

# Enabling Efficient and Scalable Read Disturbance Mitigation via New Experimental Insights into Modern Memory Chips



[agyaglikci.github.io](https://agyaglikci.github.io)

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11 March 2024

Huawei Cambridge

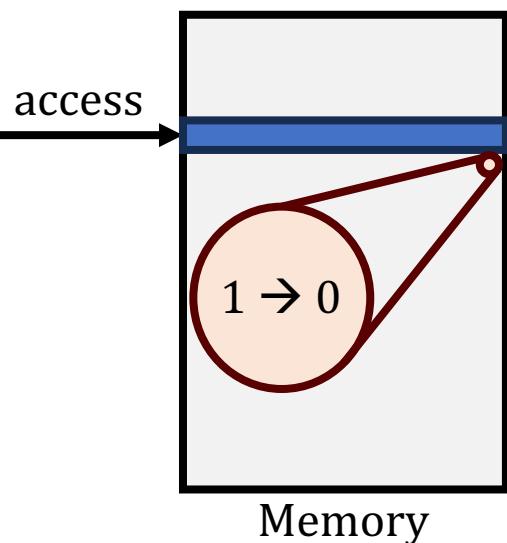


[safari.ethz.ch](https://safari.ethz.ch)

**SAFARI**

**ETH zürich**

# Lack of Memory Isolation



Data **Loss** or **Corruption**



Compromise Application **Correctness**



**Leak** Private Information

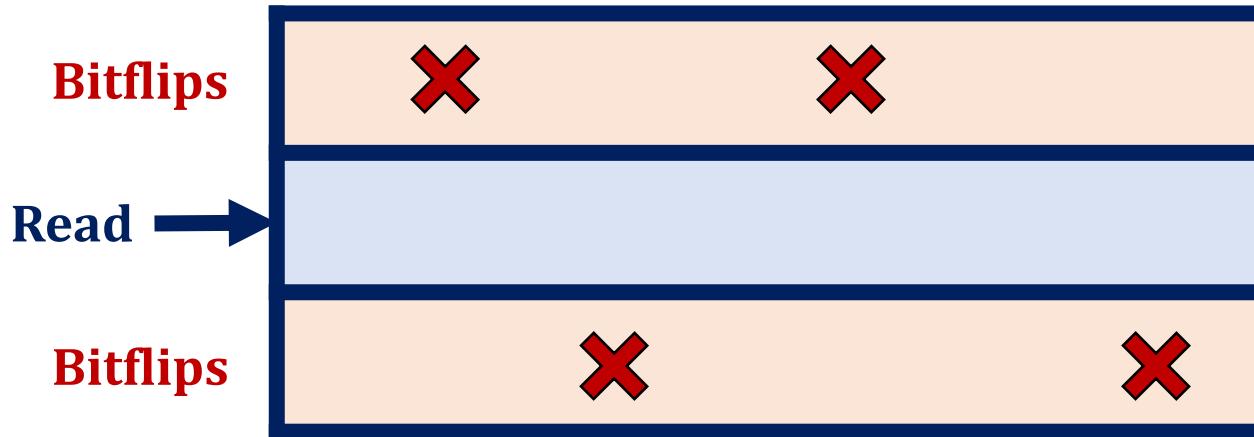


**Take Over** a Computer

An access to one memory address  
should not have **unintended side effects**  
on data stored in **other addresses**

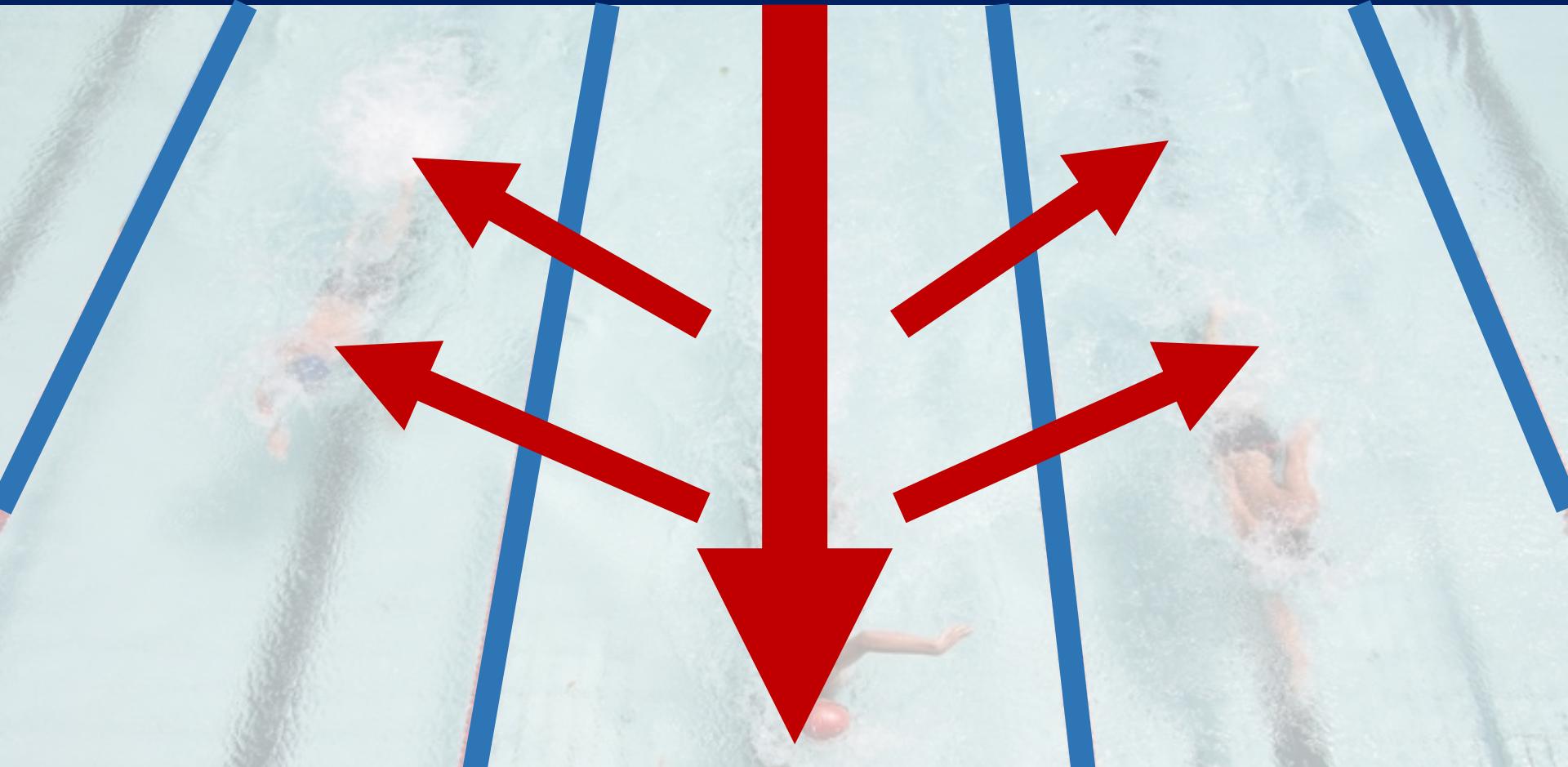
Memory isolation is **difficult in modern memory chips**

# DRAM Read Disturbance



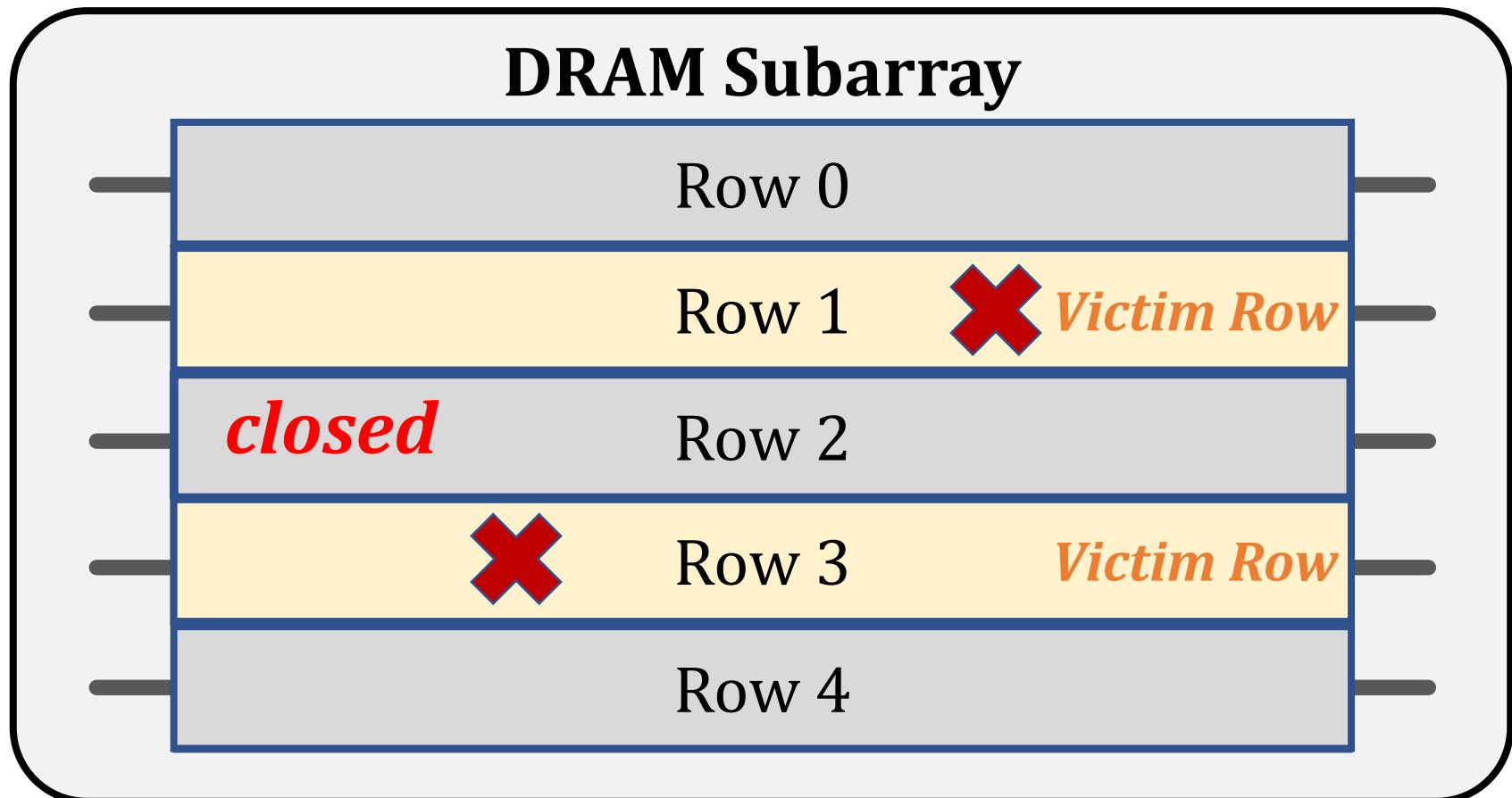
**Reading** from a memory location  
**disturbs** data in **physically nearby** locations

