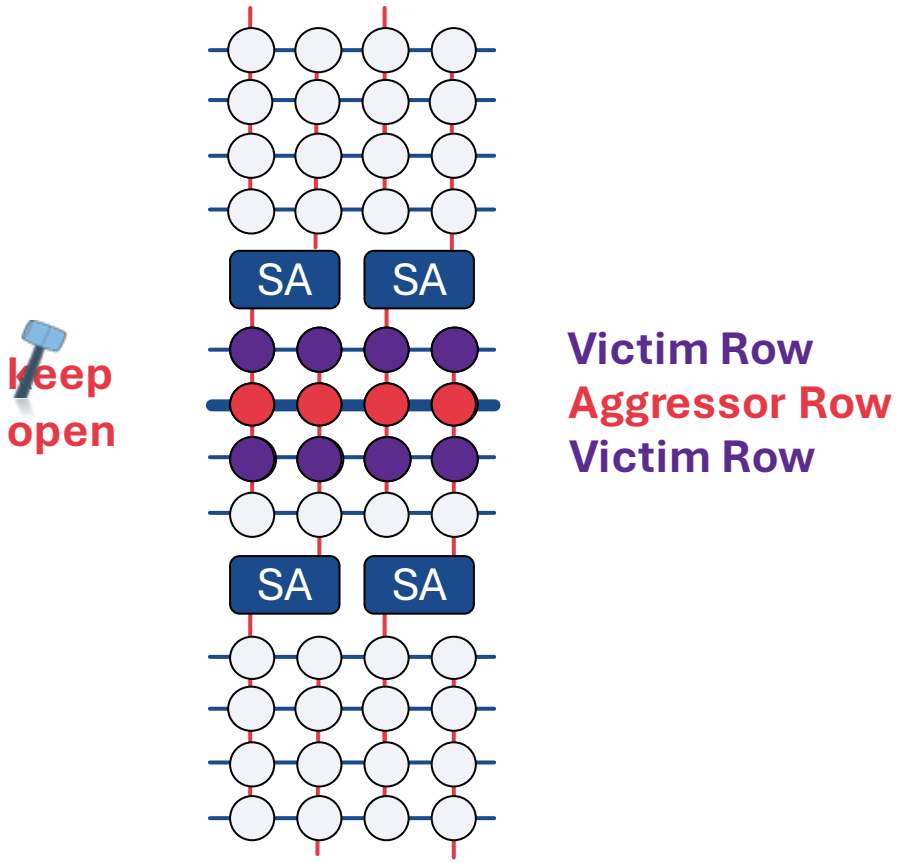


RowHammer causes bitflips in **adjacent rows** in the **same subarray**

DRAM Read Disturbance: RowPress

Read disturbance in DRAM **breaks memory isolation**

Another prominent example: **RowPress**



DRAM Read Disturbance: RowPress

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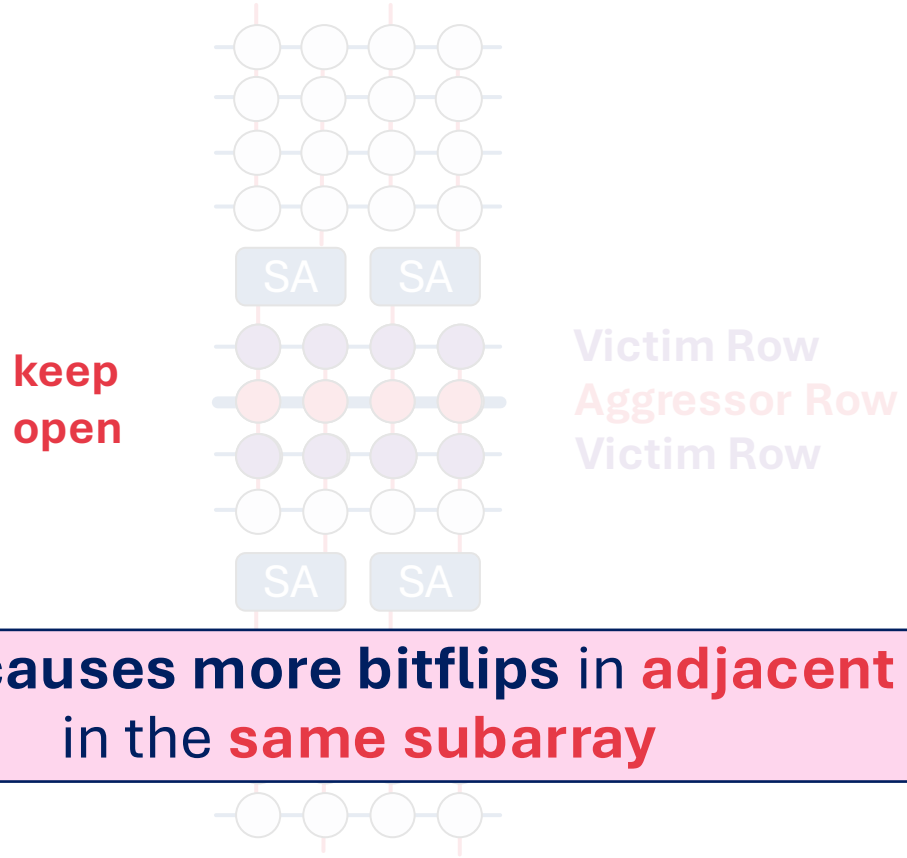
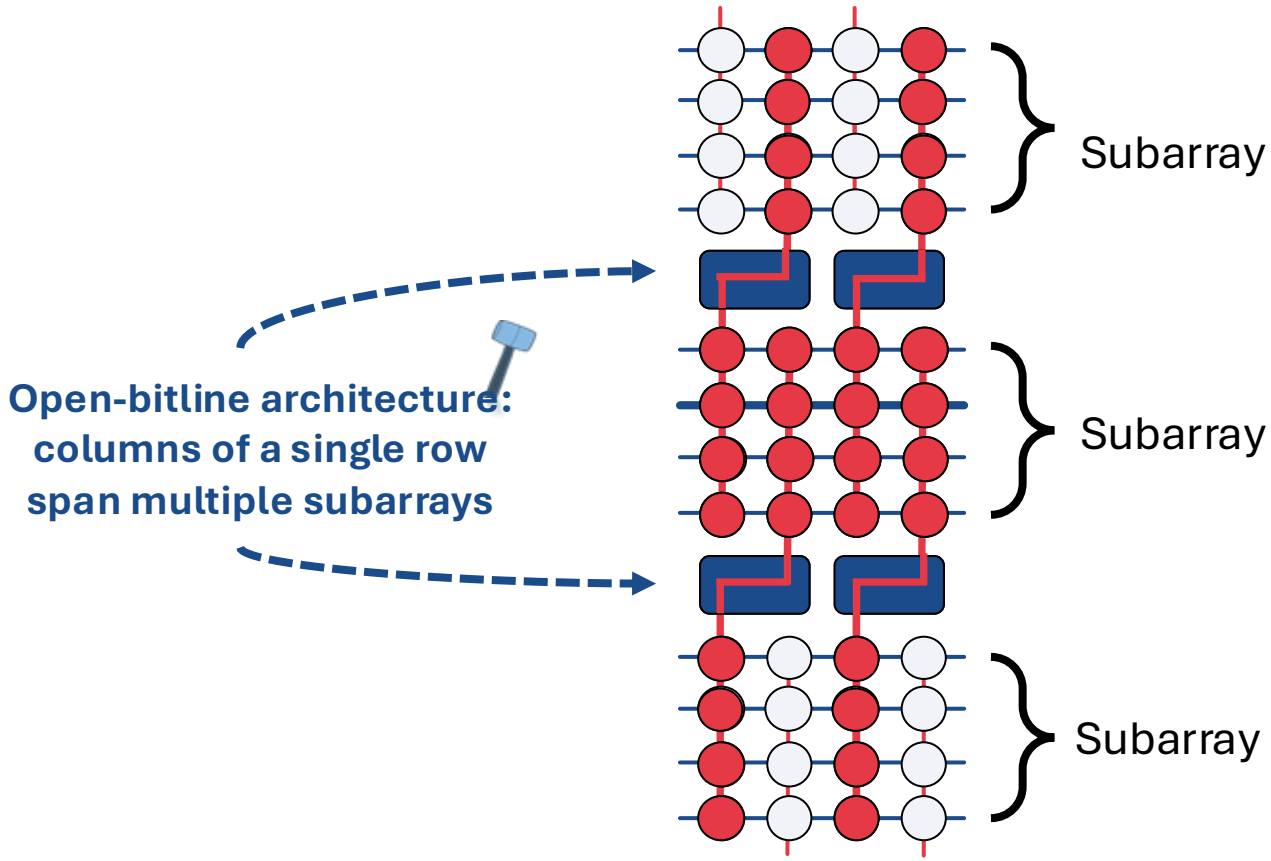


RowPress causes more bitflips in **adjacent rows** in the **same subarray**

DRAM Read Disturbance: ColumnDisturb

ColumnDisturb: Repeatedly **hammering** or **pressing** a DRAM row **disturbs many** DRAM cells **on the same DRAM column**



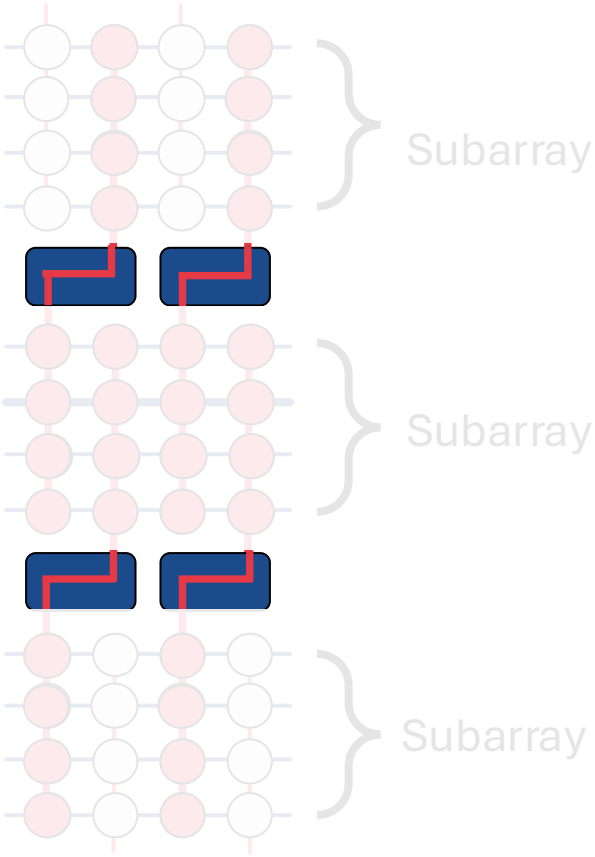
DRAM Read Disturbance: ColumnDisturb

ColumnDisturb: Repeatedly **hammering** or **pressing** a DRAM row **disturbs many** DRAM cells **on the same DRAM column**

Cells on **odd columns**

All cells

Cells on **even columns**



DRAM Read Disturbance: ColumnDisturb

ColumnDisturb: Repeatedly **hammering** or **pressing** a DRAM row **disturbs many** DRAM cells **on the same DRAM column**

ColumnDisturb affects DRAM cells across **three consecutive** DRAM **subarrays** (up to **3072** DRAM rows)

ColumnDisturb induces bitflips within **the DDR4 refresh window**

The **number of activations** required to **induce ColumnDisturb bitflips (N_{CD})** is currently ≈ **1M**

Scaling studies show **ColumnDisturb** is **getting worse** **in newer chips**

Outline

Background

Motivation

ColumnKeeper-D (Deterministic)

ColumnKeeper-P (Probabilistic)

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Mitigating ColumnDisturb (I)

The **easiest way** of mitigating ColumnDisturb is to **reduce** the DRAM refresh window so that **all rows** are refreshed **before bitflips** can **occur**

Significant performance overheads at **near-future** ColumnDisturb **thresholds:**
More than 50% for workloads with **high memory intensity**

Significant DRAM energy overheads at **near-future** ColumnDisturb **thresholds:**
More than 6x increase in **energy consumption**

Mitigating ColumnDisturb by **increasing** the **DRAM refresh rate** incurs **prohibitive overheads**

Mitigating ColumnDisturb (II)

Alternative method: Modifying **RowHammer mitigation mechanisms** to protect against ColumnDisturb

RowHammer mitigations such as **Per-Row Activation Counting** (**PRAC**):

- Track activations **at the row granularity**
- Only refresh **a few neighboring victim rows**

Using PRAC to mitigate ColumnDisturb **requires**:

- **Aggressively configuring PRAC** to fire at a low threshold
- **Refreshing** all **3072 rows** across three subarrays

Modified PRAC incurs **prohibitive overheads**

Our Goal

Design mechanisms

that **prevent ColumnDisturb bitflips**

at low performance, energy, and **area overheads**

Our Overarching Key Idea

Track activations at **subarray granularity**

Iteratively refresh **all rows** within each subarray

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Key Observation

Activations in **one subarray** affect **all columns** in that subarray but either **odd** or **even** columns **in neighboring subarrays**

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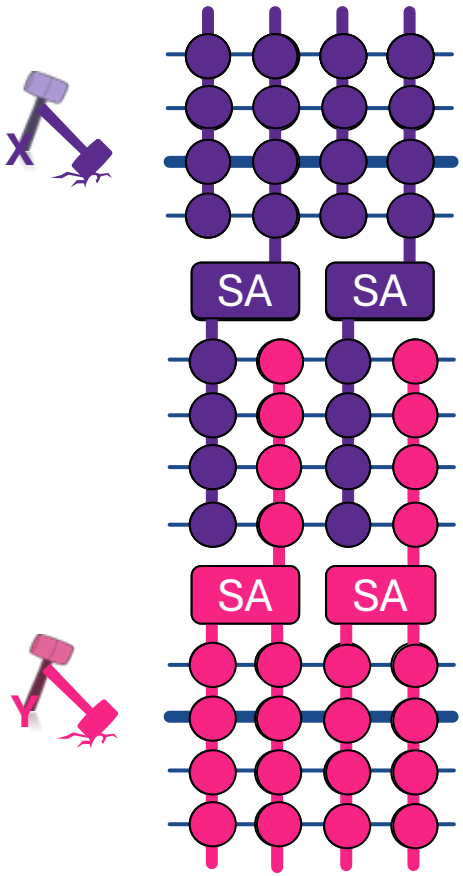


Subarray A

$N_{odd} = X$
$N_{even} = X$

Total ACTs = X
Actual ACTs = X

Subarray B

$N_{odd} = Y$
$N_{even} = X$

Total ACTs = X+Y
Actual ACTs = max{X,Y}

Subarray C

$N_{odd} = Y$
$N_{even} = Y$

Total ACTs = Y
Actual ACTs = Y

Key Observation

Activations in **one subarray** affect **all columns** in that subarray but either **odd** or **even** columns **in neighboring subarrays**

$N_{odd} = X$
$N_{even} = X$

Total ACTs = X
Actual ACTs = X

Naively counting the activations affecting a subarray **overestimates the activation count** of cells and **increases overheads**

$N_{odd} = Y$

Total ACTs = X+Y

In the **worst case** when **X = Y**

Total ACTs = 2 × Actual ACTs

$N_{odd} = Y$
$N_{even} = Y$

Total ACTs = Y
Actual ACTs = Y

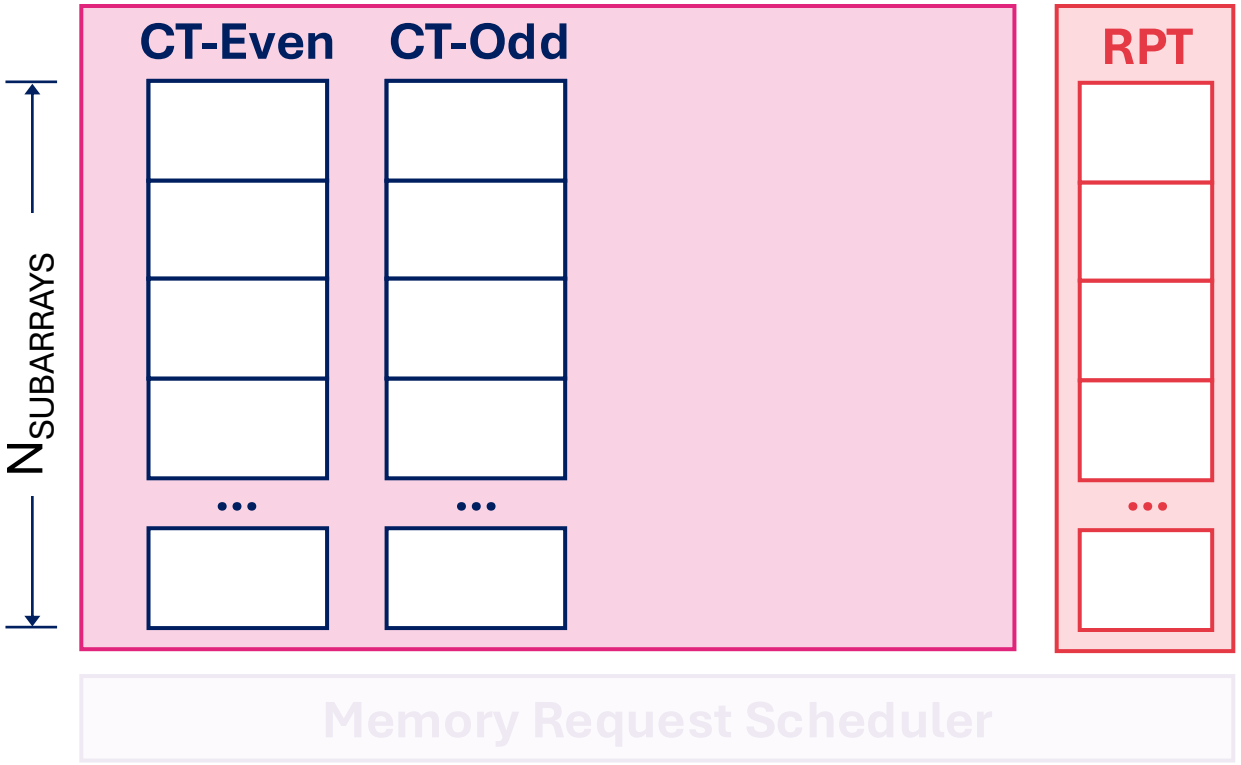
ColumnKeeper-D Key Idea

Separately count activations in **odd** and **even** columns of each subarray to **mitigate ColumnDisturb** at **low performance** and **energy overheads**