# DRAM Read Disturbance – Swimming Pool Analogy



Swimming **in a lane** disturbs **nearby lanes**

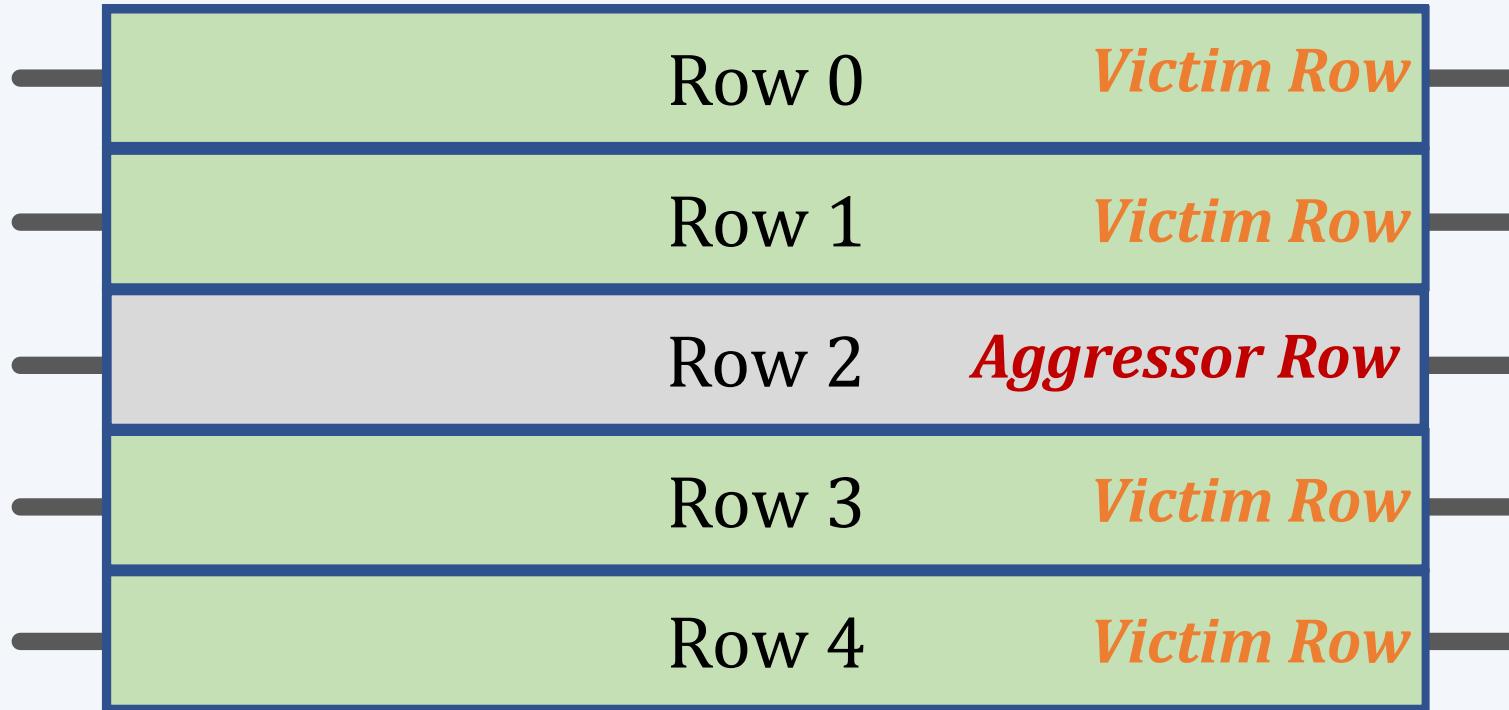
# The RowHammer Vulnerability [Kim+, ISCA'14]



Repeatedly **opening** (activating) and **closing** (precharging) a DRAM row causes **RowHammer bitflips** in nearby cells and breaks **memory isolation**

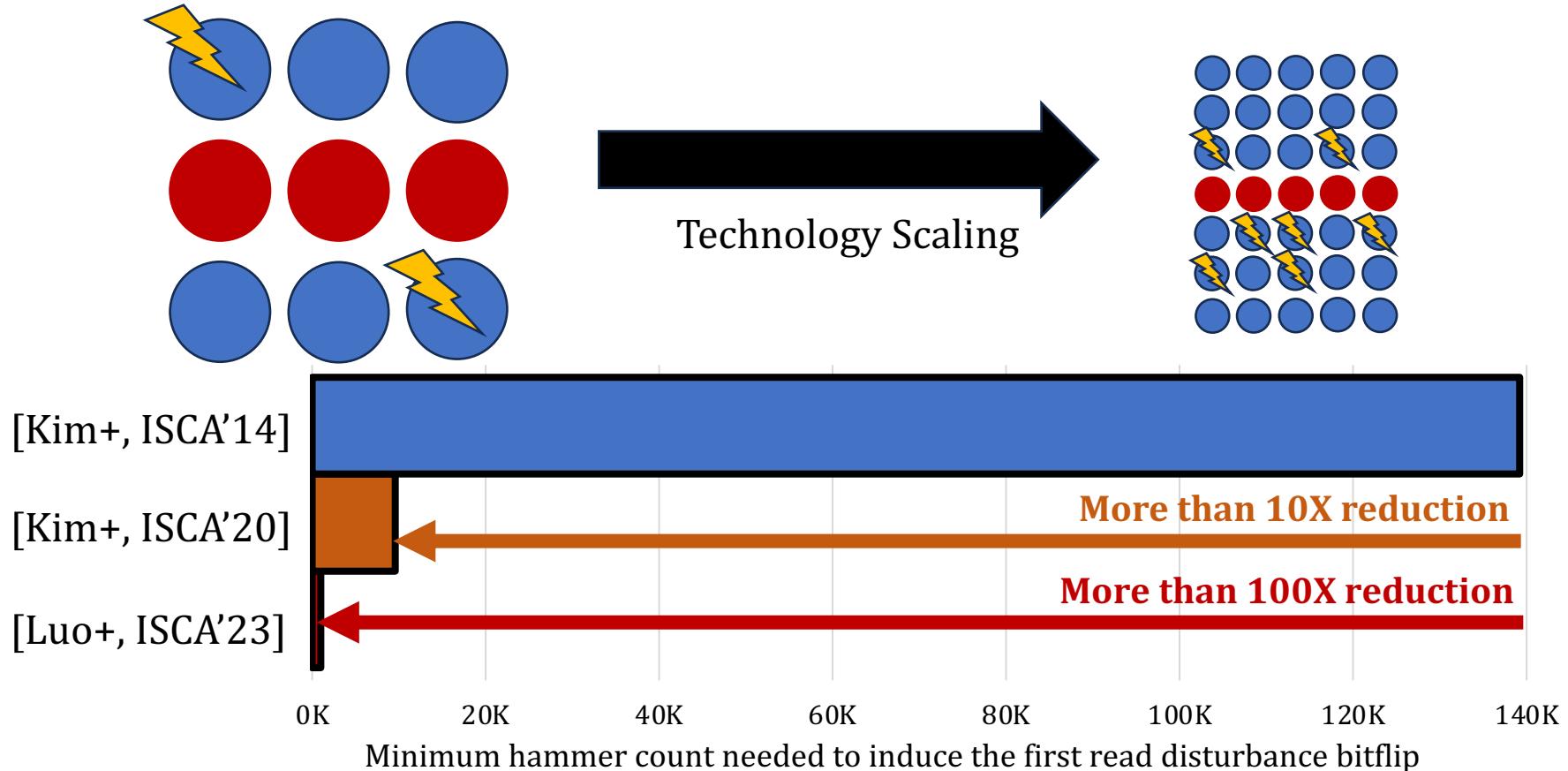
# An Example RowHammer Mitigation: Preventive Refresh

## DRAM Subarray



Refreshing potential victim rows  
mitigates read disturbance bitflips

# Motivation



DRAM chips are increasingly more vulnerable to read disturbance with technology scaling

# Two Main Types of DRAM Refresh

## Periodic Refresh:

- 1 Periodically **restores** the charge which DRAM cells leak **over time** **once** in every **32ms** or **64ms**



## Preventive Refresh:

- 2 Mitigates read disturbance by **refreshing potential victim rows**



## Putting into Perspective:

- Bitflips occur at **~1000 row activations** scattered across **32ms**
- **32ms** is **as large as** to accommodate **640,000 activations**
- An attack needs **only 0.16%** of the **activation budget**
- **640 rows** can be **concurrently hammered**
- Even with a perfect tracker, **640 additional refresh** needed

# Two Main Types of DRAM Refresh

## Periodic Refresh:

An attacker can keep **low profile**  
(e.g., uses 0.16% of activation budget)  
and **induce bitflips**

Mitigates read disturbance by **refreshing potential victim rows**

Preventing bitflips requires  
**tracking many rows and performing many refreshes**

- **640 rows** can be **concurrently hammered**
- Even with a perfect tracker, **640 additional refresh** needed