ColumnKeeper-D Overview

ColumnKeeper-D consists of:

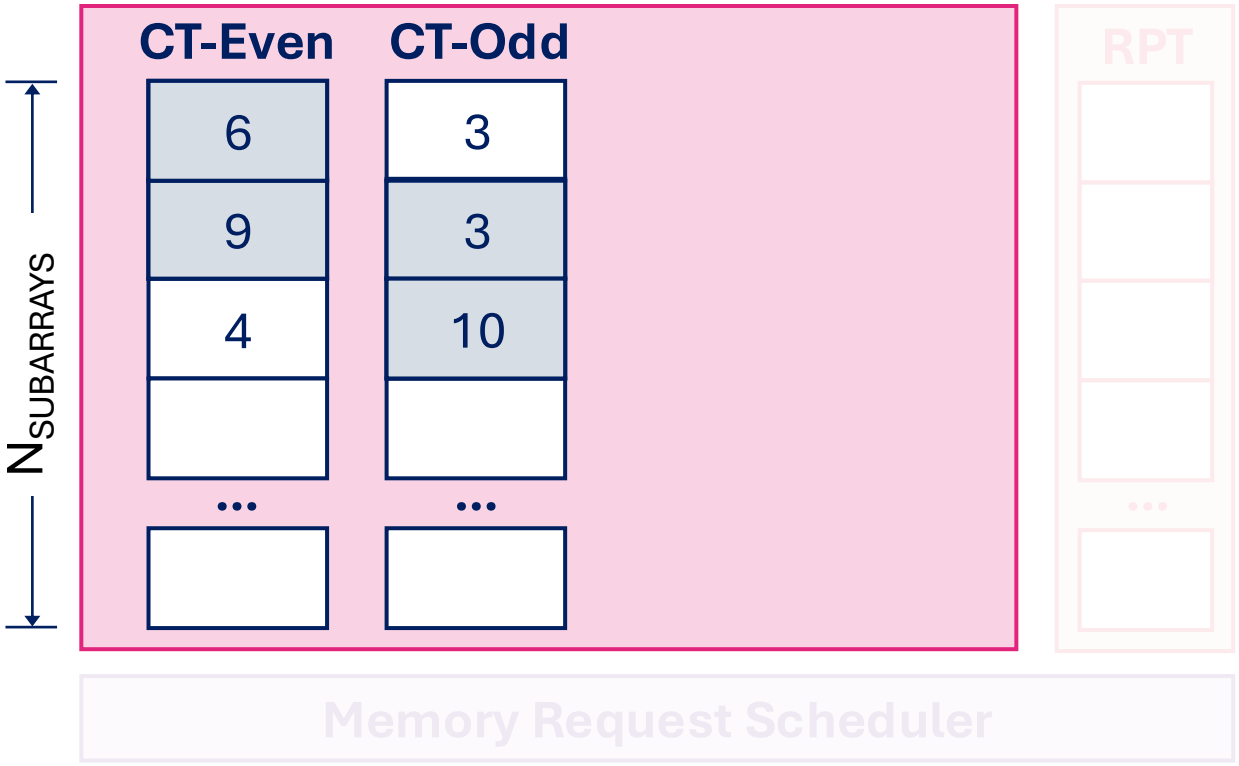
- **Counter Table – Even (CT-Even):** Counts activations in even columns
- **Counter Table – Odd (CT-Odd):** Counts activations in odd columns
- **Row Pointer Table (RPT):** Points to the next row to be preventively refreshed in each subarray



ColumnKeeper-D Overview

Upon a row activation in subarray k, ColumnKeeper-D:

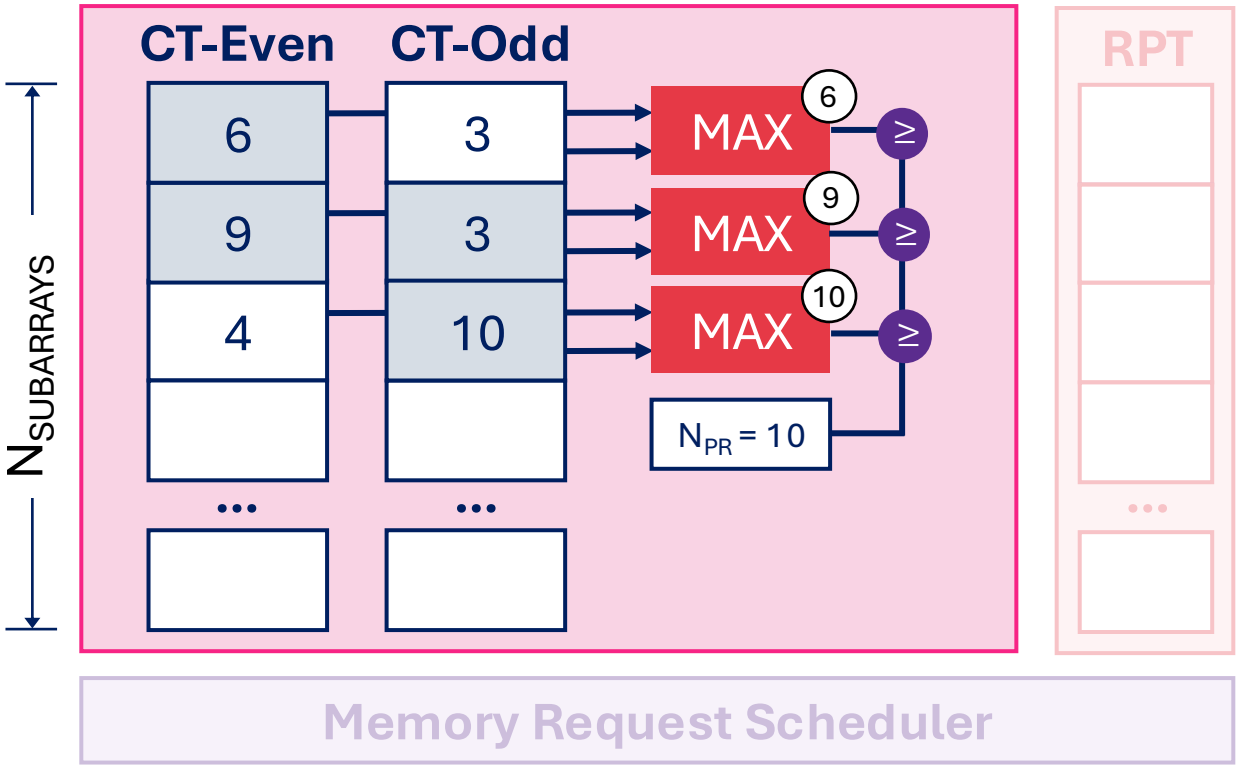
- Increments **both** the **CT-Even and CT-Odd** entries for subarray k
- Increments the **CT-Even entry** for the **previous** subarray
- Increments the **CT-Odd entry** for the **next** subarray



ColumnKeeper-D Overview

Upon a row activation in subarray k, ColumnKeeper-D:

- Calculates the **maximum value** of the two counters for the three subarrays
- **Compares** the calculated value to a **predetermined threshold (N_{PR})**



ColumnKeeper-D Overview

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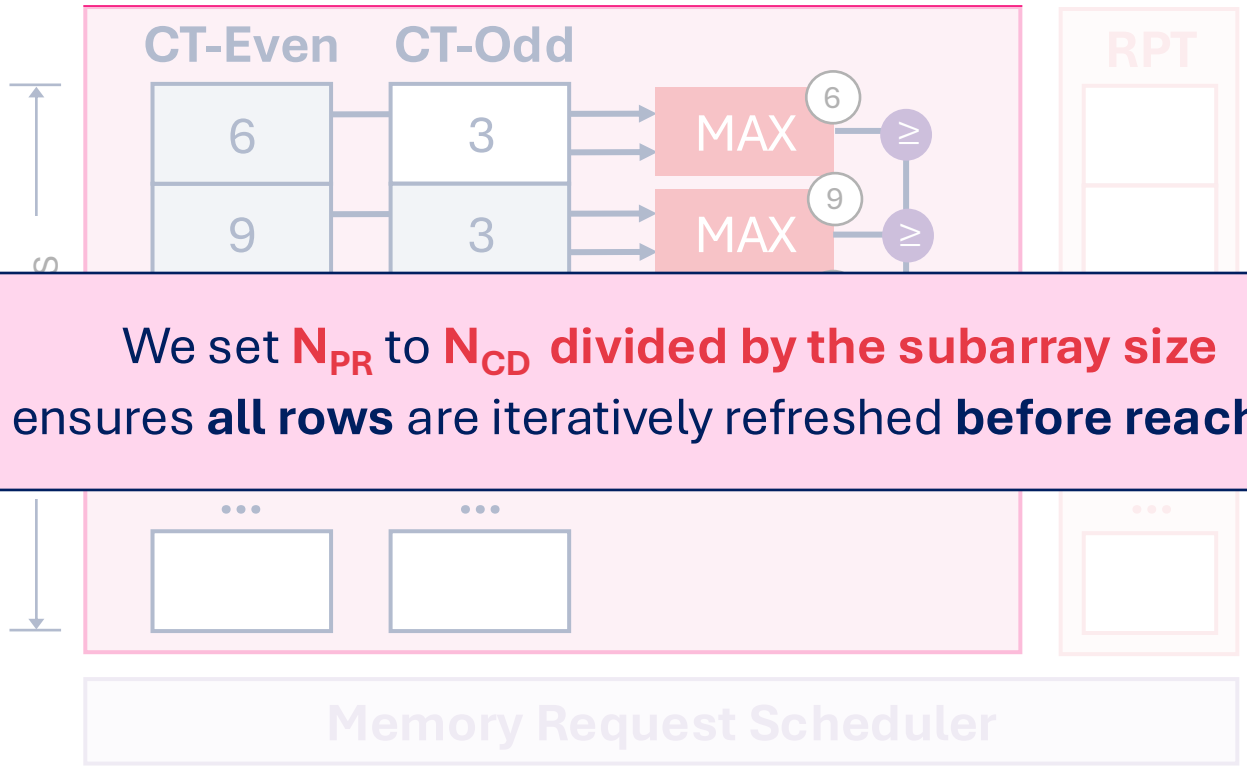


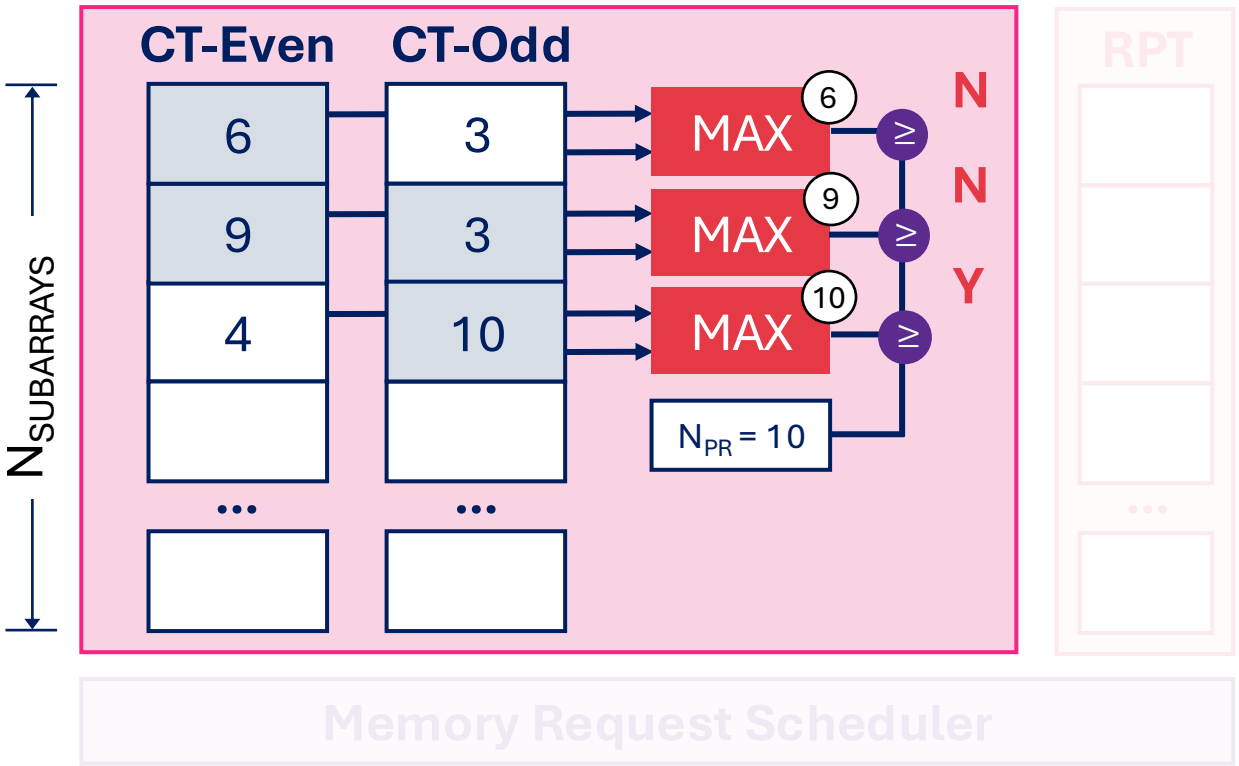
We set N_{PR} to N_{CD} **divided by the subarray size**

This ensures **all rows** are iteratively refreshed **before reaching N_{CD}**

ColumnKeeper-D Overview

Row activation in subarray k:

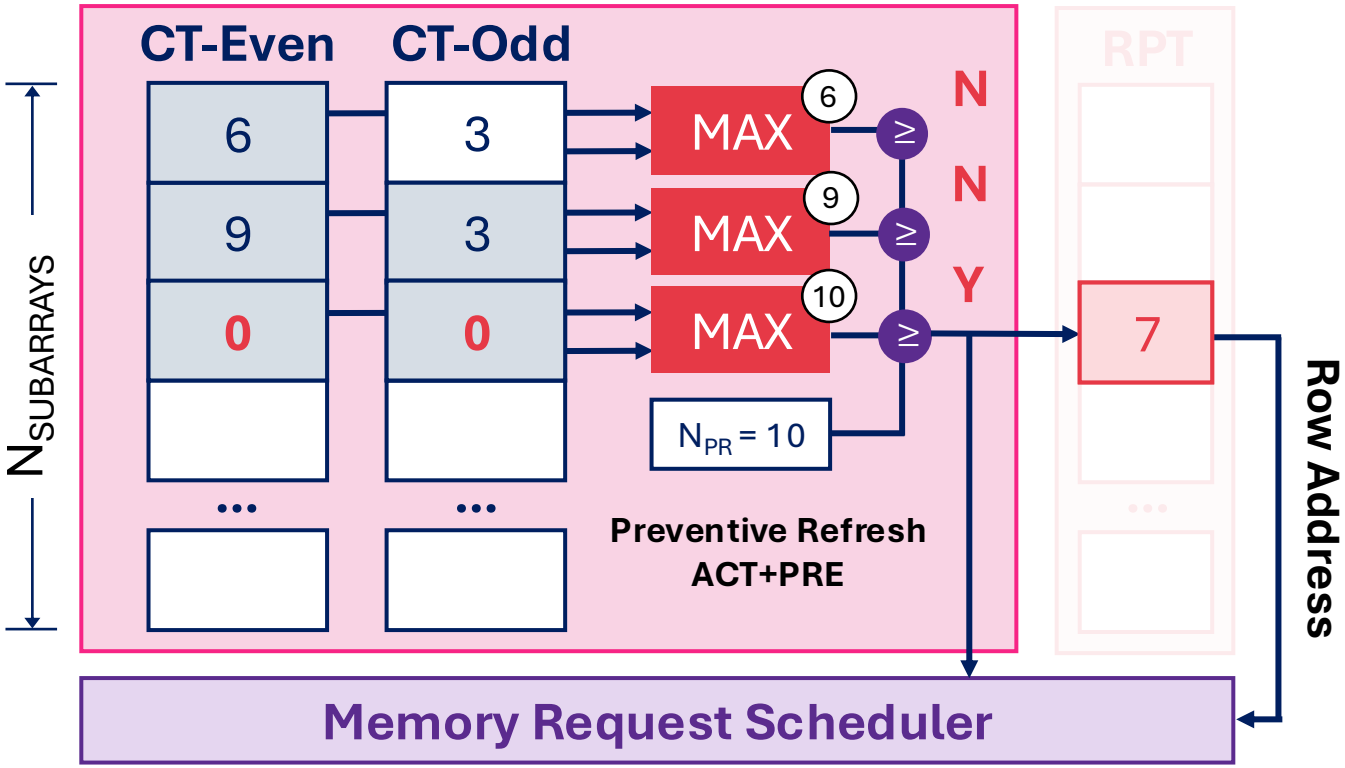
- Calculates the **maximum value** of the two counters for the three subarrays
- **Compares** the calculated value to a **predetermined threshold (N_{PR})**
- If the **maximum** counter value for a subarray **exceeds N_{PR}** ColumnKeeper-D decides to **issue a preventive refresh** for **that subarray**



ColumnKeeper-D Overview

ColumnKeeper-D:

- **Issues** an **ACT** command followed by a **PRE** command to the **Row Address** pointed by the corresponding **RPT entry**
- **Increments** the **RPT entry** to point to the **next row** in that subarray
- **Zeroes** the **CT-Even** and **CT-Odd** entries for that subarray



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ColumnKeeper-D (Deterministic)

ColumnKeeper-P (Probabilistic)

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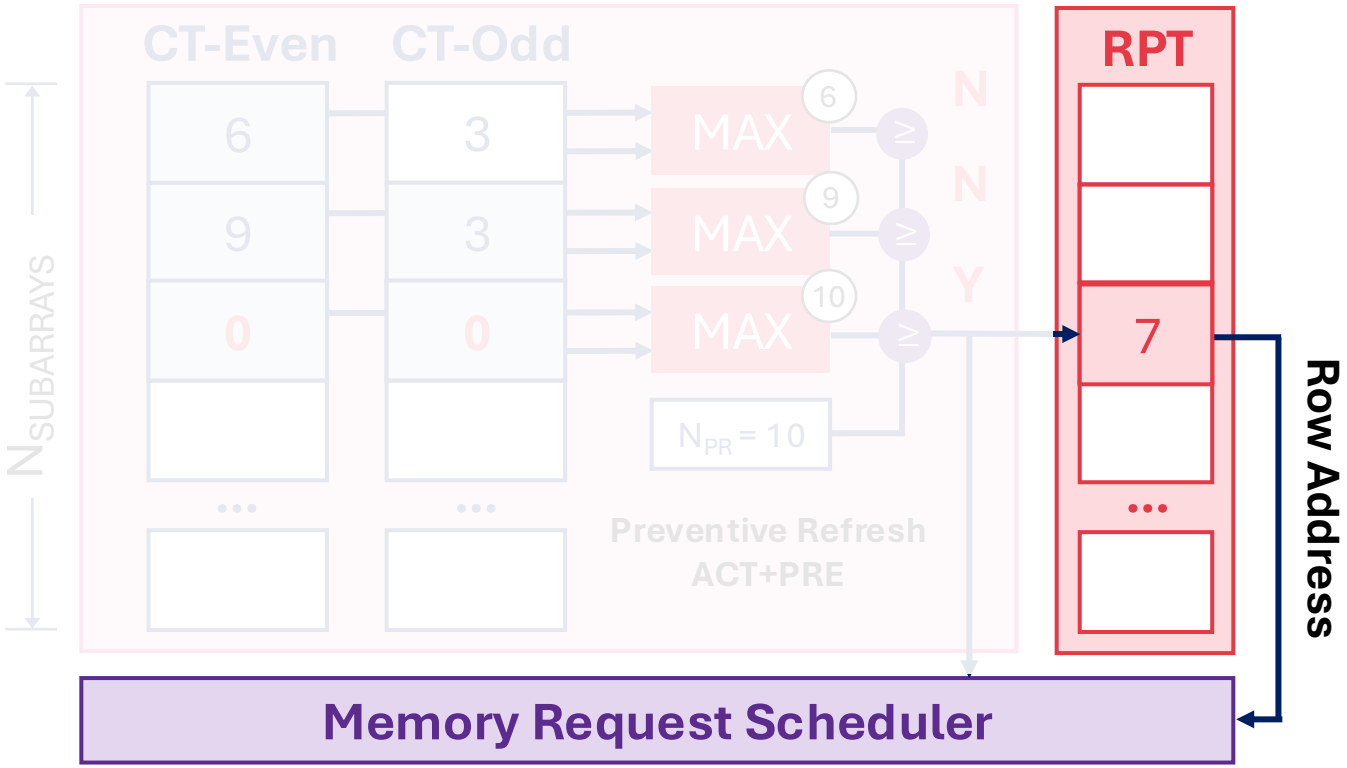
ColumnKeeper-P Key Idea

Probabilistically issue **preventive refreshes** to
avoid activation counting and
mitigate ColumnDisturb at **lower area overhead**

ColumnKeeper-P Overview

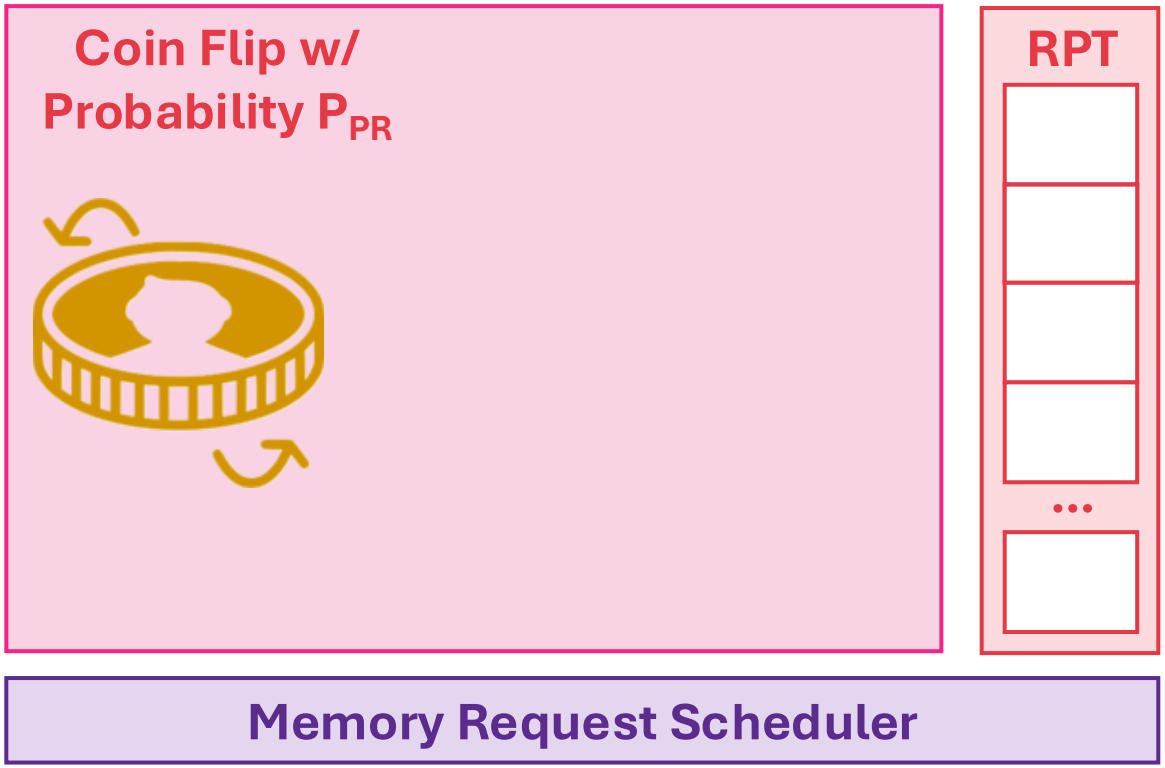
ColumnKeeper-P substitutes ColumnKeeper-D's **deterministic activation counting mechanism** with a **probabilistic one**



ColumnKeeper-P Overview

Upon a row activation in one subarray:

- **ColumnKeeper-P** flips a coin that lands heads up with a **predetermined probability (P_{PR})**



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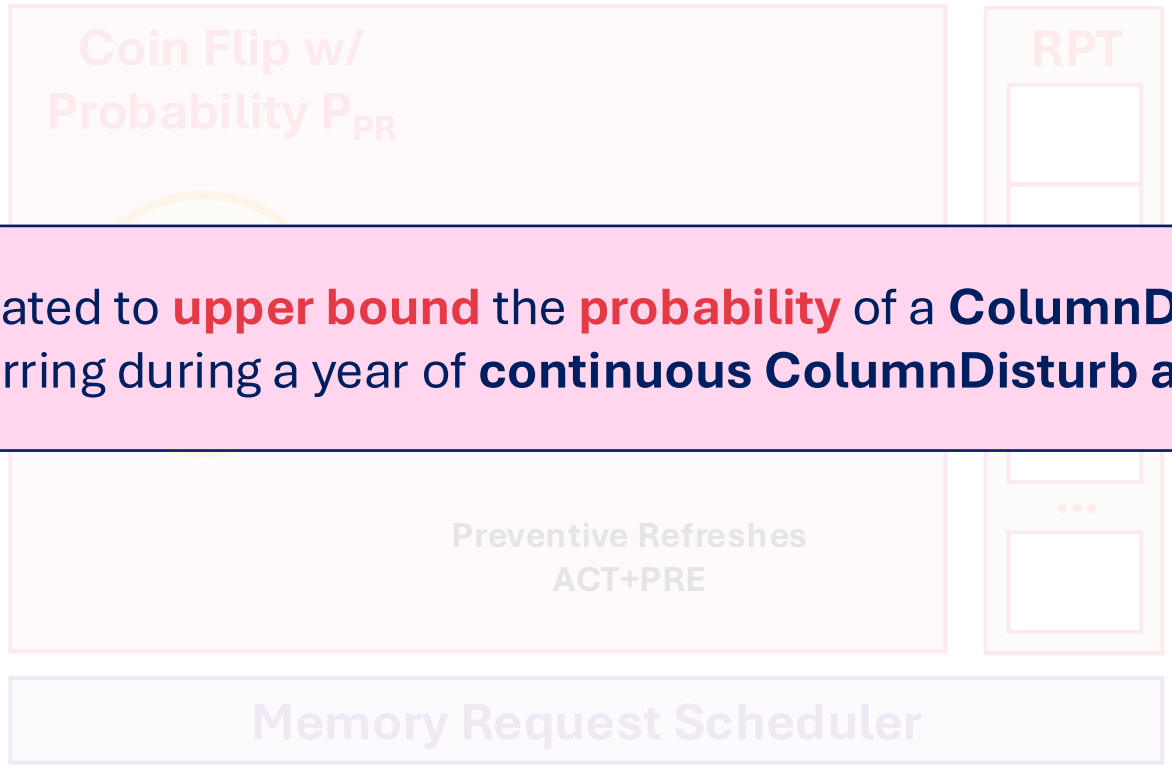
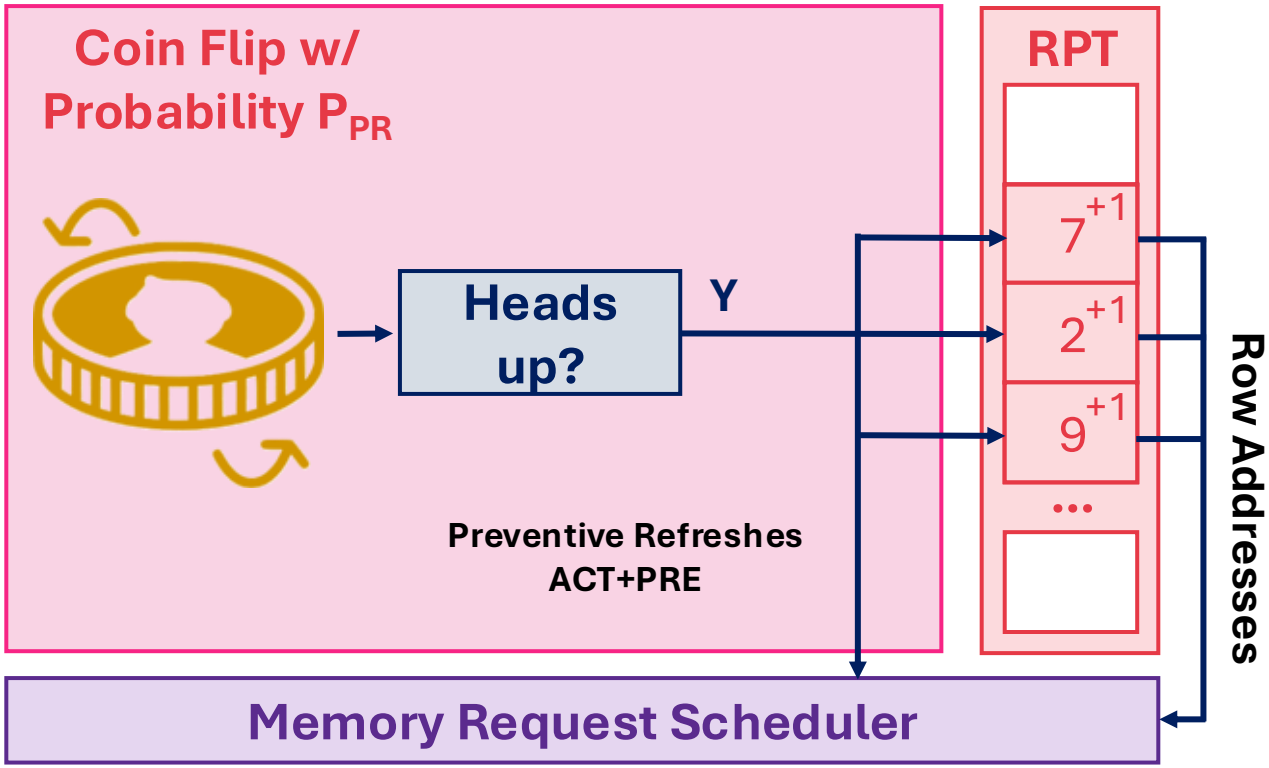


P_{PR} is calculated to **upper bound** the **probability** of a **ColumnDisturb** bitflip occurring during a year of **continuous ColumnDisturb attack**

ColumnKeeper-P Overview

Upon a row activation in one subarray:

- **ColumnKeeper-P** flips a coin that lands heads up with a **predetermined probability (P_{PR})**
- If the coin lands **heads up**, **ColumnKeeper-P** issues **preventive refreshes** for **that subarray** and **its neighbors** and **increments all three** RPT entries



More Details in the Paper

- Detailed **calculation of N_{PR}** for **ColumnKeeper-D**
- **Security analysis** of **ColumnKeeper-D**
- Detailed **calculation of P_{PR}** for **ColumnKeeper-P**
- **Monte-Carlo security analysis** of **ColumnKeeper-P**

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Methodology

Performance and energy consumption evaluation: cycle-level simulations using **Ramulator2 [Luo+, CAL 2023]** and **DRAMPower [Chandrasekar+, DATE 2013]**

System Configuration:

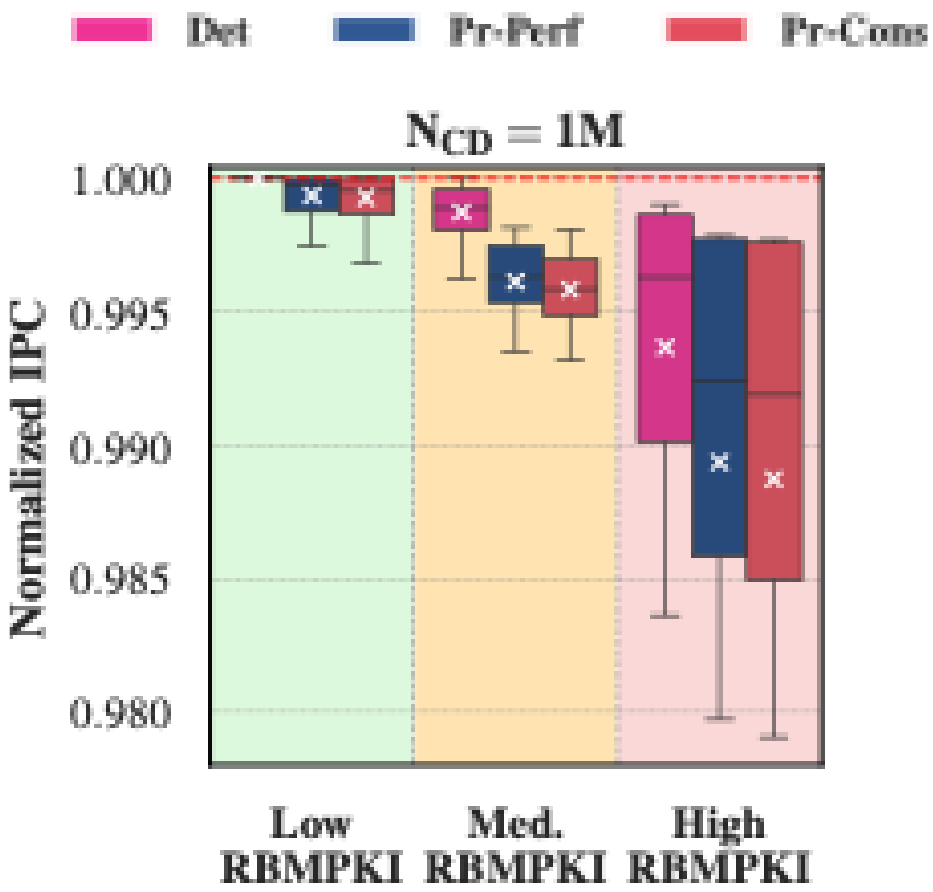
Processor	1 or 4 cores, Last-Level Cache: 2 MiB/core
DRAM	16GB DDR4, 1 channel, 2 rank/channel, 4 bank groups, 4 banks/bank group, 64K rows/bank, 1K rows/subarray
Mem. Ctrl.	64-entry read/write request queue, Scheduling policy: FR-FCFS, Open-Row Policy, Address mapping: RoBaRaCoCh