# How Large is 1000 Activations?

- Bitflips occur at **~1000 activations**
- Mitigation mechanisms trigger **preventive actions** (e.g., preventive refresh) at **~500 activations**
- Is 500 a **distinctive activation count**?
- Benign workloads activate **hundreds of rows** more than **500 times** in a refresh window

## Memory intensive workloads

from SPEC'06, SPEC'17, TPC, YCSB, and MediaBench

Workload	MPKI	ACT-64+	ACT-128+	ACT-512+
429.mcf	68.27	2564	2564	2564
470.lbm	28.09	7089	6596	664
462.libquantum	25.95	1	0	0
549.fotonik3d	25.28	10065	88	0
459.GemsFDTD	24.93	10572	218	0
519.lbm	24.37	5824	5455	2482
434.zeusmp	22.24	11085	4825	292
510.parest	17.79	803	185	94
433.milc	17.22	321	92	0
437.leslie3d	15.82	4678	631	7
483.xalancbmk	13.67	4354	776	113
482.sphinx3	12.59	1385	762	304
505.mcf	11.35	1582	1384	732
471.omnetpp	10.72	1015	419	122
tpch2	9.09	875	307	88
520.omnetpp	9.00	1185	84	32
tpch17	7.43	1196	158	26
473.astar	5.18	5957	22	0
436.cactusADM	4.94	6151	2354	1134
jp2_encode	4.18	0	0	0

Benign workloads **might not be so benign**

# Read Disturbance is an Outstanding Problem

Increasing DRAM chip density  
exacerbates DRAM read disturbance

**Attackers** can keep **low profile**  
(using <0.16% of the row activation budget)

**Benign** applications become **not-so-benign**

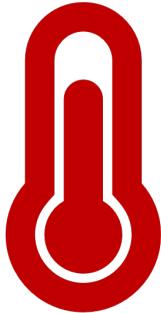
**Efficient and scalable** solutions are needed

# Thesis

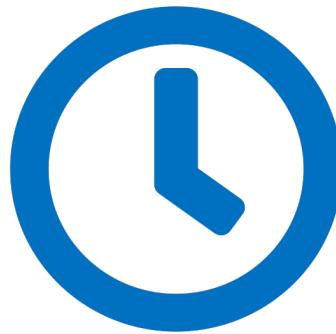
A deeper understanding of  
DRAM read disturbance  
is the key to enable  
**efficient and scalable** solutions

# My Dissertation Works

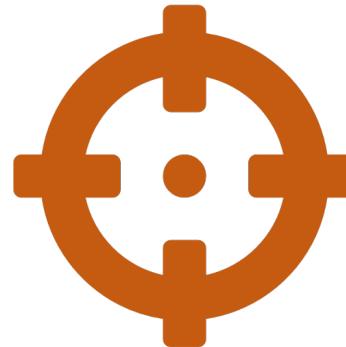
- A deeper look into DRAM read disturbance



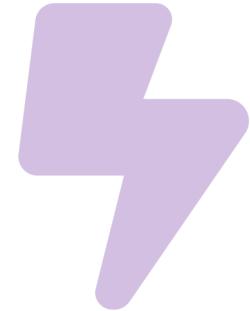
Temperature



Memory access patterns



Victim cell's  
physical location



Voltage

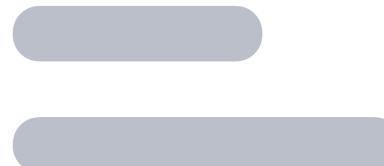
- Solutions to DRAM read disturbance



Leveraging  
Heterogeneity

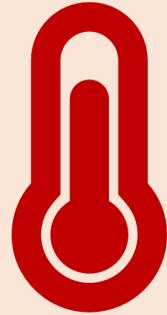


Throttling Unsafe  
Accesses

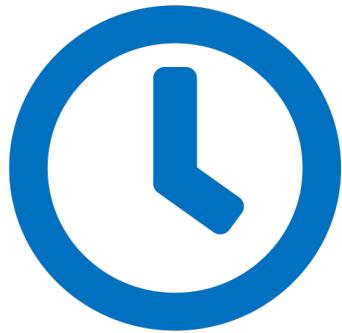


Parallelizing  
Preventive Actions

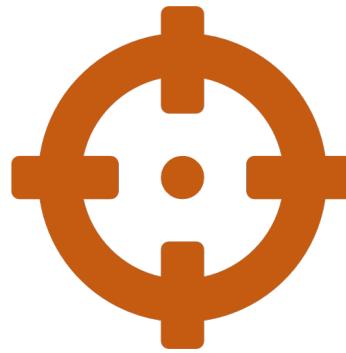
# Our Recent Works



Temperature



Memory access patterns



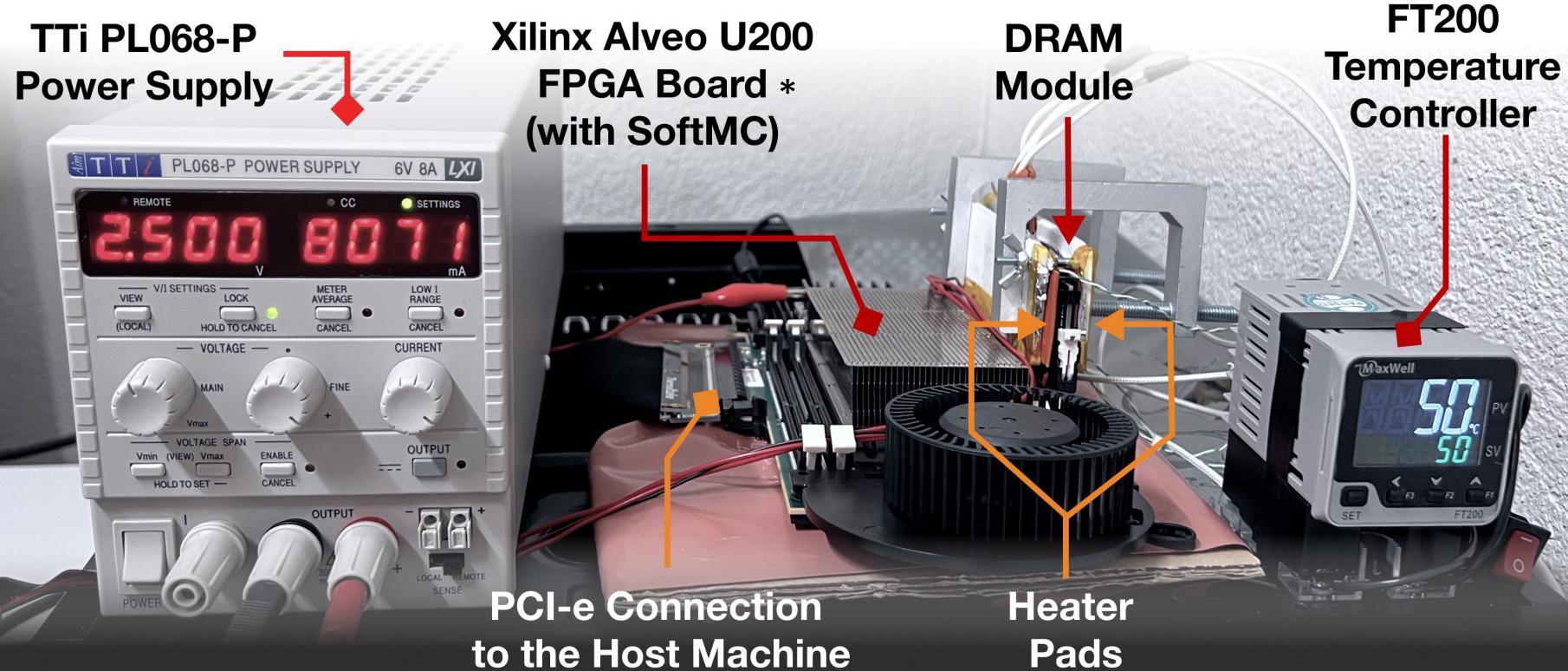
Victim cell's  
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Leveraging  
Heterogeneity

# DRAM Testing Infrastructure

## DRAM Bender on a Xilinx Virtex UltraScale+ XCU200



Fine-grained control over DRAM commands, timing parameters ( $\pm 1.5\text{ns}$ ), temperature ( $\pm 0.5^\circ\text{C}$ ), and wordline voltage ( $\pm 1\text{mV}$ )

# DRAM Chips Tested

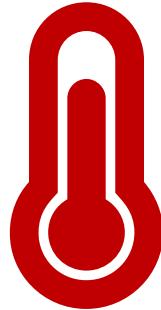
Mfr.	DDR4 DIMMs	DDR3 SODIMMs	# Chips	Density	Die	Org.
A (Micron)	9	1	144 (8)	8Gb (4Gb)	B (P)	x4 (x8)
B (Samsung)	4	1	32 (8)	4Gb (4Gb)	F (Q)	x8 (x8)
C (SK Hynix)	5	1	40 (8)	4Gb (4Gb)	B (B)	x8 (x8)
D (Nanya)	4	-	32 (-)	8Gb (-)	C (-)	x8 (-)