ColumnKeeper-D (***Det***) *or*
ColumnKeeper-P w/ yearly failure probability of 10^{-3} (***Pr-Perf***) or 10^{-12} (***Pr-Cons***)

Workloads:

- **62 single-core workloads** from SPEC CPU2006, SPEC CPU2017, TPC, MediaBench, and YCSB categorized by **Row Buffer Misses per-kilo-instructions (RBMPKI)**
- **60 quad-core workload mixes** synthesized from the resulting RBMPKI categories

Evaluation: Single-Core Performance



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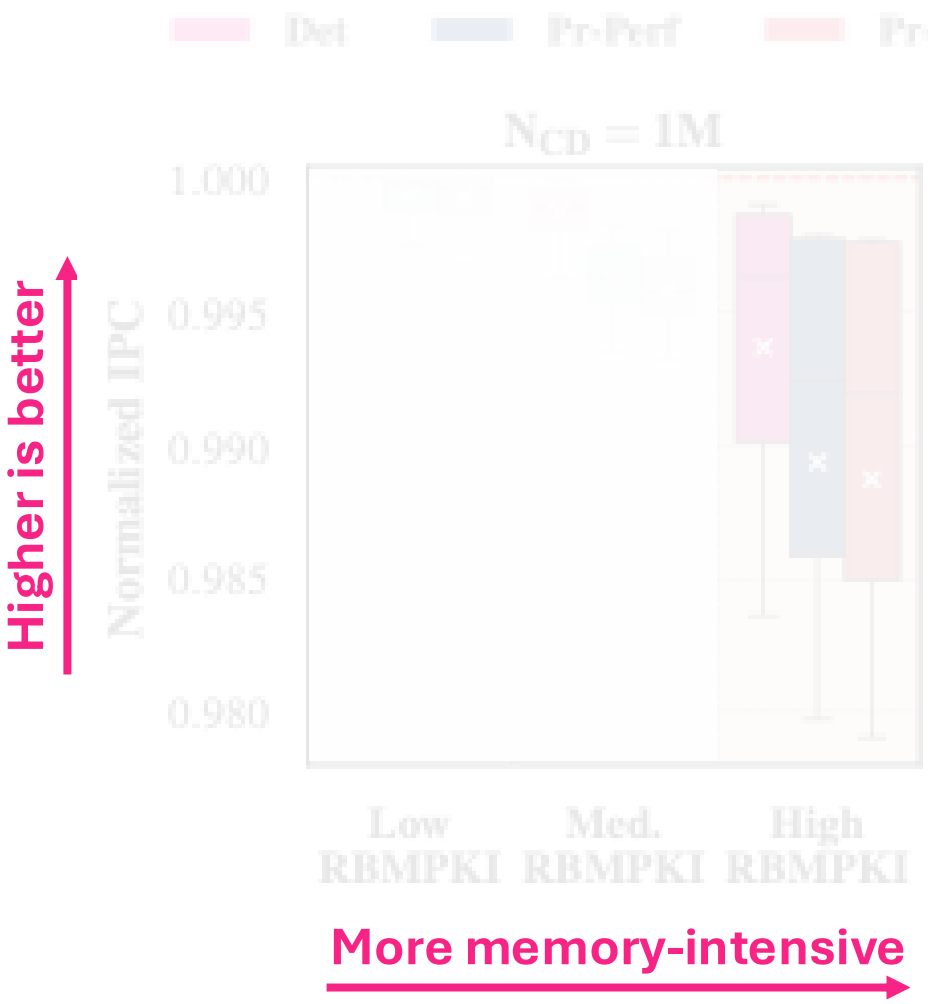

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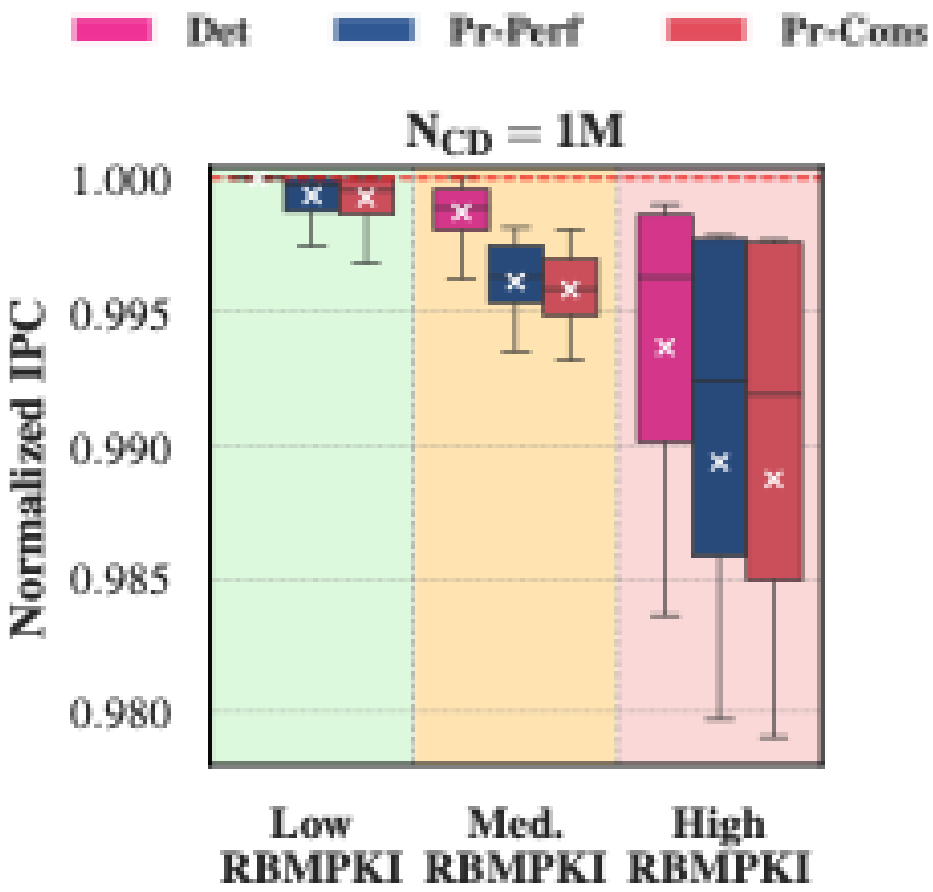
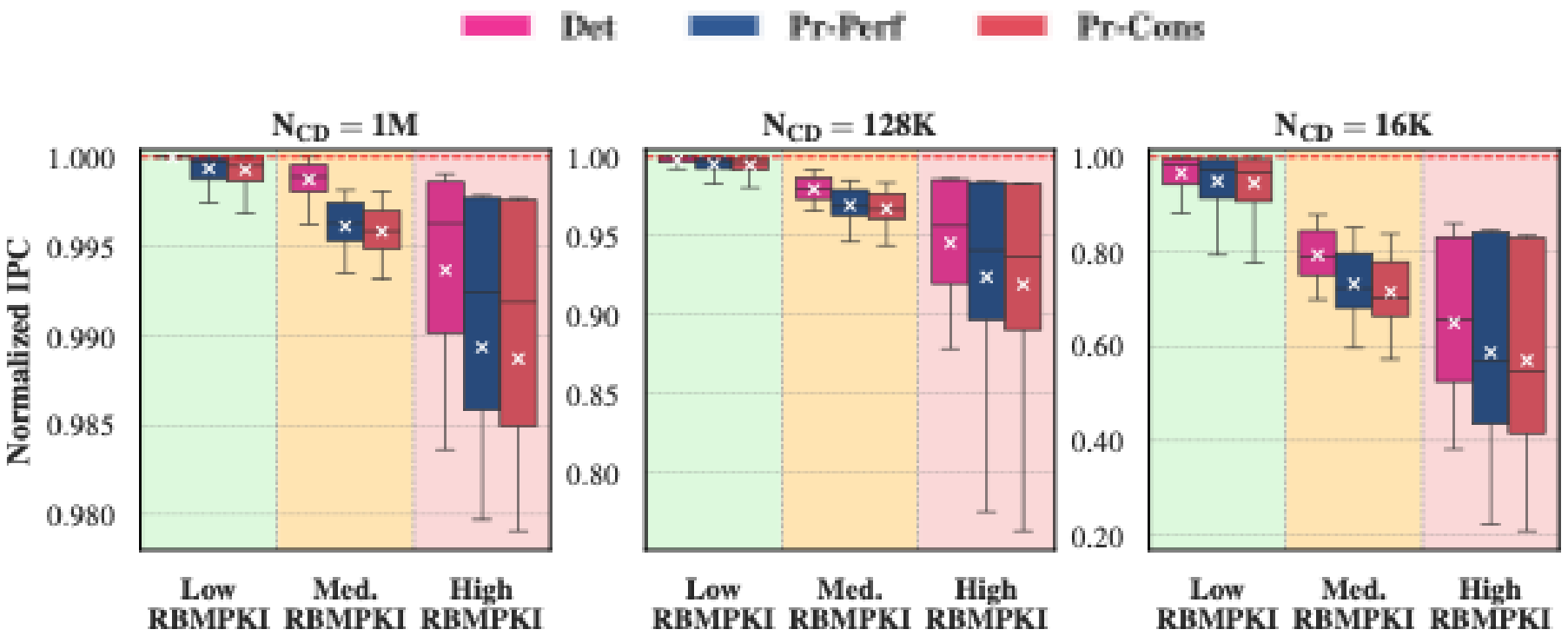


ColumnKeeper-D and –P incur **low (<1%)** average **performance overheads** for **current** ColumnDisturb **thresholds** (**1M**)

Evaluation: Single-Core Performance



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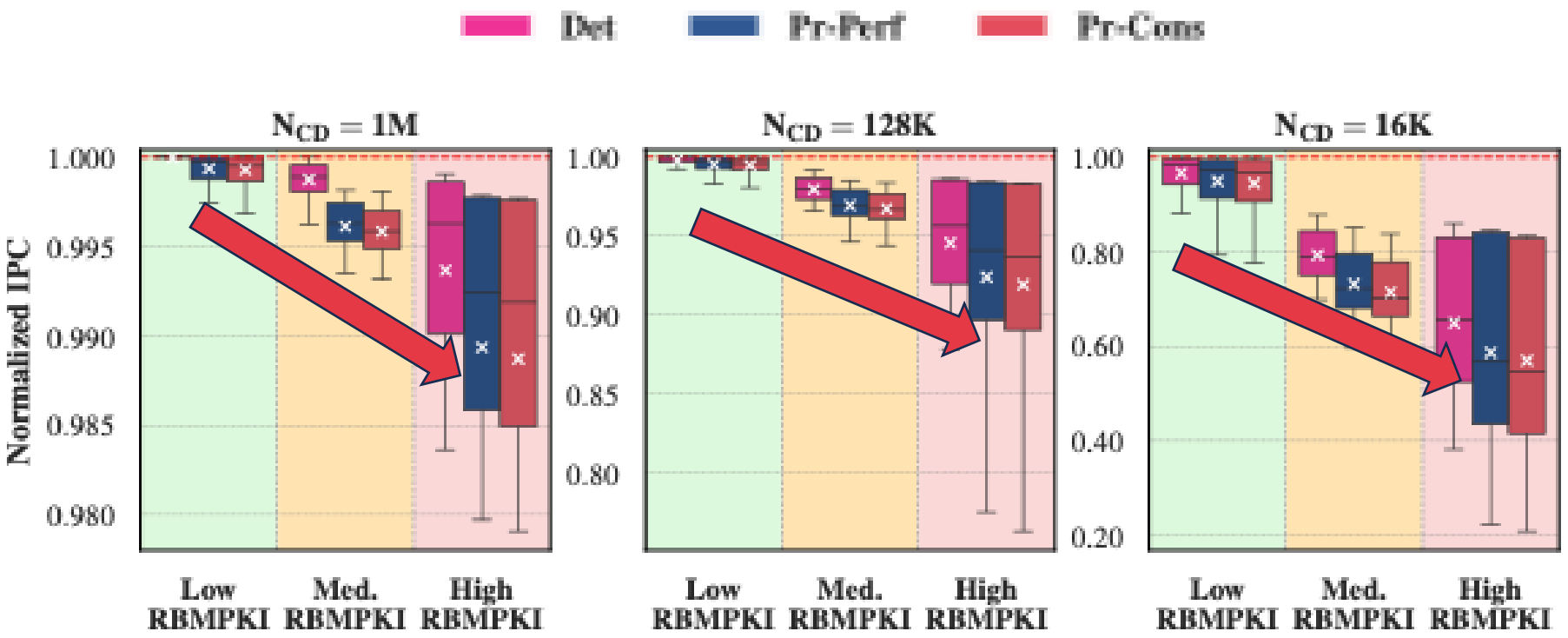
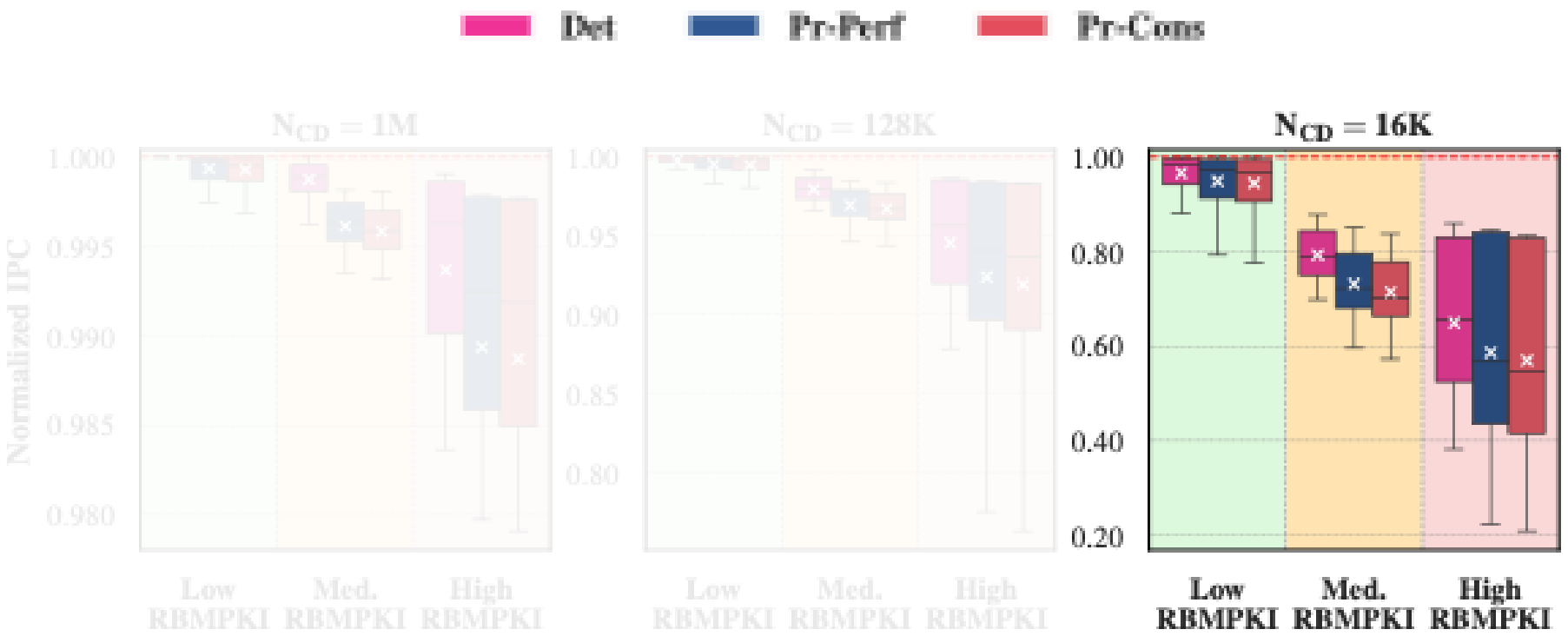


Performance overheads increase for more **memory-intensive** workloads

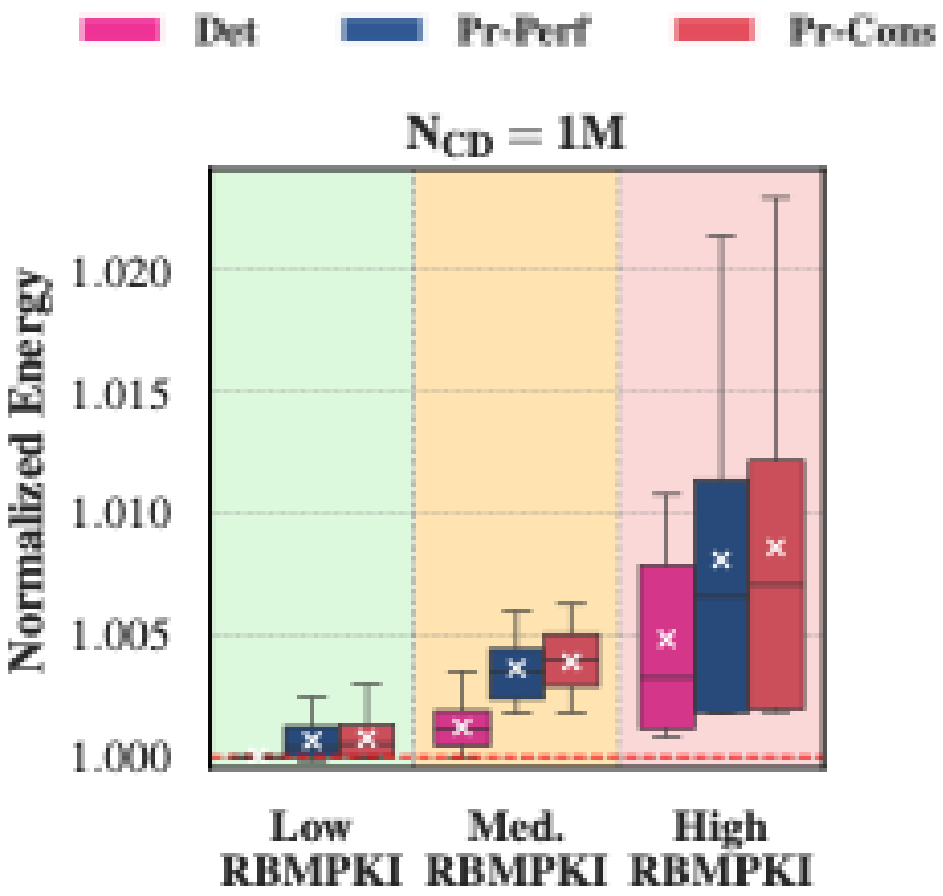
Evaluation: Single-Core Performance



Performance overheads increase for more **memory-intensive** workloads

All ColumnKeeper mechanisms **incur significant performance overheads** at **low ColumnDisturb thresholds** of **N_{CD}=16K**

Evaluation: DRAM Energy (Single-Core)



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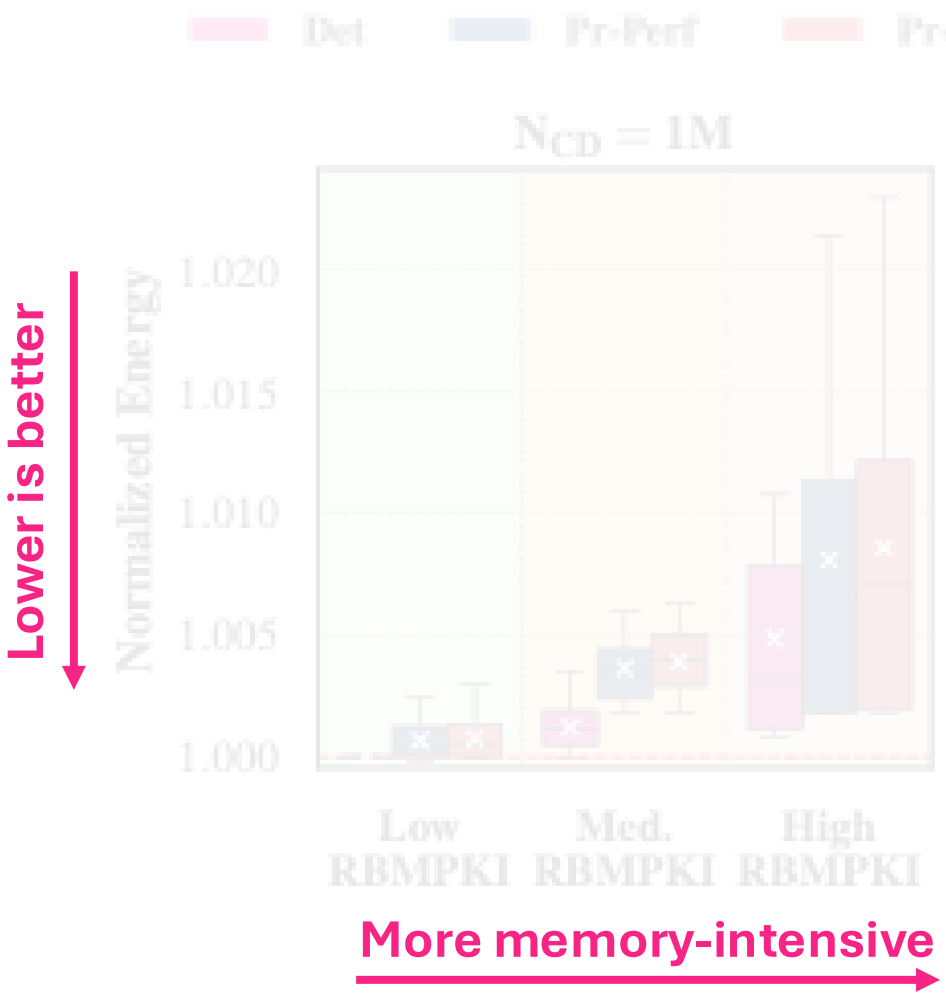

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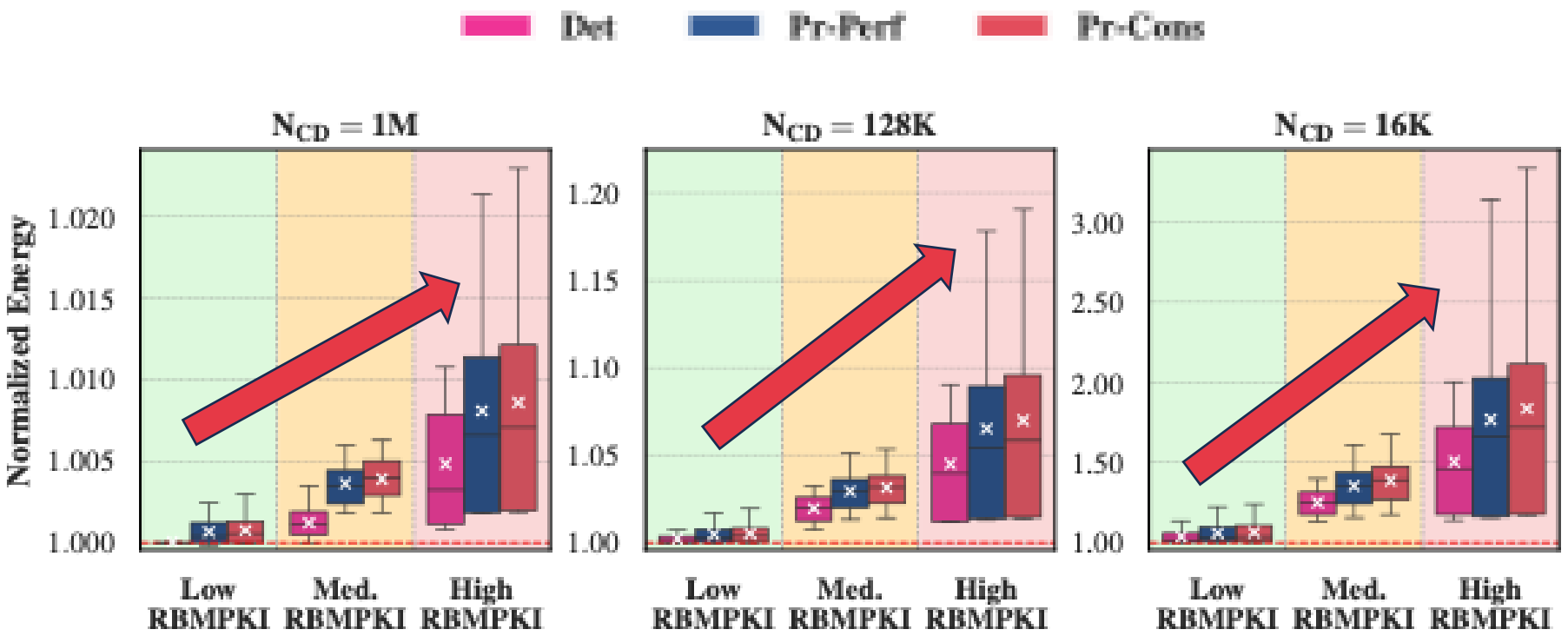
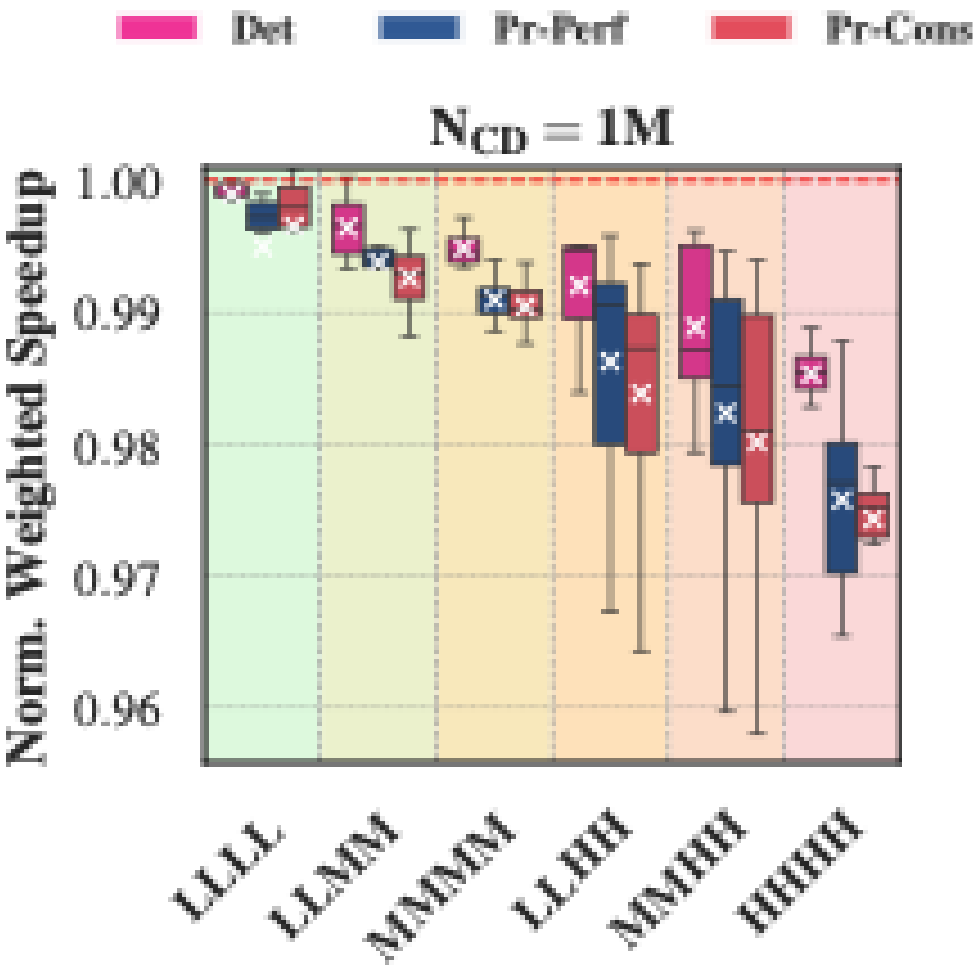


Energy overheads increase for more **memory-intensive** workloads

Low energy overheads for **current thresholds**

Significant energy overheads for **future low thresholds**

Evaluation: Multi-Core Performance



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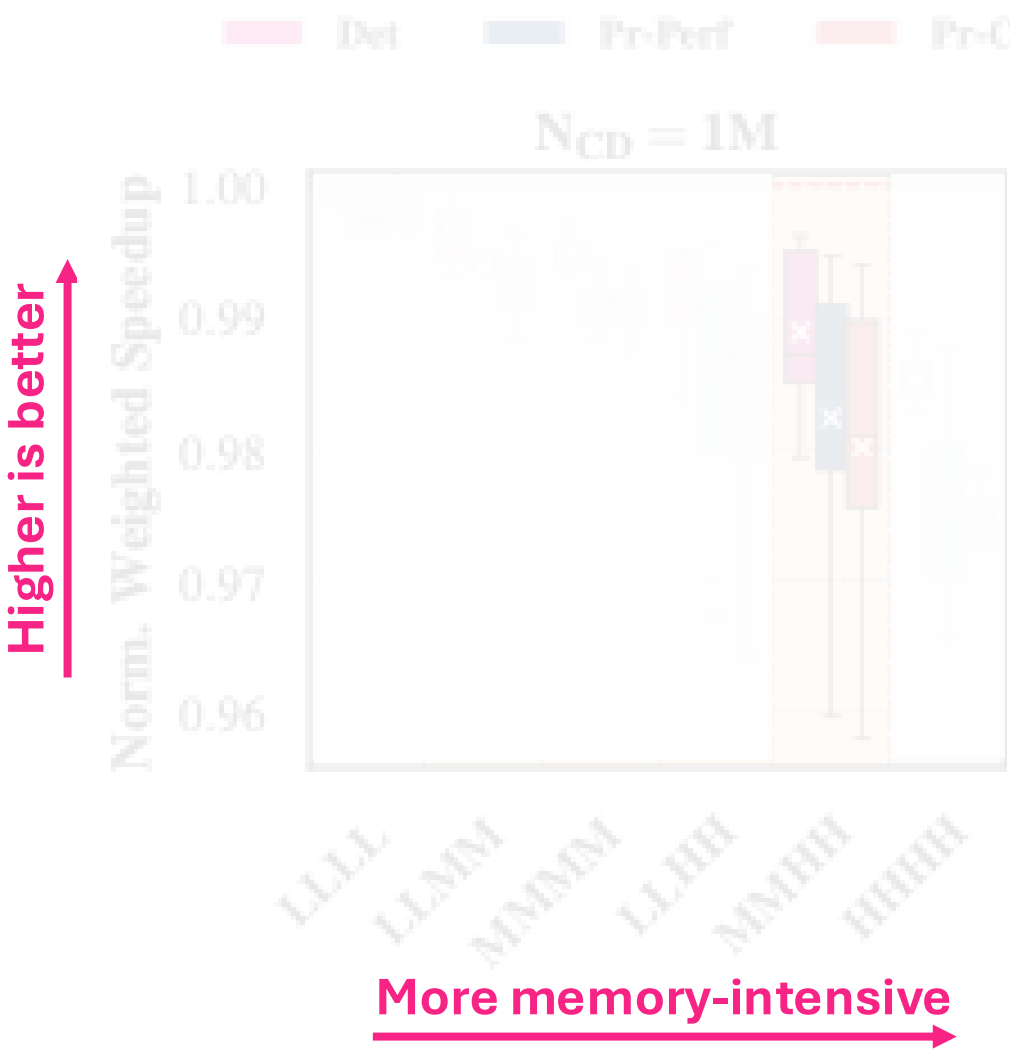

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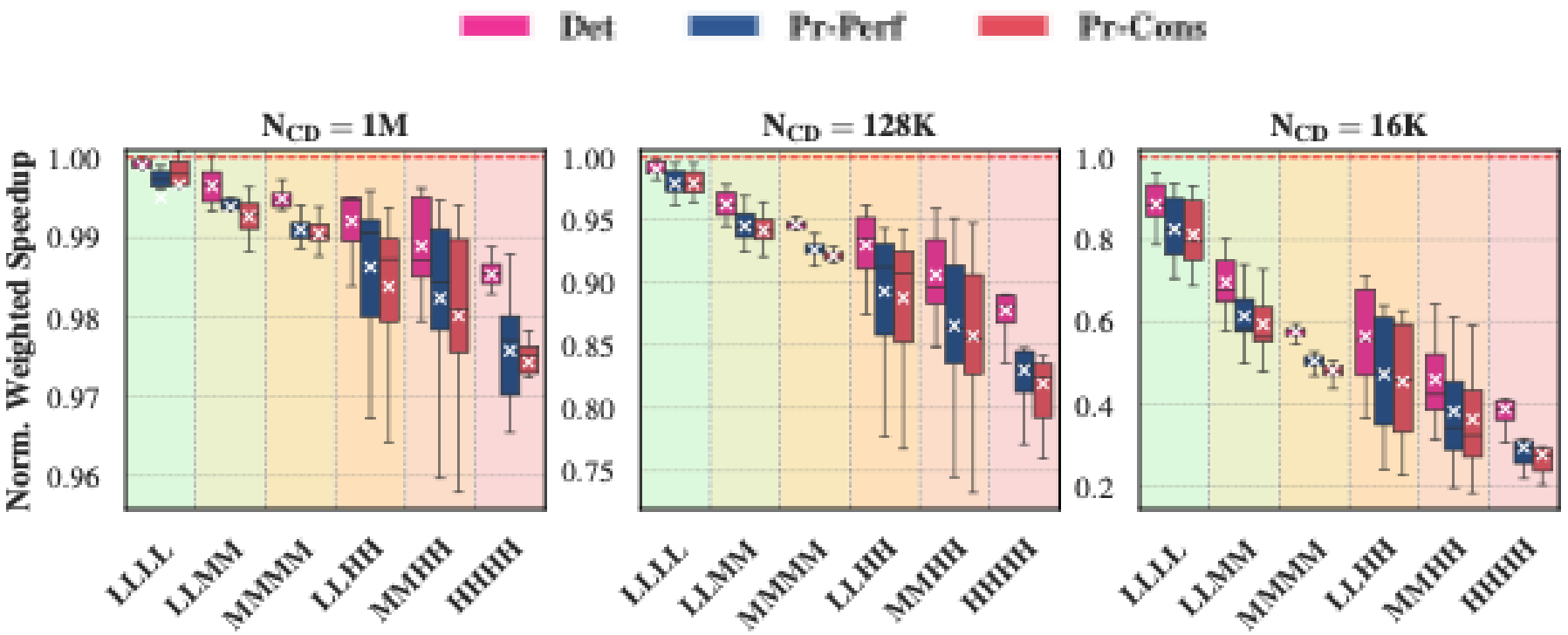