Two DRAM standards

4 Major Manufacturers

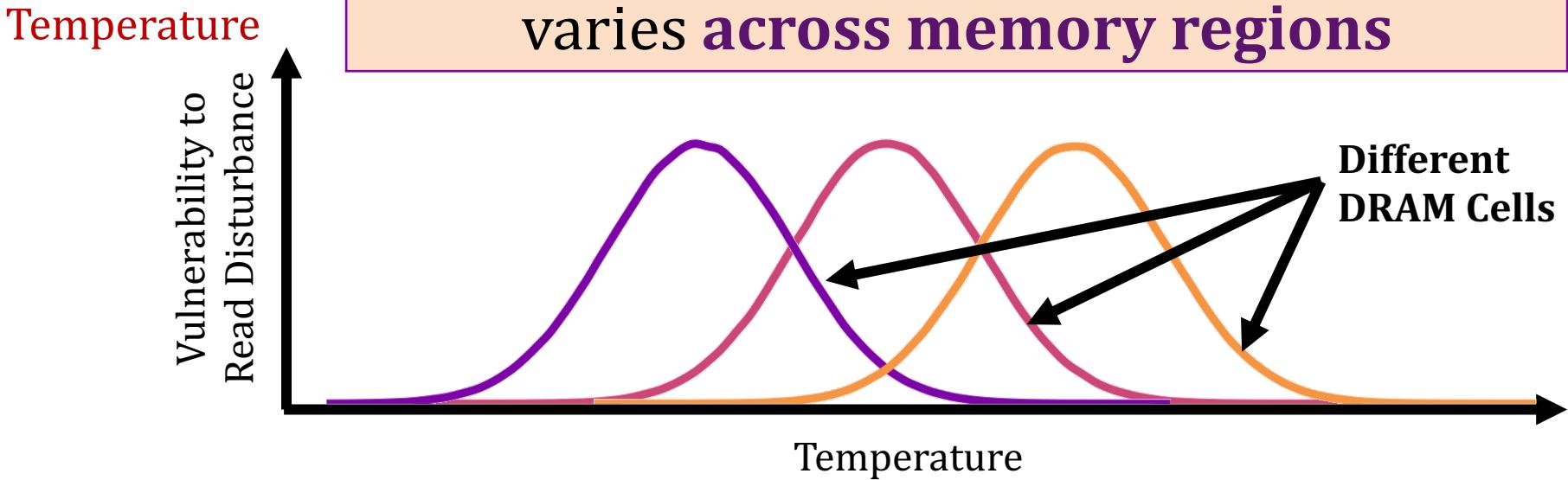
272 DRAM Chips in total

# Key Findings: Temperature



DRAM read disturbance is more effective  
**within a temperature range**

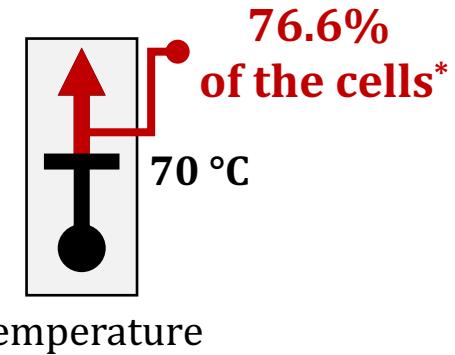
Vulnerable temperature range  
varies **across memory regions**



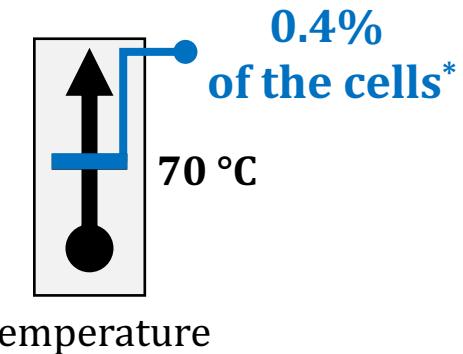
A DRAM cell should be tested  
at **each possible** operating temperature

# Example Attack Improvement: Temperature-Dependent Trigger

1. Identify **abnormal increase** in temperature to attack a data center **during its peak hours**



2. Precisely measure the temperature **to trigger an attack** exactly at the desired temperature



\*Example fraction values from SK Hynix modules

# Contributions to Understanding RowHammer

- Lois Orosa\*, **Abdullah Giray Yağlıkçı\***, Haocong Luo, Ataberk Olgun, Jisung Park, Hasan Hassan, Minesh Patel, Jeremie S. Kim, and Onur Mutlu,  
"A Deeper Look into RowHammer's Sensitivities: Experimental Analysis of Real DRAM Chips and Implications on Future Attacks and Defenses"  
*Proceedings of the 54th International Symposium on Microarchitecture (MICRO)*, Virtual, October 2021.  
[[Slides \(pptx\)](#) ([pdf](#))] [[Talk Video](#) (21 minutes)]  
[[Short Talk Slides \(pptx\)](#) ([pdf](#))]  
[[Lightning Talk Slides \(pptx\)](#) ([pdf](#))] [[Lightning Talk Video](#) (1.5 minutes)]  
[[arXiv version](#)]

## A Deeper Look into RowHammer's Sensitivities: Experimental Analysis of Real DRAM Chips and Implications on Future Attacks and Defenses

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ETH Zürich

Onur Mutlu  
ETH Zürich

# A Follow-Up Work: SpyHammer [Orosa+, arXiv'22]

## SpyHammer: Using RowHammer to Remotely Spy on Temperature

Lois Orosa<sup>1,2</sup>

Ulrich Rührmair<sup>3,4</sup>

A. Giray Yağlıkçı<sup>1</sup>

Haocong Luo<sup>1</sup>

Ataberk Olgun<sup>1</sup>

Patrick Jattke<sup>1</sup> Minesh Patel<sup>1</sup>

Jeremie Kim<sup>1</sup>

Kaveh Razavi<sup>1</sup>

Onur Mutlu<sup>1</sup>

<sup>1</sup>ETH Zürich

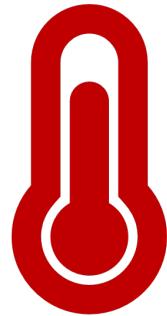
<sup>2</sup>Galicia Supercomputing Center (CESGA)

<sup>3</sup>LMU München

<sup>4</sup>University of Connecticut

<https://arxiv.org/pdf/2210.04084.pdf>

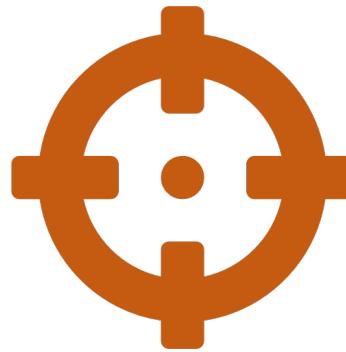
# Our Recent Works



Temperature



Memory access patterns



Victim cell's  
physical location



Leveraging  
Heterogeneity

# Key Findings: Memory Access Patterns



Read disturbance is **more effective** if the **read memory region** stays **active longer**

Memory Access  
Patterns

State-of-the-Art

Our Finding

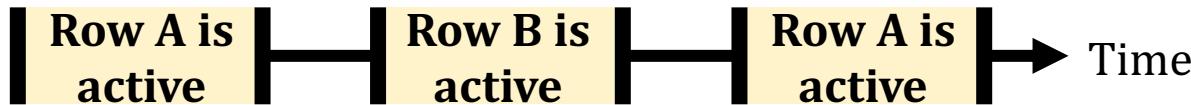


Minimum hammer count to induce the first bitflip

**Fewer reads** cause a **more significant** read disturbance when the read memory region stays **active longer**

# Example Attack Improvement: Bypassing Defenses with Aggressor Row Active Time

Activating aggressor rows **as frequently as possible**:



Keeping the aggressor rows **active for a longer time**:



**Reduces** the minimum activation count to induce a bit flip **by 36%**

**Bypasses defenses** that do not account for this reduction

# Contributions to Understanding RowHammer

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# RowPress [Luo+, ISCA 2023] (Follow up of our analysis)

- Haocong Luo, Ataberk Olgun, Giray Yaglikci, Yahya Can Tugrul, Steve Rhyner, M. Banu Cavlak, Joel Lindegger, Mohammad Sadrosadati, and Onur Mutlu,  
**"RowPress: Amplifying Read Disturbance in Modern DRAM Chips"**

*Proceedings of the 50th International Symposium on Computer Architecture (ISCA), Orlando, FL, USA, June 2023.*

[[Slides \(pptx\)](#) [\(pdf\)](#)]

[[Lightning Talk Slides \(pptx\)](#) [\(pdf\)](#)]

[[Lightning Talk Video \(3 minutes\)](#)]

[[RowPress Source Code and Datasets](#) (*Officially Artifact Evaluated with All Badges*)]

***Officially artifact evaluated as available, reusable and reproducible.***

***Best artifact award at ISCA 2023.***



## RowPress: Amplifying Read-Disturbance in Modern DRAM Chips

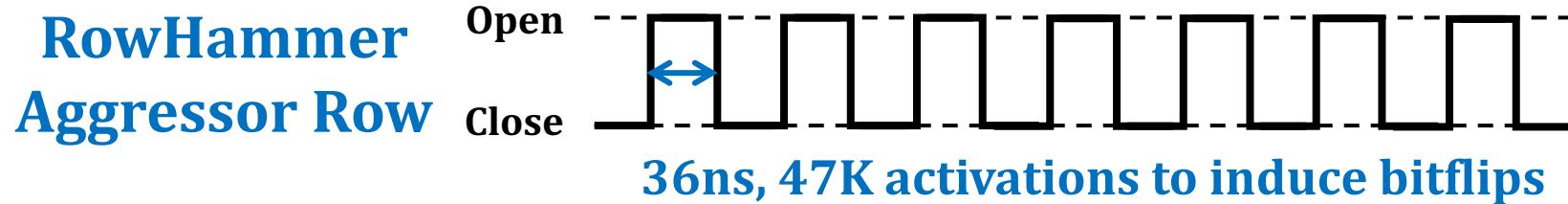
Haocong Luo   Ataberk Olgun   A. Giray Yağlıkçı   Yahya Can Tuğrul   Steve Rhyner  
Meryem Banu Cavlak   Joël Lindegger   Mohammad Sadrosadati   Onur Mutlu

ETH Zürich

# RowPress vs. RowHammer

Instead of using a high activation count,

- ☛ increase the time that the aggressor row stays open



We observe bitflips even with **ONLY ONE activation** in extreme cases where the row stays open for 30ms

# RowPress [Luo+, ISCA 2023]

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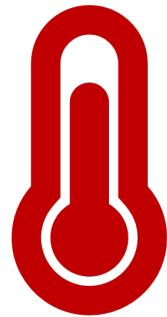