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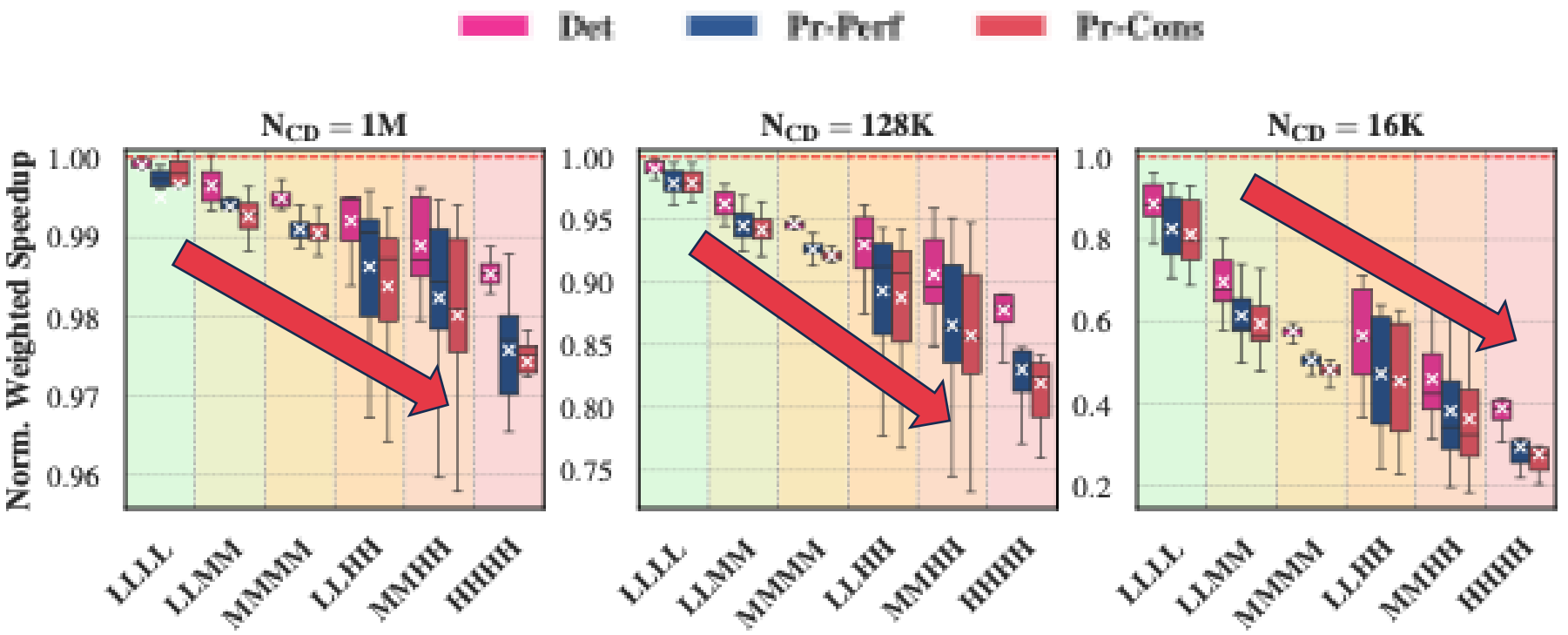
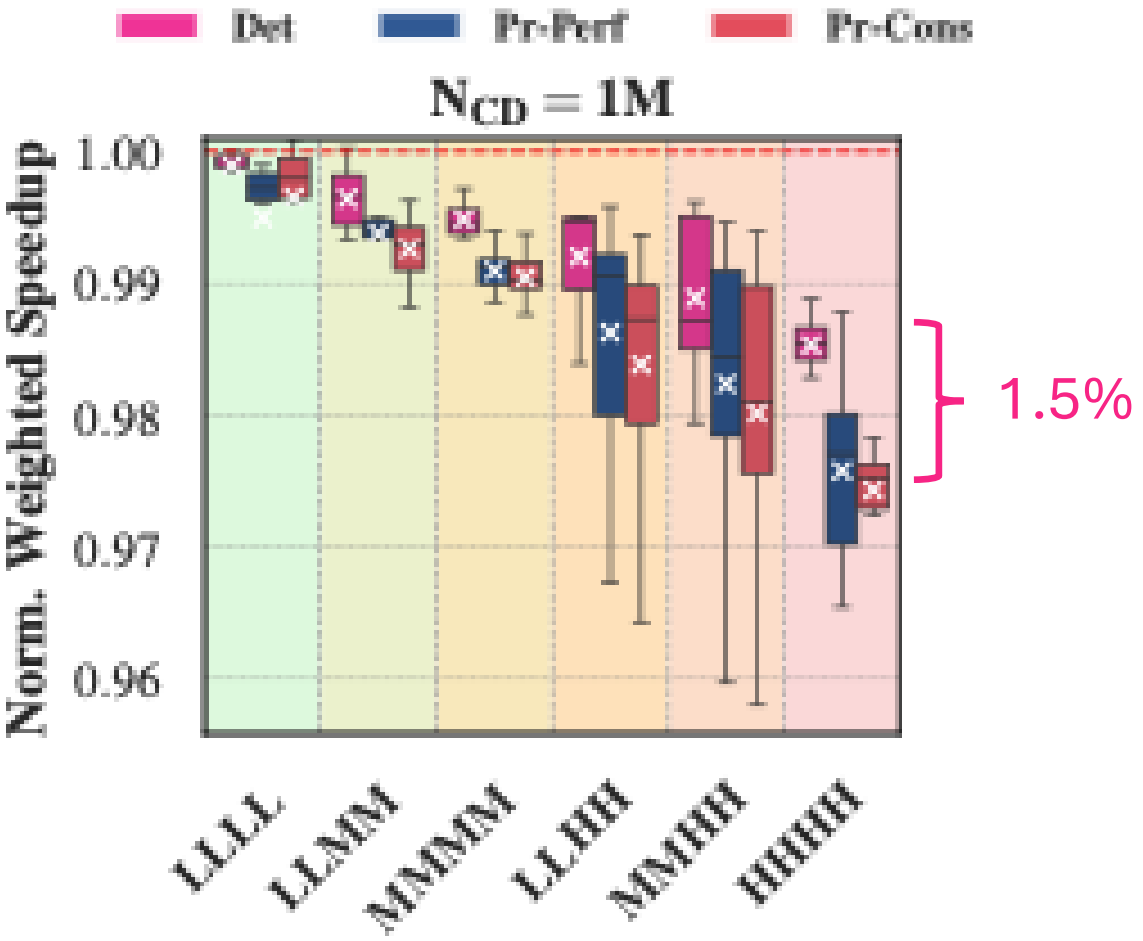


Performance overheads increase for **memory-intensive** workload mixes

Low performance overheads for **current thresholds**

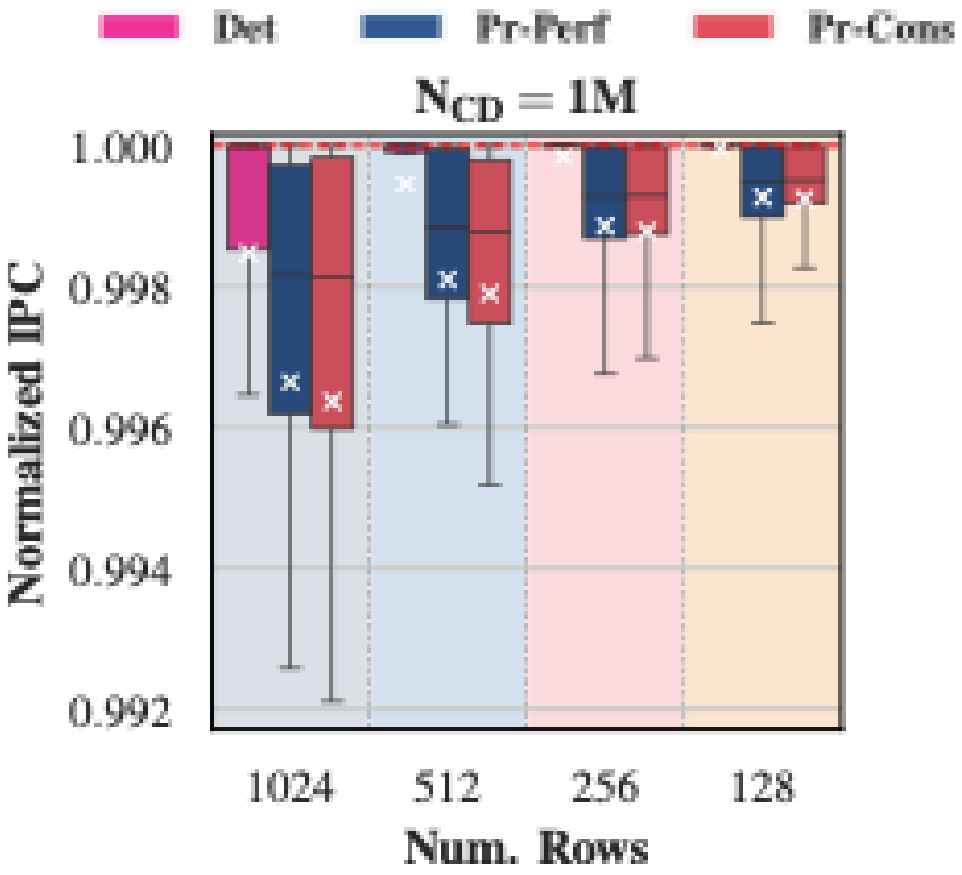
Significant performance overheads for **future low thresholds**

Evaluation: Multi-Core Performance



More pronounced difference between **CK-D** an **CK-P** than **single-core**

Evaluation: Sensitivity to Subarray Size



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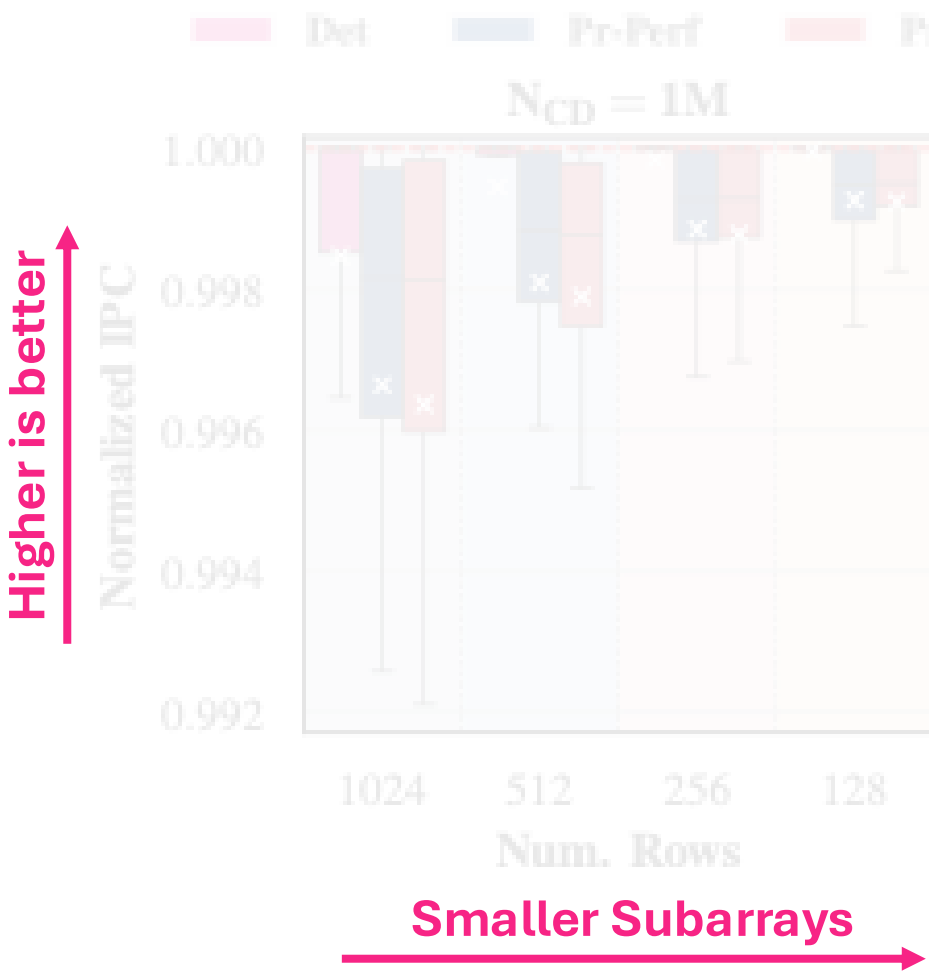
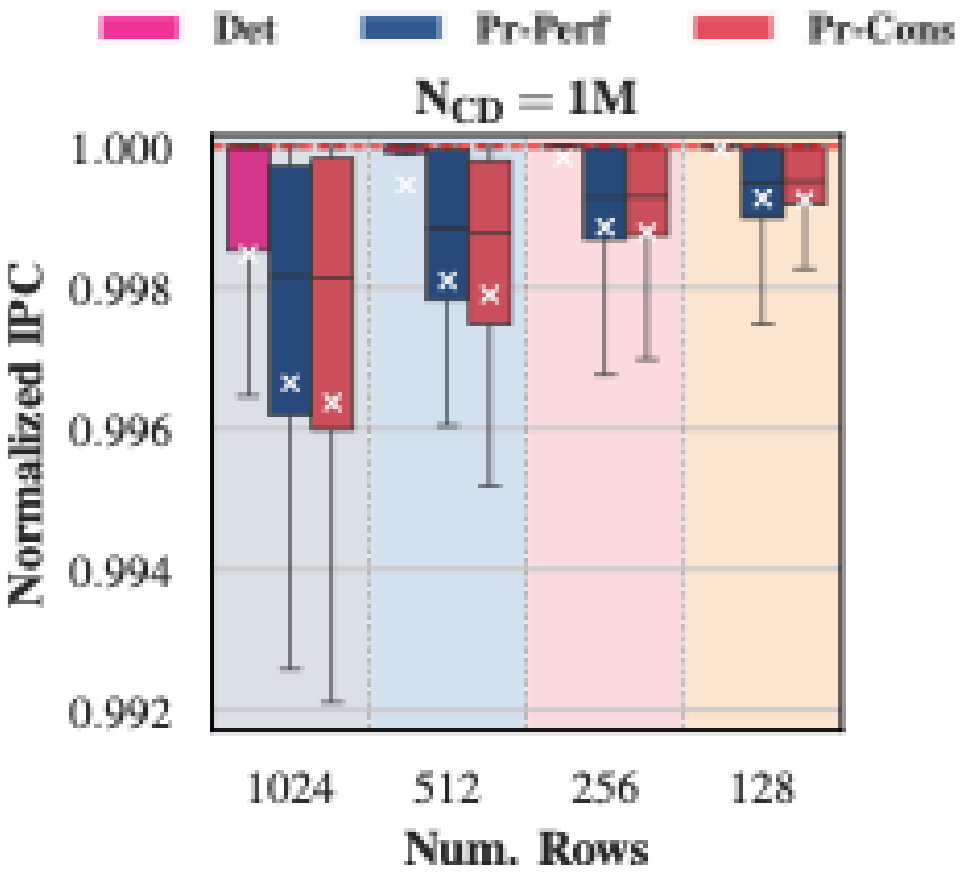
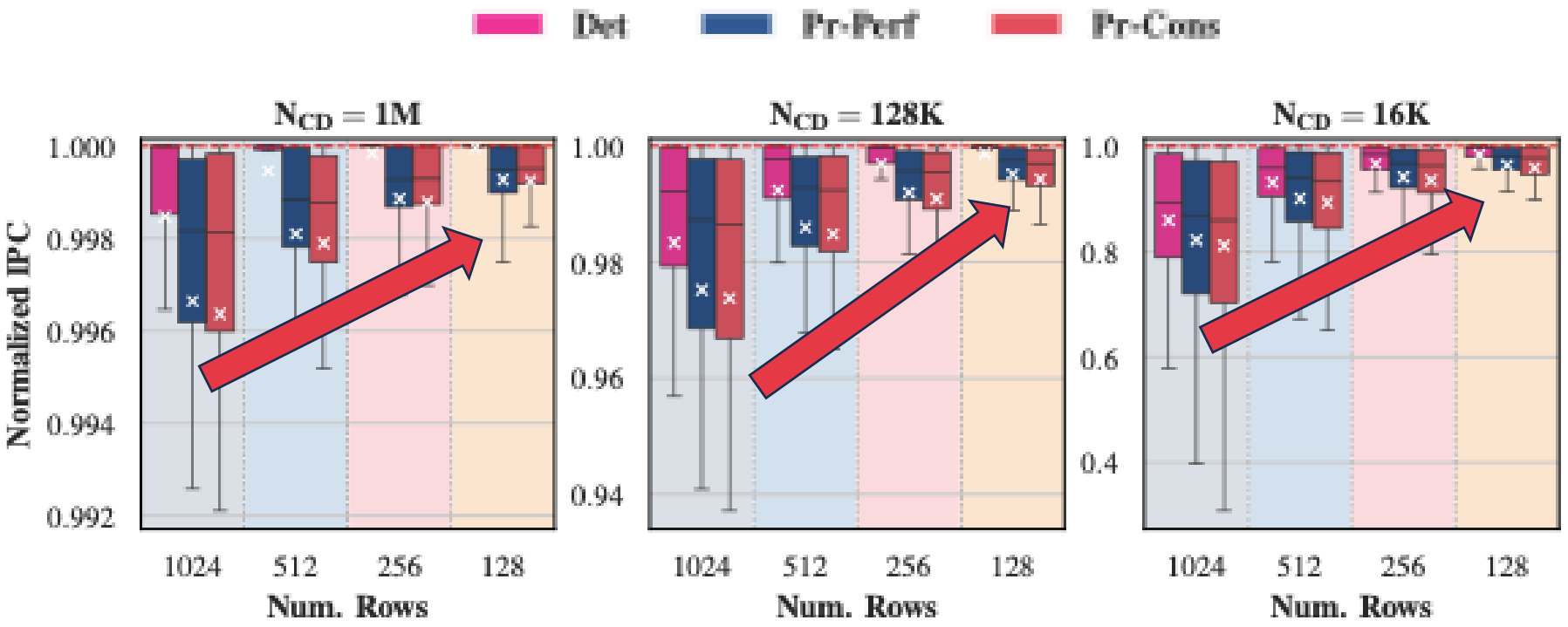