## RowPress: Amplifying Read-Disturbance in Modern DRAM Chips

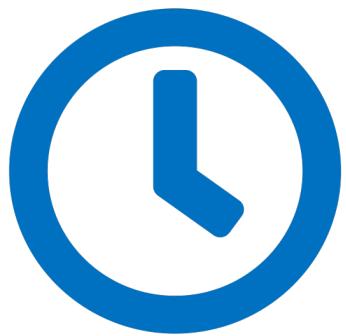
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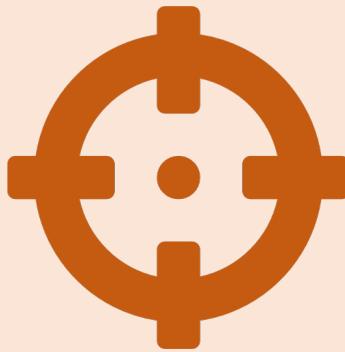
# Our Recent Works



Temperature



Memory access patterns



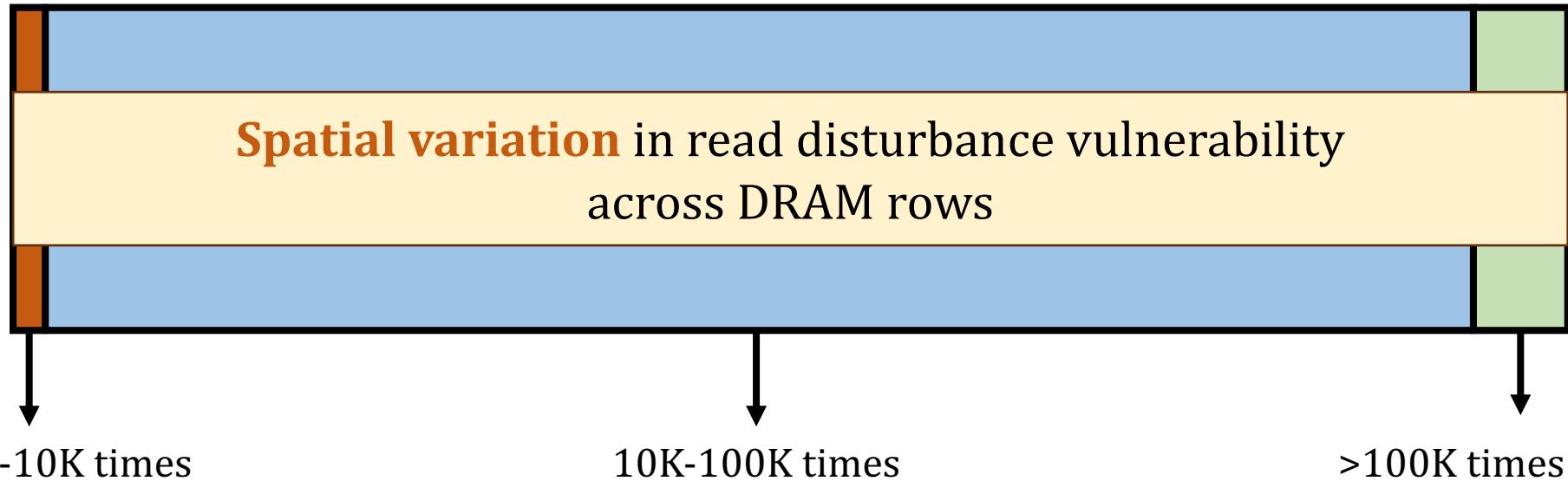
Victim cell's  
physical location



Leveraging  
Heterogeneity

# Spatial Variation in Read Disturbance Vulnerability Across DRAM Rows

- To induce a **read disturbance bitflip**, one should access a row



- Read disturbance solutions are configured **for the worst row**
- Not all rows** need the **same level** of protection
- Read disturbance solutions incur **large performance overheads** due to **overprotecting many rows**

# Tested DRAM Chips

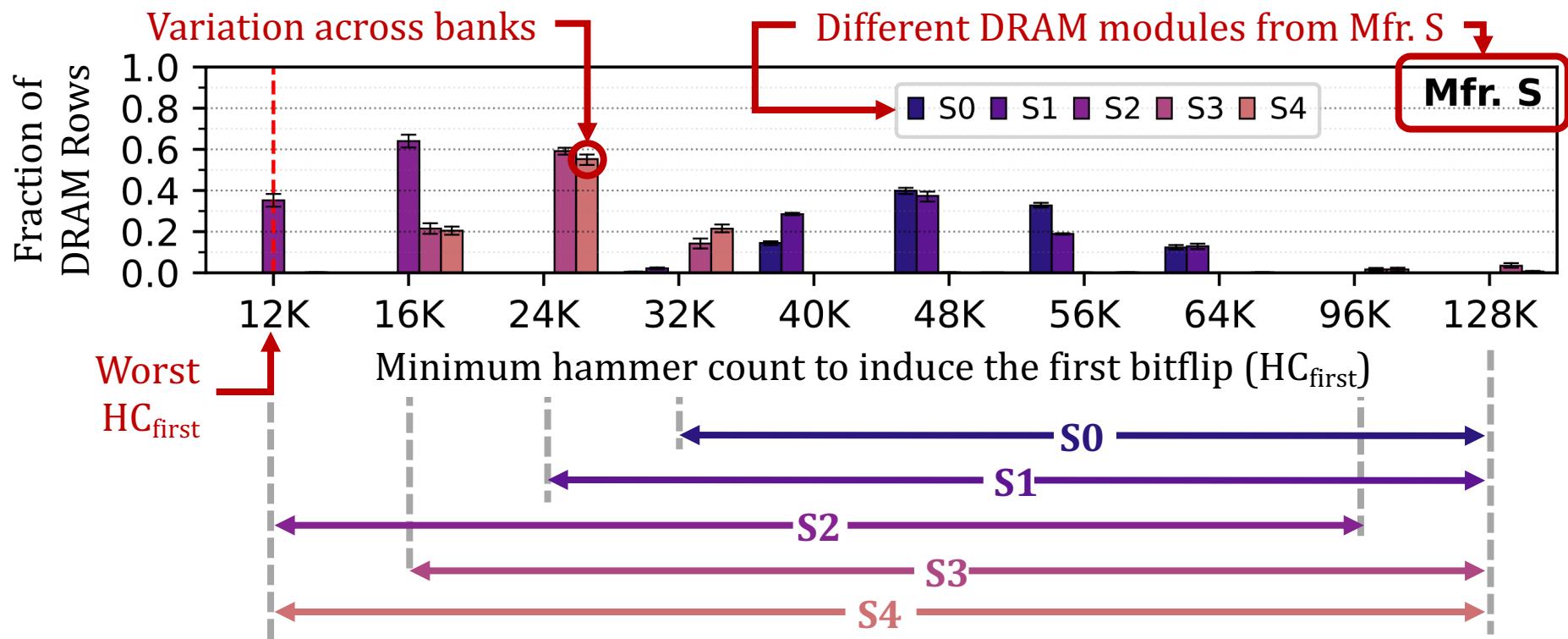
144 DRAM chips from SK Hynix, Micron, and Samsung

Mfr.	DIMM ID	# of Chips	Density Die Rev.	Chip Org.	Date (ww-yy)
Mfr. H (SK Hynix)	H0	8	16Gb – A	x8	51-20
	H1, H2, H3	3 × 8	16Gb – C	x8	48-20
	H4	8	8Gb – D	x8	48-20
Mfr. M (Micron)	M0	4	16Gb – E	x16	46-20
	M1, M3	2 × 16	8Gb – B	x4	N/A
	M2	16	16Gb – E	x4	14-20
	M4	4	16Gb – B	x16	26-21
Mfr. S (Samsung)	S0, S1	2 × 8	8Gb – B	x8	52-20
	S2	8	8Gb – B	x8	10-21
	S3	8	4Gb – F	x8	N/A
	S4	16	8Gb – C	x4	35-21

# Key Takeaway from Real Chip Experiments

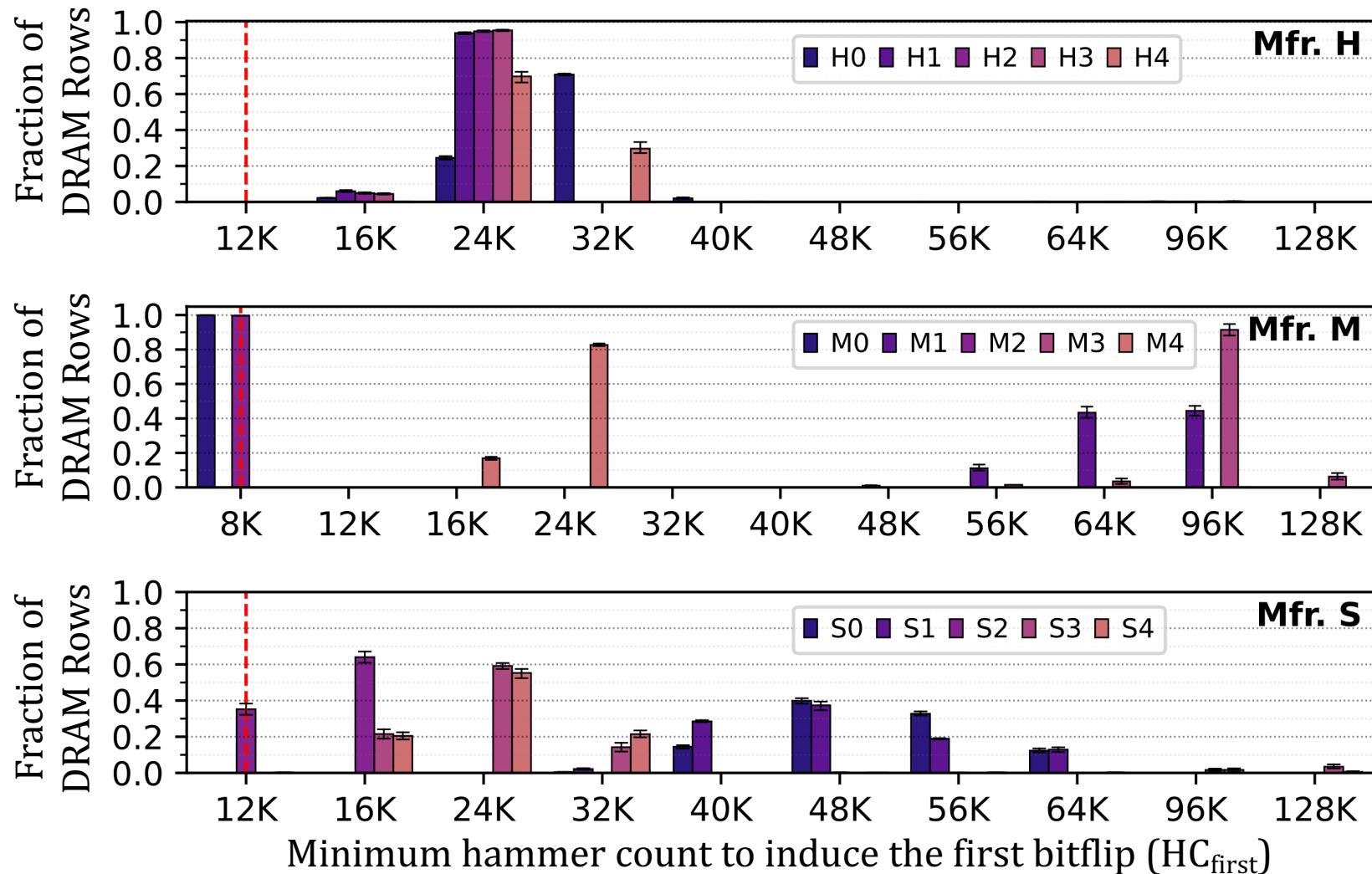
Read disturbance vulnerability varies  
**significantly** and **irregularly**  
across DRAM rows