Evaluation: Sensitivity to Subarray Size



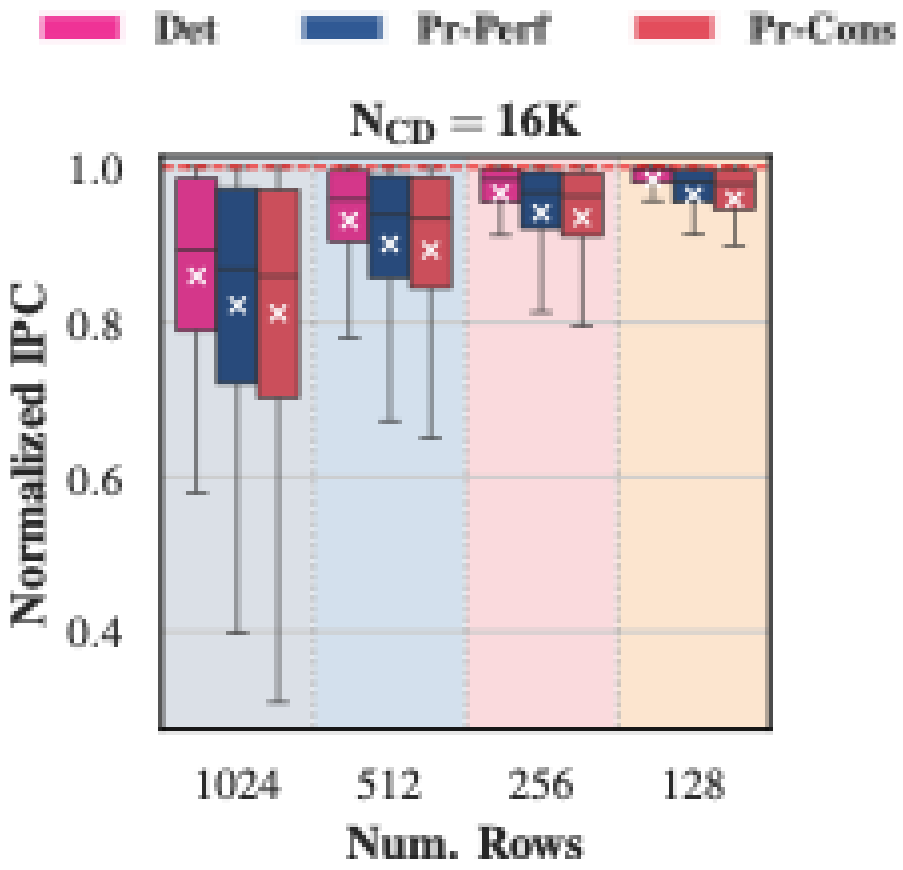
Smaller subarrays (128 rows) eliminate the overheads of ColumnKeeper **for current** ColumnDisturb **thresholds (1M)**

Evaluation: Sensitivity to Subarray Size

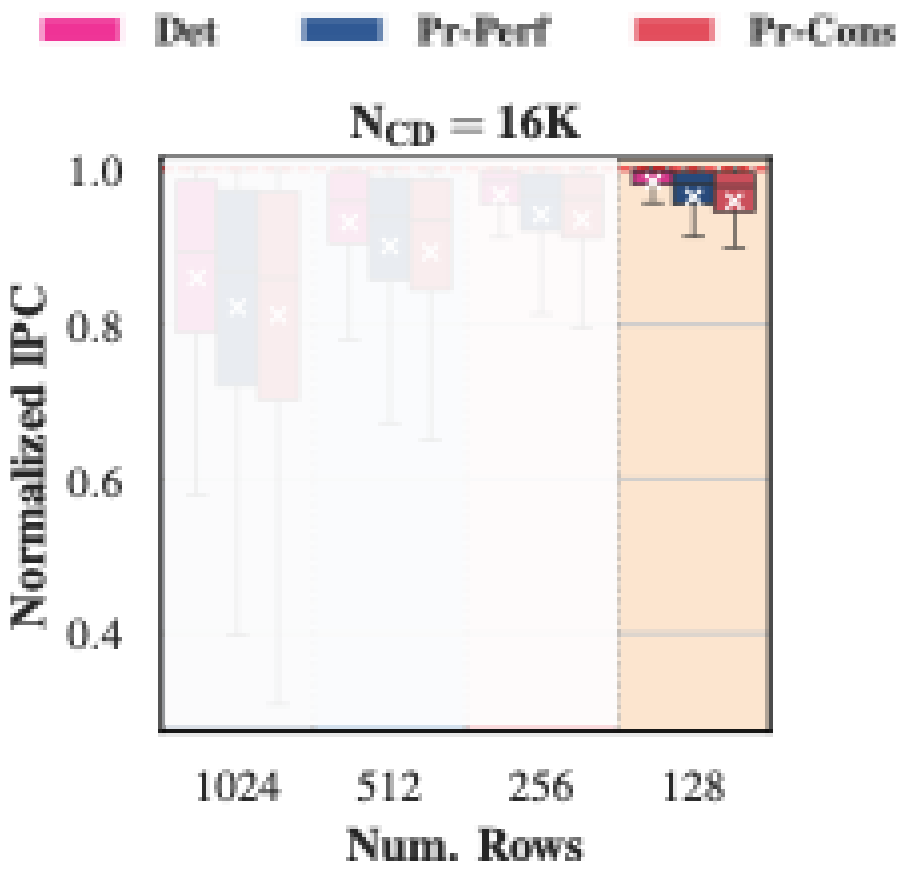


Smaller subarrays reduce the overheads of ColumnKeeper for **all ColumnDisturb thresholds**

Evaluation: Sensitivity to Subarray Size



Evaluation: Sensitivity to Subarray Size



Smaller subarrays reduce the overheads of ColumnKeeper **even at very low thresholds**

Evaluation: Area and Power Overheads

ColumnKeeper requires:

- **7.5 KB** of SRAM for **ColumnKeeper-D**
- **2.5 KB** of SRAM for **ColumnKeeper-P**

Hardware Implementation & Synthesis:

- **ColumnKeeper** implemented in **Verilog**
- **OpenRoad + NanGate 45nm** Open-Source Cell Library

Area Overheads:

- **0.1 mm^2** for **ColumnKeeper-D**
- **0.03 mm^2** for **ColumnKeeper-P**

Power Overheads:

- **50 mW** for **ColumnKeeper-D**
- **15 mW** for **ColumnKeeper-P**

More in the Paper

- Evaluation of ColumnKeeper with **Subarray-level Parallelism** [Kim+, ISCA 2012]
- **Impact** of physical page allocation policy on the **performance overheads** of ColumnKeeper
- **Performance evaluation** of ColumnKeeper integrated with **RowHammer mitigation mechanisms**
- **Performance evaluation** under **adversarial workloads**
- An **in-DRAM implementation** of our design

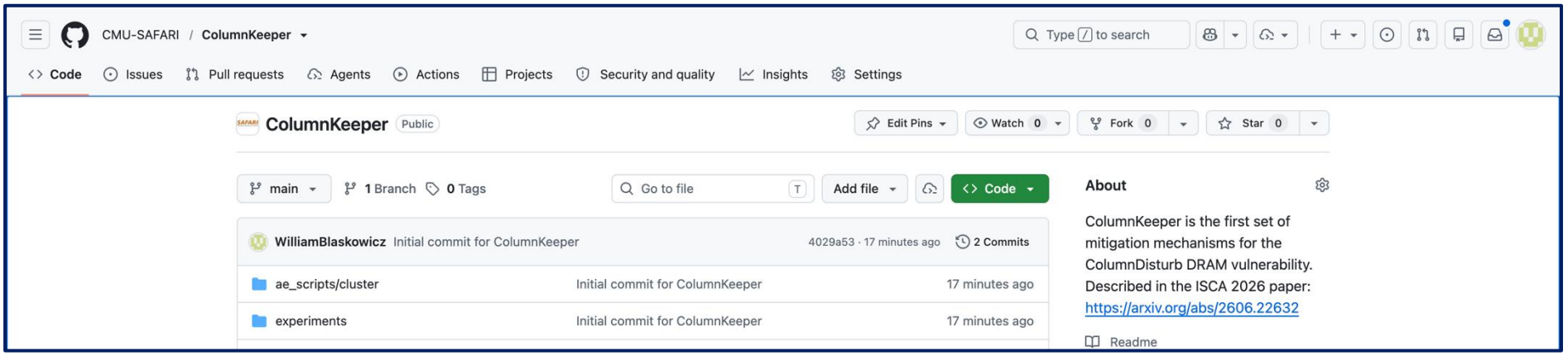
Available on arXiv

ColumnKeeper: Efficient Solutions to the ColumnDisturb Vulnerability in DRAM-based Systems

Andreas Kosmas Kakolyris[1] F. Nisa Bostancı[1] Ataberk Olgun[1] İsmail Emir Yüksel[1]
Harsh Songara[1] Konstantinos Marios Sgouras[1] Umut Başer[1,2]
Konstantinos Kanellopoulos[1] A. Giray Yağlıkçı[3] Onur Mutlu[1]
[1]ETH Zürich [2]TOBB ETÜ [3]CISPA

https://arxiv.org/pdf/2606.22632

Artifact Evaluated & Open-Source



GitHub

https://github.com/CMU-SAFARI/ColumnKeeper

Outline

Background

Motivation

ColumnKeeper-D (Deterministic)

ColumnKeeper-P (Probabilistic)

Evaluation

Conclusion

Conclusion

Goal: Mitigate ColumnDisturb bitflips at **low overhead**

Key Idea: Track row activations **at subarray granularity** and iteratively refresh **all affected rows** in a subarray

ColumnKeeper-D: Uses **separate** activation counters for **odd** and **even columns** of each subarray
ColumnKeeper-P: ***Probabilistically*** **issues** refreshes to one row in **three consecutive subarrays** upon a row activation in the middle subarray

Key Results:

- **ColumnKeeper prevents** ColumnDisturb bitflips with **low overheads** for **current** and **near-future thresholds**
- **ColumnKeeper can prevent** ColumnDisturb bitflips at **low overheads for low thresholds** with **changes to DRAM** microarchitecture

ColumnKeeper: Efficient Solutions to the ColumnDisturb Vulnerability in DRAM-based Systems

Paper

Code

SAFARI ETH zürich CISPA

ColumnKeeper: Efficient Solutions to the ColumnDisturb Vulnerability in DRAM-based Systems

Backup Slides

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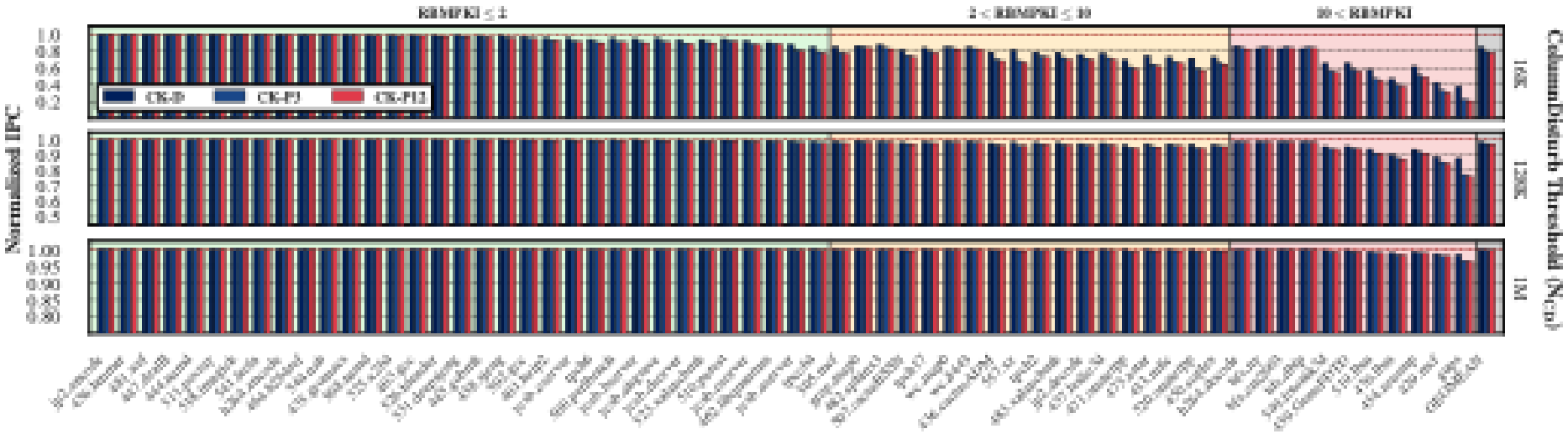
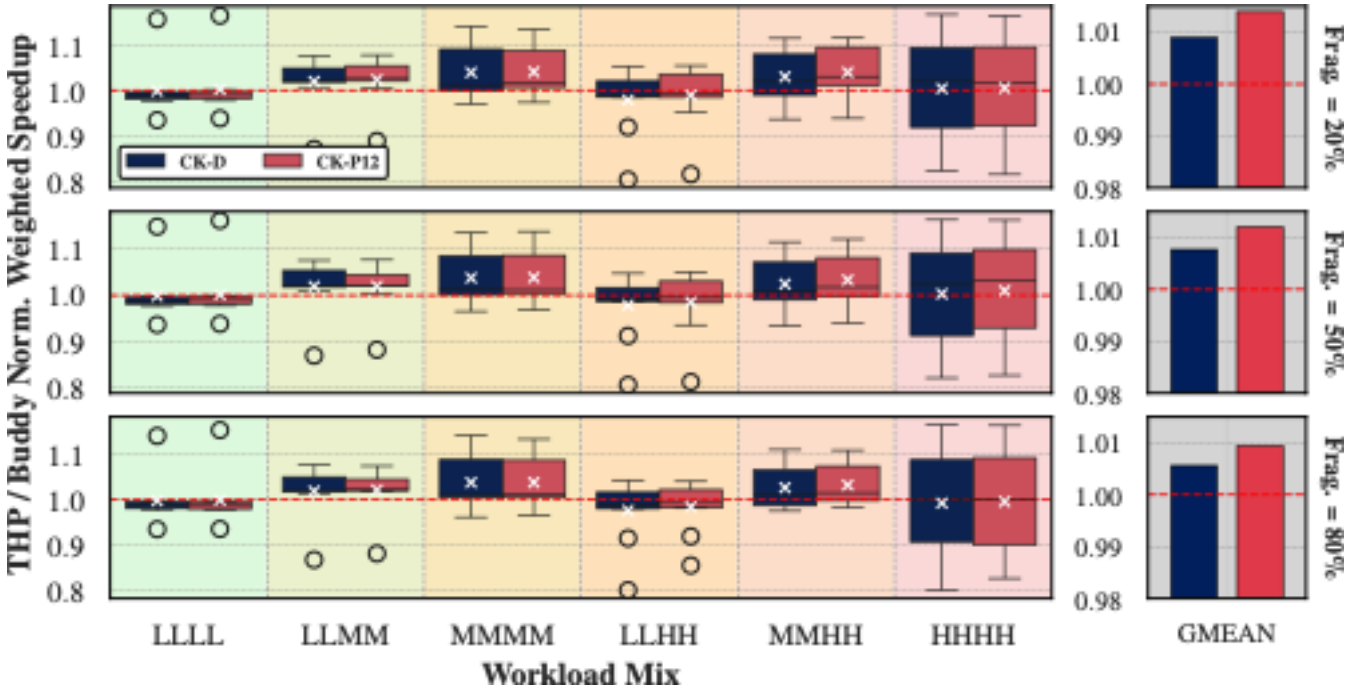
SAFARI
ETH zürich
CISPA