# Spatial Variation in the Minimum Hammer Count to Induce the First Bitflip across DRAM Rows

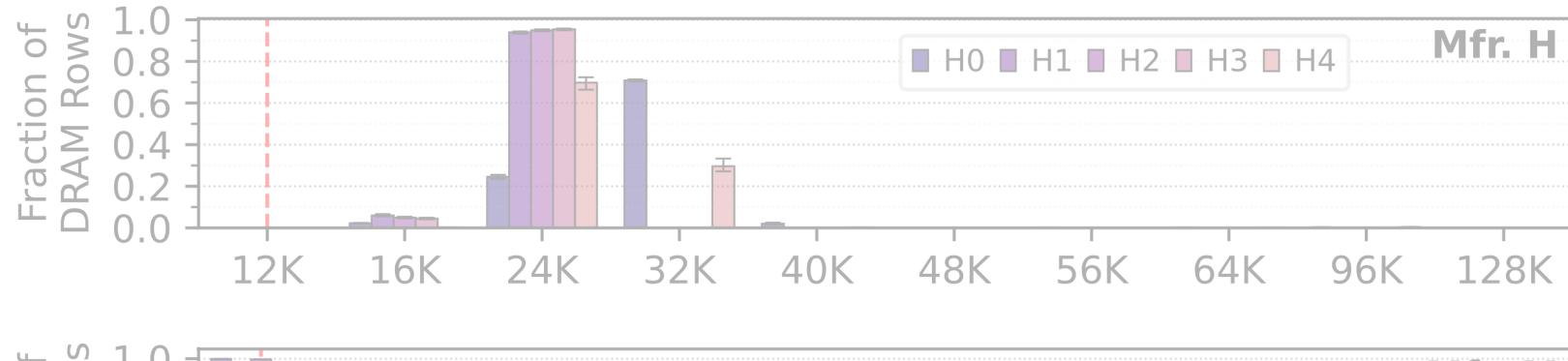


The minimum hammer count to induce the first bitflip  
**significantly varies across rows** in a DRAM bank

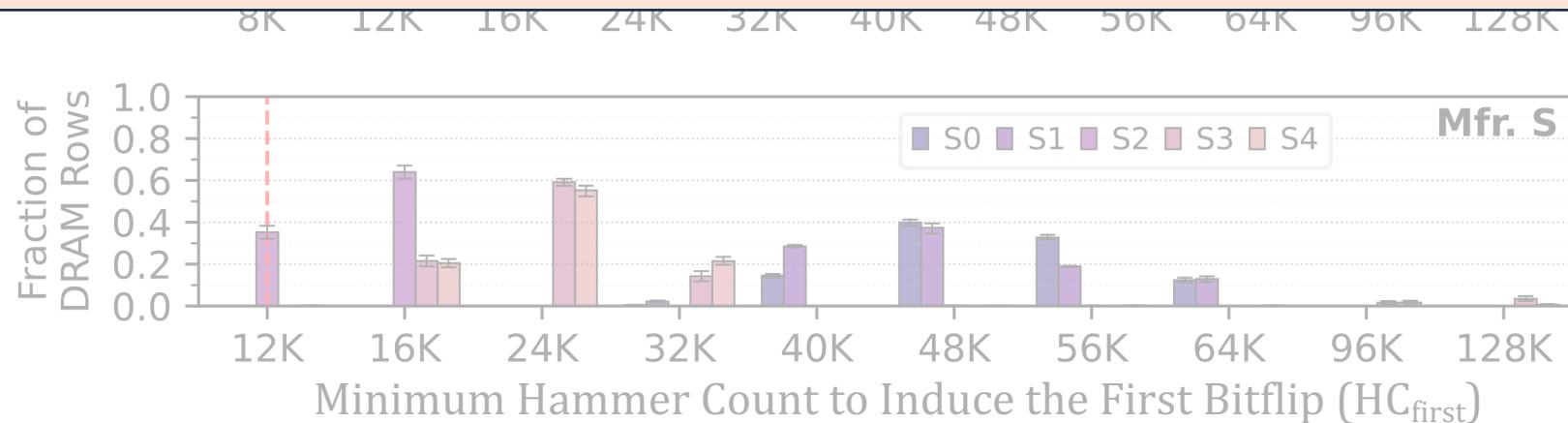
# Spatial Variation in the Minimum Hammer Count to Induce the First Bitflip across DRAM Rows



# Spatial Variation in the Minimum Hammer Count to Induce the First Bitflip across DRAM Rows



The minimum hammer count to induce the first bitflip **significantly varies across rows** in a DRAM bank



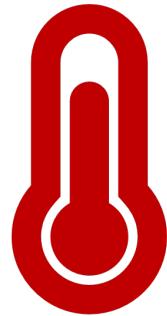
# More Detailed Information in the Extended Version

Table 5: Characteristics of the tested DDR4 DRAM modules.

Module Label	Module Vendor	Module Identifier Chip Identifier	Freq (MT/s)	Mfr. Date ww-yy	Chip Den.	Die Rev.	Chip Org.	Num. of Rows per Bank	$HC_{first}$	Min.	Avg.	Max.
H0	SK Hynix	HMAA4GU6AJR8N-XN [287] H5ANAG8NAJR-XN [288]	3200	51-20	16Gb	A	×8	128K	16K	46.2K	96K	
H1		HMAA4GU7CJR8N-XN [289] H5ANAG8NCJR-XN [231]	3200	51-20	16Gb	C	×8	128K	12K	54.0K	128K	
H2		HMAA4GU7CJR8N-XN [289] H5ANAG8NCJR-XN [231]	3200	36-21	16Gb	C	×8	128K	12K	55.4K	128K	
H3		HMAA4GU7CJR8N-XN [289] H5ANAG8NCJR-XN [231]	3200	36-21	16Gb	C	×8	128K	12K	57.8K	128K	
H4		KSM32RD8/16HDR [290] H5AN8G8NDJR-XNC [232]	3200	48-20	8Gb	D	×8	64K	16K	38.1K	96K	
M0	Micron	MTA4ATF1G64HZ-3G2E1 [233] MT40A1G16KD-062E [234]	3200	46-20	16Gb	E	×16	128K	8K	24.5K	40K	
M1		MTA18ASF2G72PZ-2G3B1QK [235] MT40A2G4WE-083E:B [291]	2400	N/A	8Gb	B	×4	128K	40K	64.5K	96K	
M2		MTA36ASF8G72PZ-2G9E1TI [236] MT40A4G4JC-062E:E [292]	2933	14-20	16Gb	E	×4	128K	8K	28.6K	48K	
M3		MTA18ASF2G72PZ-2G3B1QK [235] MT40A2G4WE-083E:B [291]	2400	36-21	8Gb	B	×4	128K	56K	90.0K	128K	
M4		MTA4ATF1G64HZ-3G2B2 [237] MT40A1G16RC-062E:B [293]	3200	26-21	16Gb	B	×16	128K	12K	42.2K	96K	
S0	Samsung	M393A1K43BB1-CTD [294] K4A8G085WB-BCTD [230]	2666	52-20	8Gb	B	×8	64K	32K	57.0K	128K	
S1		M393A1K43BB1-CTD [294] K4A8G085WB-BCTD [230]	2666	52-20	8Gb	B	×8	64K	24K	59.8K	128K	
S2		M393A1K43BB1-CTD [294] K4A8G085WB-BCTD [230]	2666	10-21	8Gb	B	×8	64K	12K	42.7K	96K	
S3		F4-2400C17S-8GNT [295] K4A4G085WF-BCTD [296]	2400	04-21	4Gb	F	×8	32K	16K	59.2K	128K	
S4		M393A2K40CB2-CTD [229] K4A8G045WC-BCTD [297]	2666	35-21	8Gb	C	×4	128K	12K	55.4K	128K	

<https://arxiv.org/pdf/2402.18652.pdf>

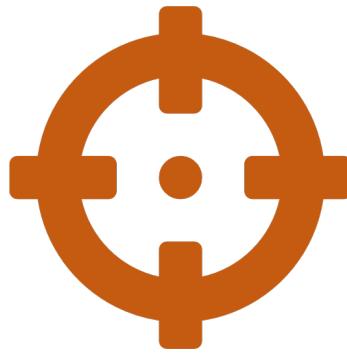
# Our Recent Works



Temperature



Memory access patterns



Victim cell's  
physical location



Leveraging  
Heterogeneity

# Motivation

**DRAM read disturbance worsens  
as DRAM chip density increases**

Existing solutions become **more aggressive**

**Overprotecting many rows** significantly  
increases their **performance overhead**

# Motivation

Can we **leverage the variation** in  
read disturbance **vulnerability**  
across **DRAM rows**

to **reduce the performance overheads**  
of existing read disturbance solutions?