Evaluation: Detailed Single-Core Results

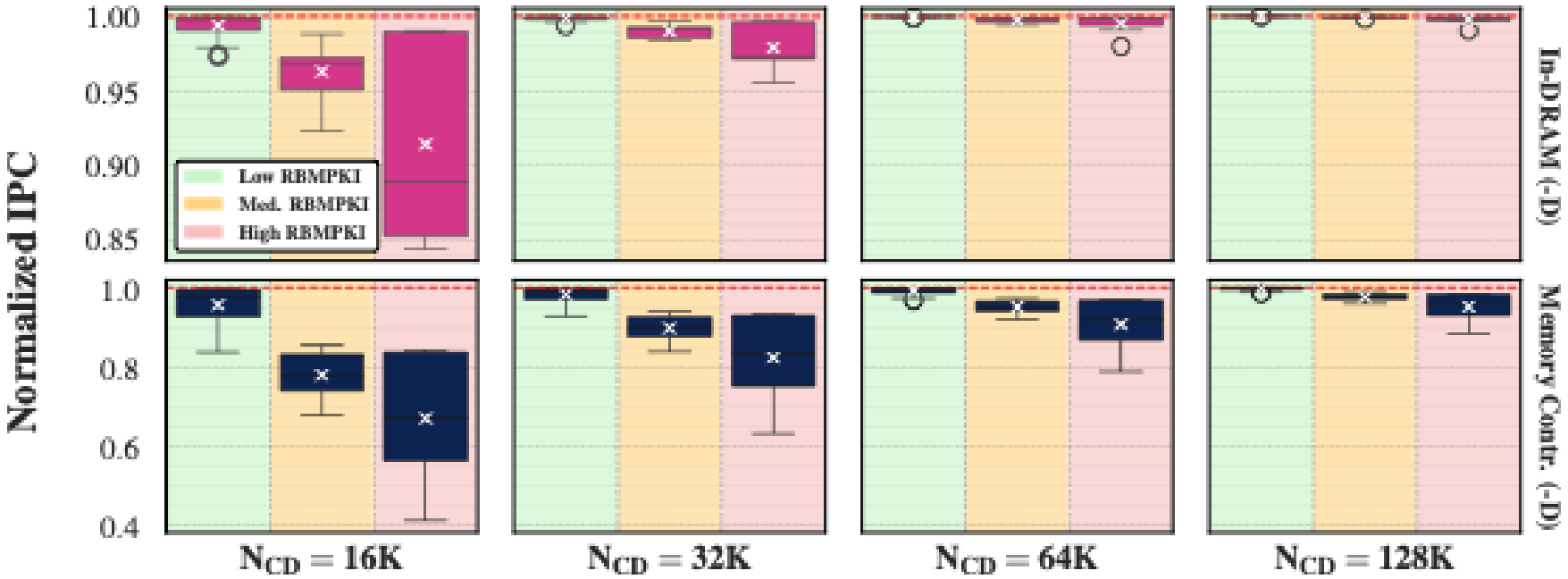


Evaluation: Sensitivity to Page Allocation



No significant difference in performance between the two allocators

Evaluation: In-DRAM Implementation



The in-DRAM implementation of ColumnKeeper-D reduces its overheads at low ColumnDisturb thresholds

ColumnKeeper-P: P_{PR} Calculation

Methodology

- Similar to the one proposed in HiRA [Yaglikci+, MICRO 2022]
- Considers the maximum number of attacks that can happen in a refresh window
- At least one of these attacks has to succeed

To induce bitflips: The number of preventive issues issued to a subarray must be lower than the subarray size (S) when the ColumnDisturb threshold is reached

Total number of preventive refreshes issued after N activations (M_N):

- Sum of Bernoulli random variables
- M_N follows a binomial distribution

$$P(M_N \leq k) = I_q(N-k, 1+k), q = 1 - P_{PR}$$

ColumnKeeper-P: P_{PR} Calculation

We substitute:

- $N = N_{CD} - 1$
- $k = S - 1$

A single ColumnDisturb attack succeeds with probability P_1:

$$P_1 = P\left(M_{N_{CD}} < S\right) = P\left(M_{N_{CD}} \leq S - 1\right) = I_q(N_{CD} - S, S)$$

Probability of a successful attack within a refresh window based on maximum number of attacks:

$$P_{REFW} = 1 - (1 - P_1)^A, A = \frac{t_{REFW}}{t_F} + 1, t_F = (1 + 3S) \cdot t_{RC}$$

Probability of a successful attack within a year (P_Y):

$$P_Y = 1 - (1 - P_{REFW})^{492.7 \cdot 10^6}$$

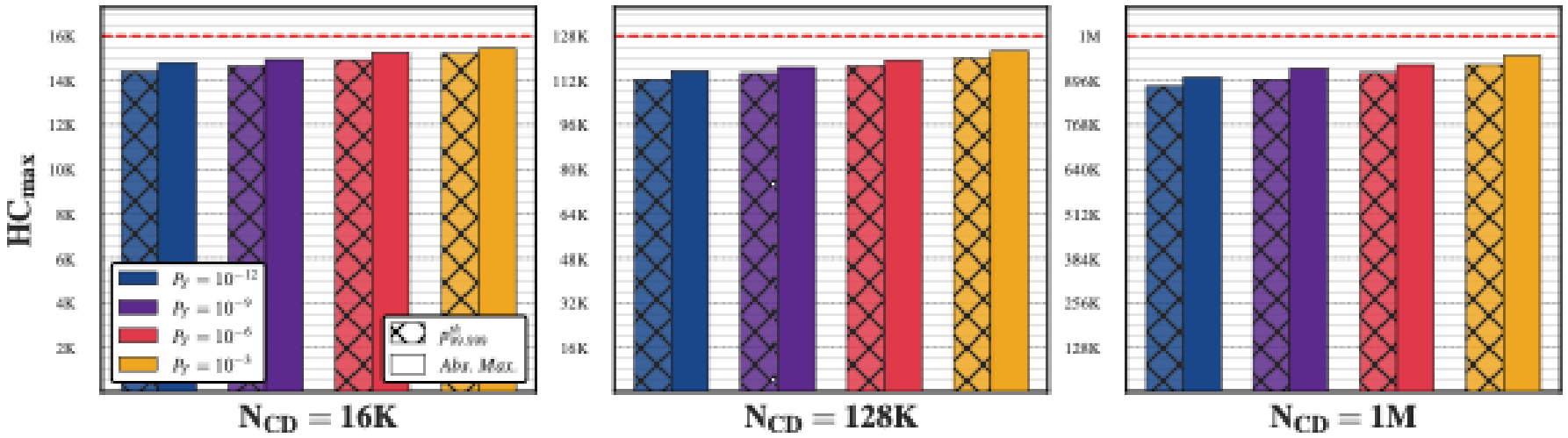
ColumnKeeper-P Configuration

Table 1: Configuration parameters of ColumnKeeper-P.

P_Y	10^{-3}	10^{-6}	10^{-9}	10^{-12}
P_{REFW}	2.03×10^{-12}	2.03×10^{-15}	2.03×10^{-18}	2.03×10^{-21}
P_1	4.39×10^{-15}	4.38×10^{-18}	4.38×10^{-21}	4.38×10^{-24}
N_{CD}	**Preventive Refresh Probability (P_{PR})**			
$1M$	1.23×10^{-3}	1.26×10^{-3}	1.29×10^{-3}	1.32×10^{-3}
$128K$	1.00×10^{-2}	1.02×10^{-2}	1.05×10^{-2}	1.07×10^{-2}
$16K$	8.92×10^{-2}	9.13×10^{-2}	9.32×10^{-2}	9.50×10^{-2}

Small increases in P_{PR} significantly increase security for the same N_{CD}

ColumnKeeper-P: Monte-Carlo Simulation



Lower P_Y leads to more preventive refreshes and a lower HC_{max}

Evaluation: Integration w/ RH Mitigations

ColumnKeeper issues ACT+PRE commands:

- ACTs and PREs are transparent to RowHammer mitigation mechanisms

RowHammer mitigation mechanisms issue:

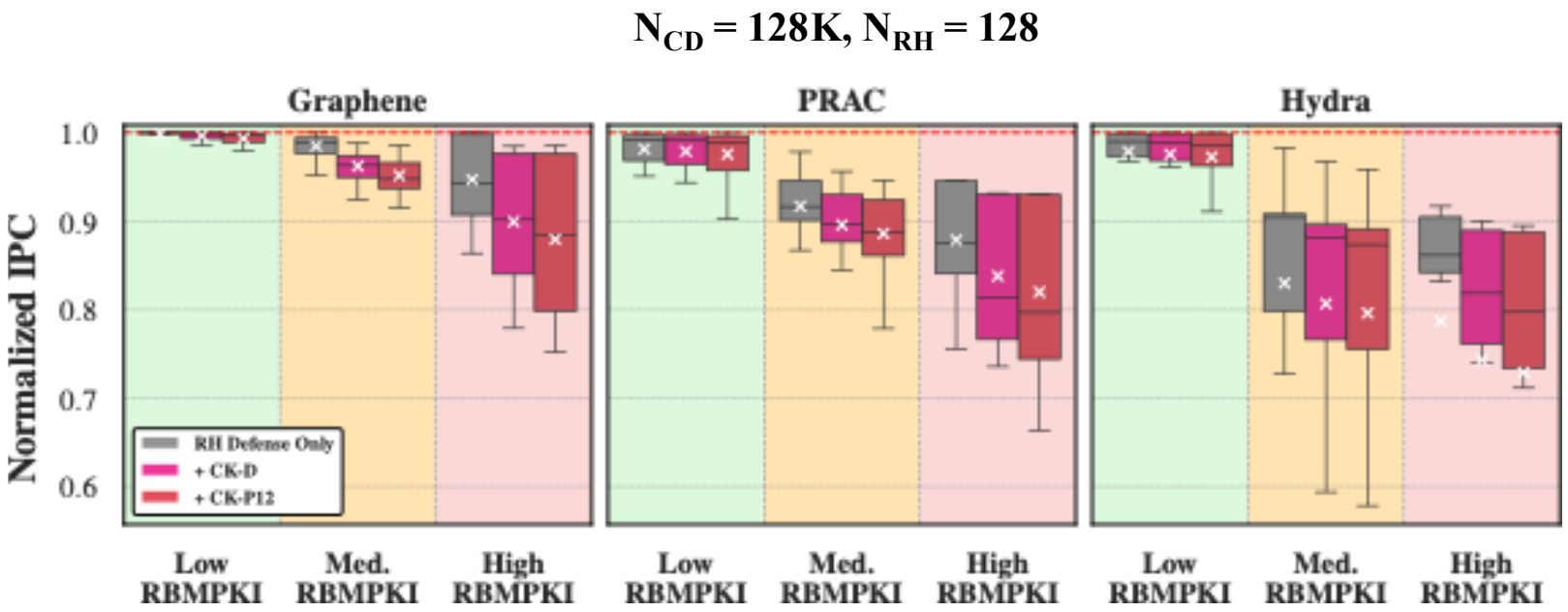
- ACT + PRE commands
- RFM commands

RFM commands accounted by incrementing all activation counters in affected banks

ColumnKeeper operates transparently to RowHammer mitigation mechanisms

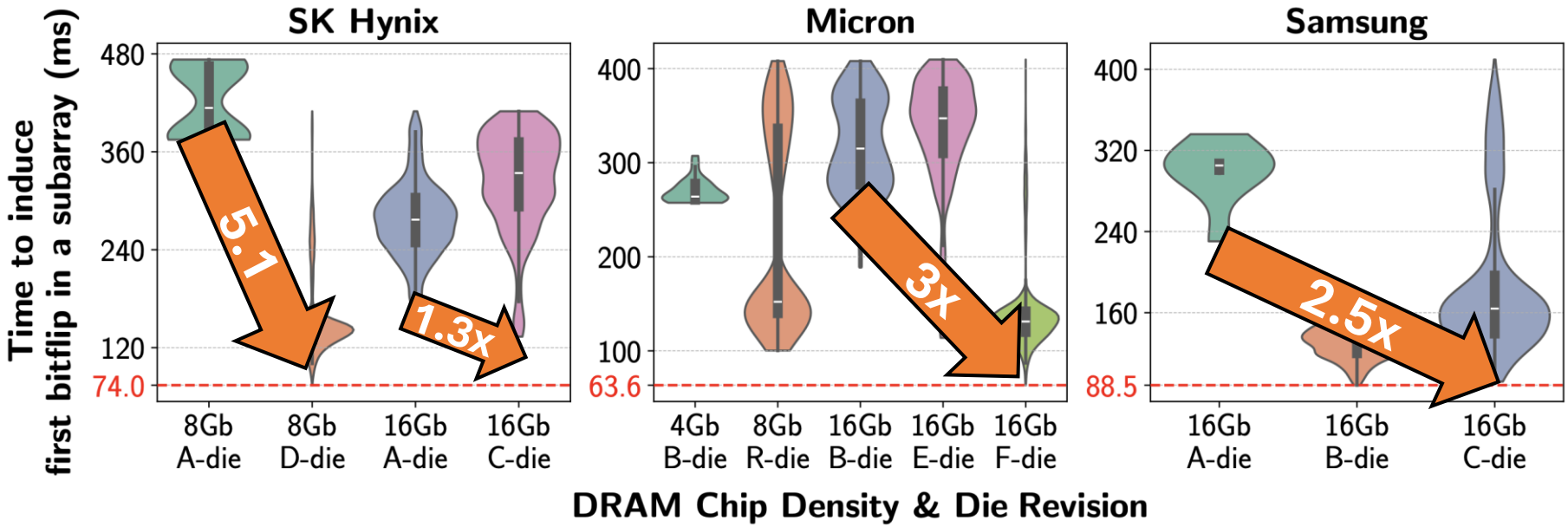
RowHammer mitigation mechanisms operate transparently to ColumnKeeper

Evaluation: Integration w/ RH Mitigations



No destructive interference between
RowHammer mitigation mechanisms and **ColumnKeeper**

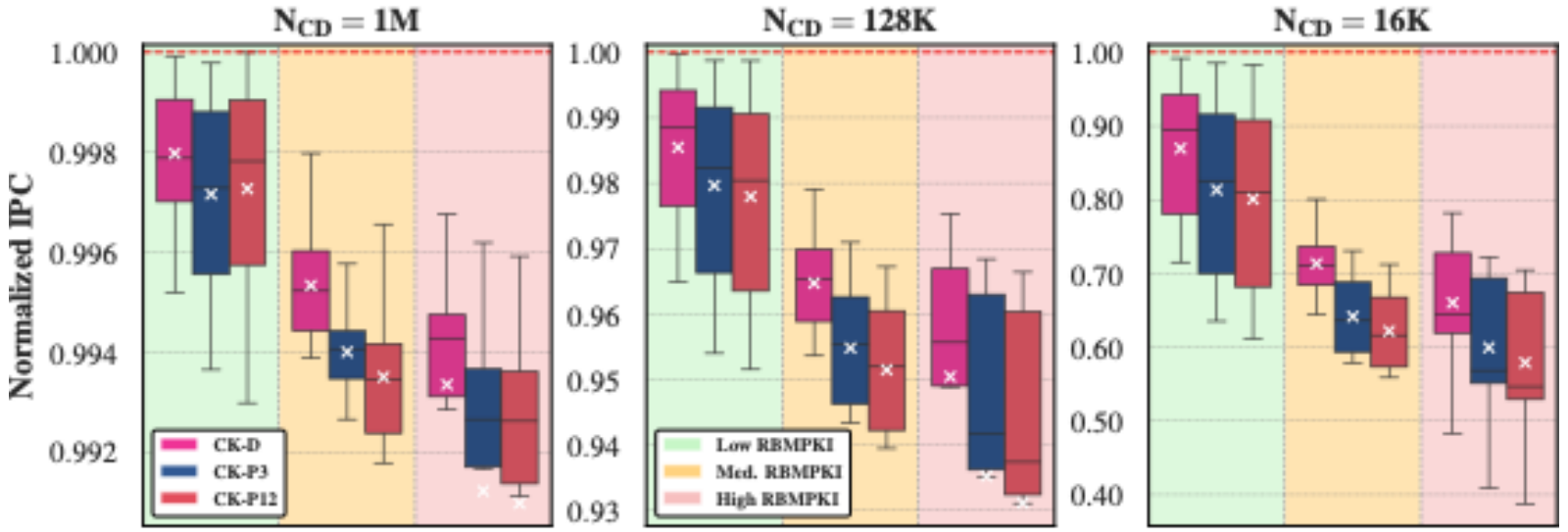
ColumnDisturb: Newer Chips are More Vulnerable



Newer chips tend to be
more vulnerable to ColumnDisturb bitflips

This trend is **consistent across all tested manufacturers**

Evaluation: Adversarial Workloads



Low performance overheads for **current** and **near-future thresholds**

Significant performance overheads for **future low thresholds**