# Svärd: Spatial Variation-Aware Read Disturbance Defenses

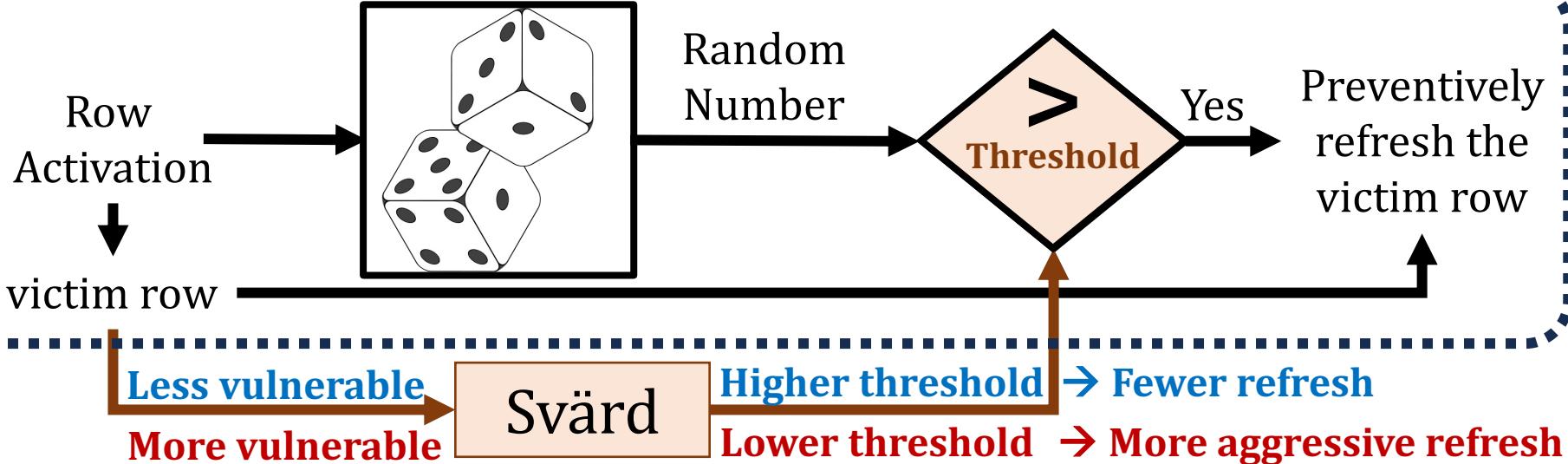
- Dynamically tunes the aggressiveness of existing solutions to **the victim row's read disturbance vulnerability**
- Svärd performs **fewer preventive actions (e.g., refresh)** for rows that are **less vulnerable to read disturbance**
- Svärd performs **more preventive actions (e.g., refresh)** for rows that are **more vulnerable to read disturbance**



Svärd significantly **reduces**  
**the performance overhead** of existing solutions

# Svärd: Integration with Existing Read Disturbance Solutions

## PARA: Probabilistic Row Activation [Kim+, ISCA'14]



Svärd dynamically tunes PARA's threshold to the victim row's vulnerability

Svärd works with many read disturbance solutions, including:

**BlockHammer**  
[Yaglikci+, HPCA'21]

**Hydra**  
[Qureshi+, ISCA'22]

**RRS**  
[Saileshwar+, ASPLOS'22]

**AQUA**  
[Saxena+, MICRO'22]

# Svärd: Metadata Management

- Classifies DRAM rows into **several vulnerability bins**  
Maintains **a few (e.g., four) bits** per DRAM row
- Implemented **where the read disturbance solution is**
- Memory controller-based implementation:  
Metadata can be maintained in
  - SRAM table in the memory controller
  - Data integrity bits in the DRAM chip
  - ...
- In-DRAM implementation:  
Metadata can be maintained in
  - DRAM rows
  - Separate DRAM array
  - ...

# Performance Evaluation

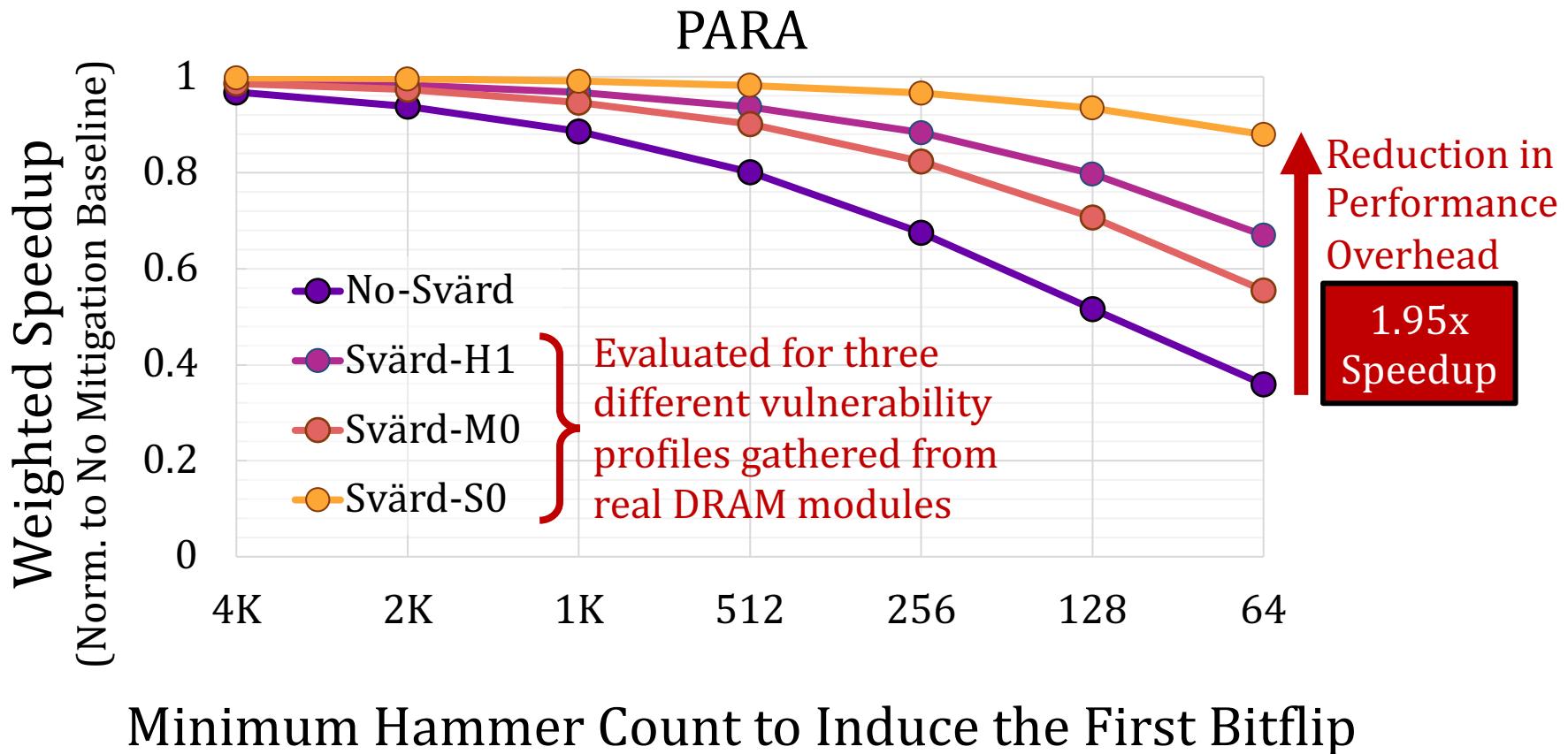
- Cycle-level simulations using **Ramulator 2.0** [Luo+, CAL 2023]  
<https://github.com/CMU-SAFARI/ramulator2>

- **System Configuration:**

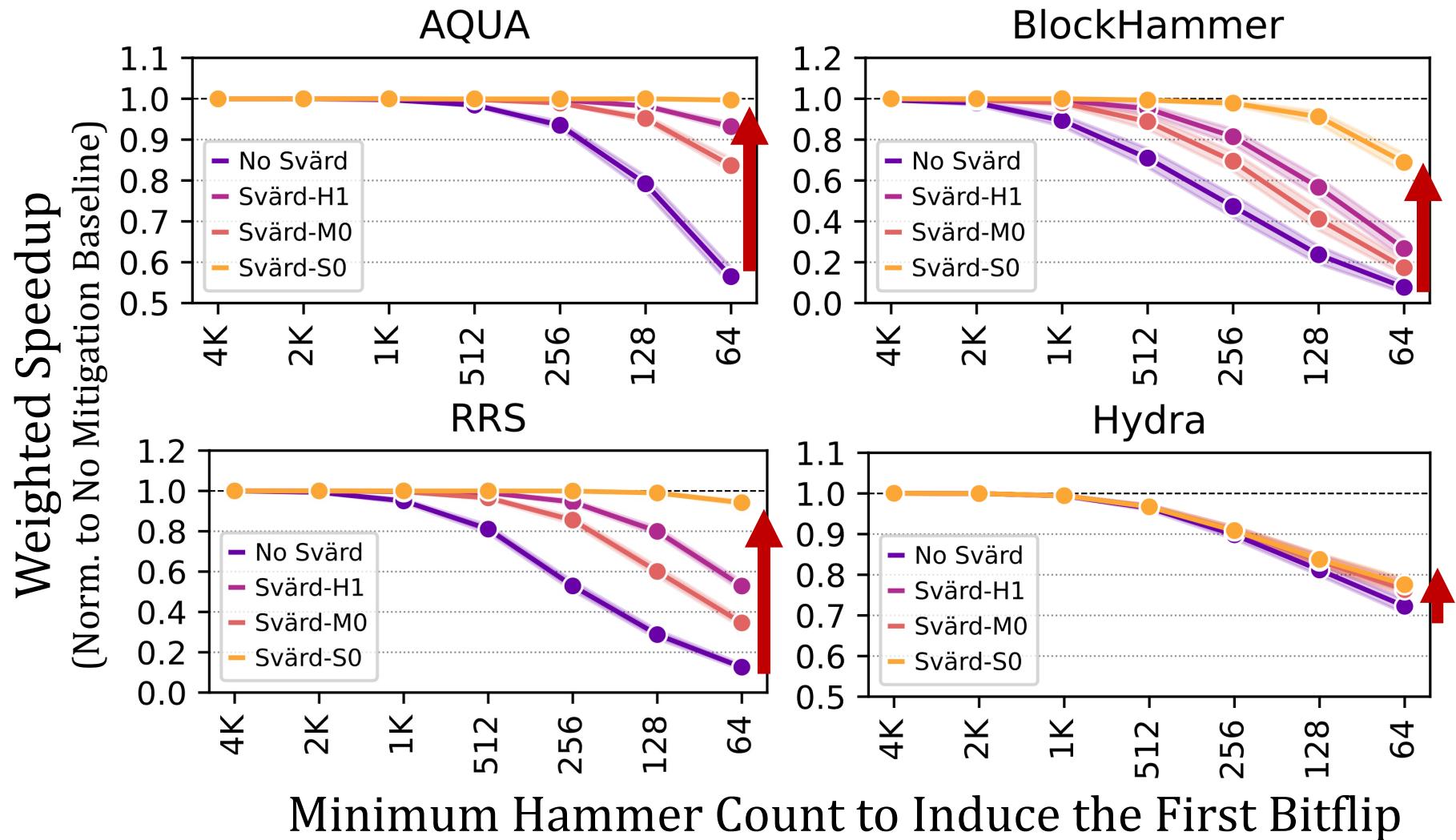
<b>Processor</b>	3.2 GHz, 8 core, 4-wide issue, 128-entry instr. window
<b>Last-Level Cache</b>	64-byte cache line, 8-way set-associative, 8 MB
<b>Memory Scheduler</b>	FR-FCFS
<b>Address Mapping</b>	Minimalistic Open Pages
<b>Main Memory</b>	DDR4, 4 bank group, 4 banks per bank group (16 banks per rank)

- **Workloads:** 120 different **8-core** multiprogrammed workloads from **SPEC CPU2006**, **SPEC CPU2017**, **TPC**, **MediaBench**, and **YCSB** benchmark suites
- Integrated with **AQUA**, **BlockHammer**, **PARA**, **Hydra**, and **RRS**
- **HC<sub>first</sub>:** {4K, 2K, 1K, 512, 256, 128, 64} hammers  
Minimum **hammer count** needed to induce **the first bitflip**

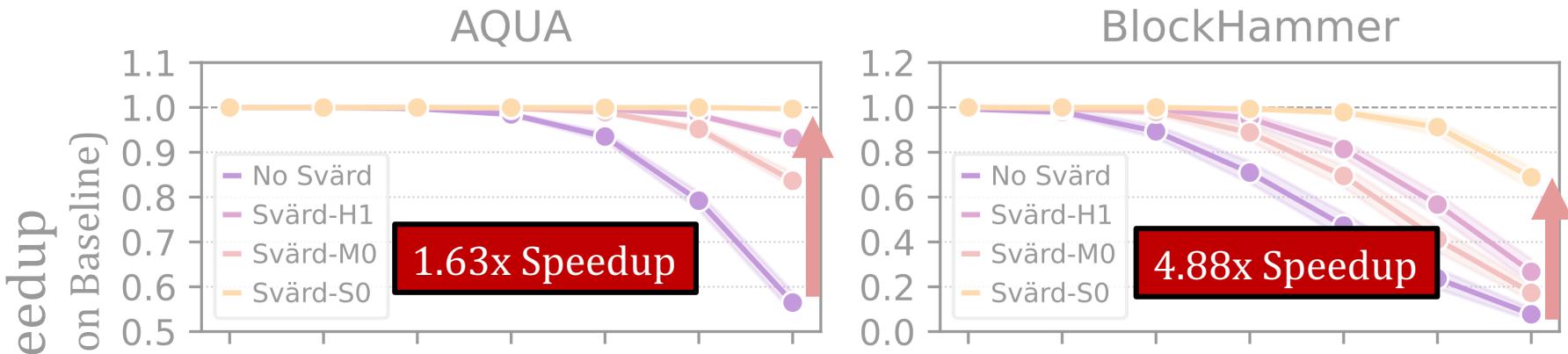
# Implications on Future Solutions



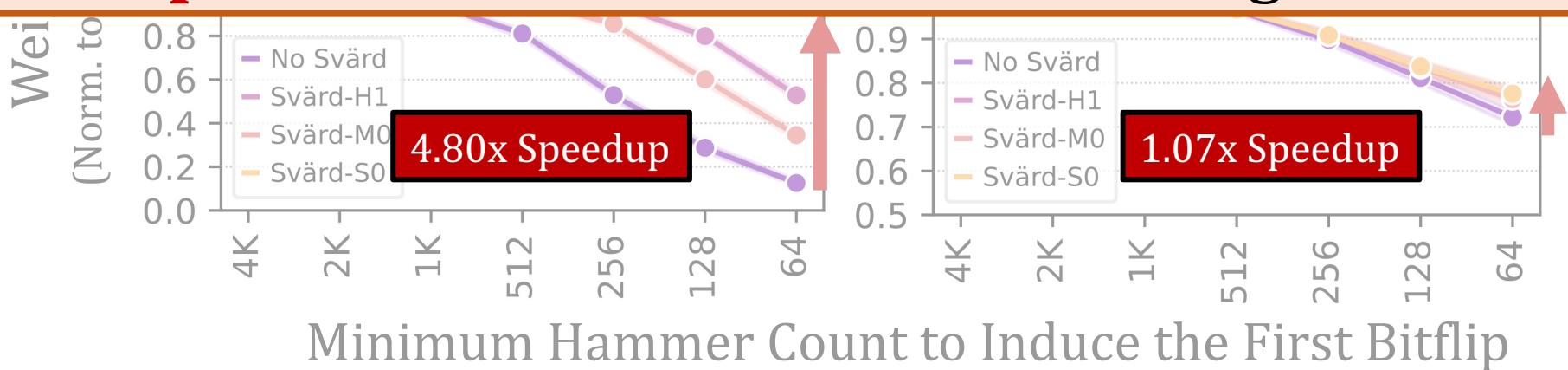
# Implications on Future Solutions



# Implications on Future Solutions



Svärd significantly **reduces**  
the performance overhead of existing solutions



# Spatial Variation-Aware Read Disturbance Defenses

- The first rigorous experimental study on the spatial variation of DRAM read disturbance across DRAM rows
  - 144 DDR4 DRAM chips from three major manufacturers
  - Characterize all rows in a bank and four banks in a DRAM chip

Read disturbance vulnerability varies **significantly** and **irregularly** across DRAM rows

- Svärd: Spatial Variation-Aware Read Disturbance Defenses
  - Dynamically tunes a solution's aggressiveness (e.g., perform more/less refresh) to the victim row's vulnerability to DRAM read disturbance
  - Implemented either in the memory controller or in the DRAM chip

Svärd significantly **reduces**  
**the performance overhead** of existing solutions

Svärd may present itself to any worthy read disturbance solution



# Enabling Efficient and Scalable Solutions

## Spatial Variation-Aware Read Disturbance Defenses: Experimental Analysis of Real DRAM Chips and Implications on Future Solutions

Abdullah Giray Yağlıkçı      Geraldo F. Oliveira      Yahya Can Tuğrul  
İsmail Emir Yüksel      Ataberk Olgun      Haocong Luo      Onur Mutlu  
ETH Zürich

*Read disturbance in modern DRAM chips is a widespread phenomenon and is reliably used for breaking memory isolation, a fundamental building block for building robust systems. RowHammer and RowPress are two examples of read disturbance in DRAM where repeatedly accessing (hammering) or keeping active (pressing) a memory location induces bitflips in other memory locations. Unfortunately, shrinking technology node size exacerbates read disturbance in DRAM chips over generations. As a result, existing defense mechanisms suffer from significant performance and energy overheads, limited effectiveness, or prohibitively high hardware complexity.*

*In this paper, we tackle these shortcomings by leveraging the spatial variation in read disturbance across different memory locations in real DRAM chips. To do so, we 1) present the*

Many prior works demonstrate attacks on a wide range of systems that exploit read disturbance to escalate privilege, leak private data, and manipulate critical application outputs [1, 3–53, 71–84]. To make matters worse, various experimental studies [1, 1, 25, 33, 36, 37, 61, 70] find that newer DRAM chip generations are more susceptible to read disturbance. For example, chips manufactured in 2018-2020 can experience RowHammer bitflips at an order of magnitude fewer row activations compared to the chips manufactured in 2012-2013 [61]. As read disturbance in DRAM chips worsens, ensuring robust (i.e., reliable, secure, and safe) operation becomes more expensive in terms of performance overhead, energy consumption, and hardware complexity [61, 85, 86]. Therefore, it is critical to understand the read disturbance vulnerabilities

<https://arxiv.org/pdf/2402.18652.pdf>

# Current and Future Challenges



Reliability



Performance



Fairness

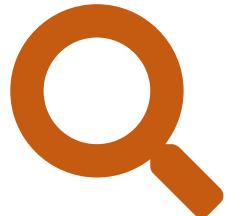


Energy  
Efficiency

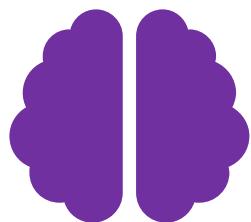
While the memory systems

1. **scale-up and are shared** across many users  
(e.g., disaggregated memory systems)
2. **scale-down** in manufacturing technology node size
3. support **processing near/using memory**

# Future Research for Better Memory Systems



Deeper Understanding of  
Physics and Vulnerabilities



Flexible and Intelligent Memory  
Chips, Interfaces, Controllers

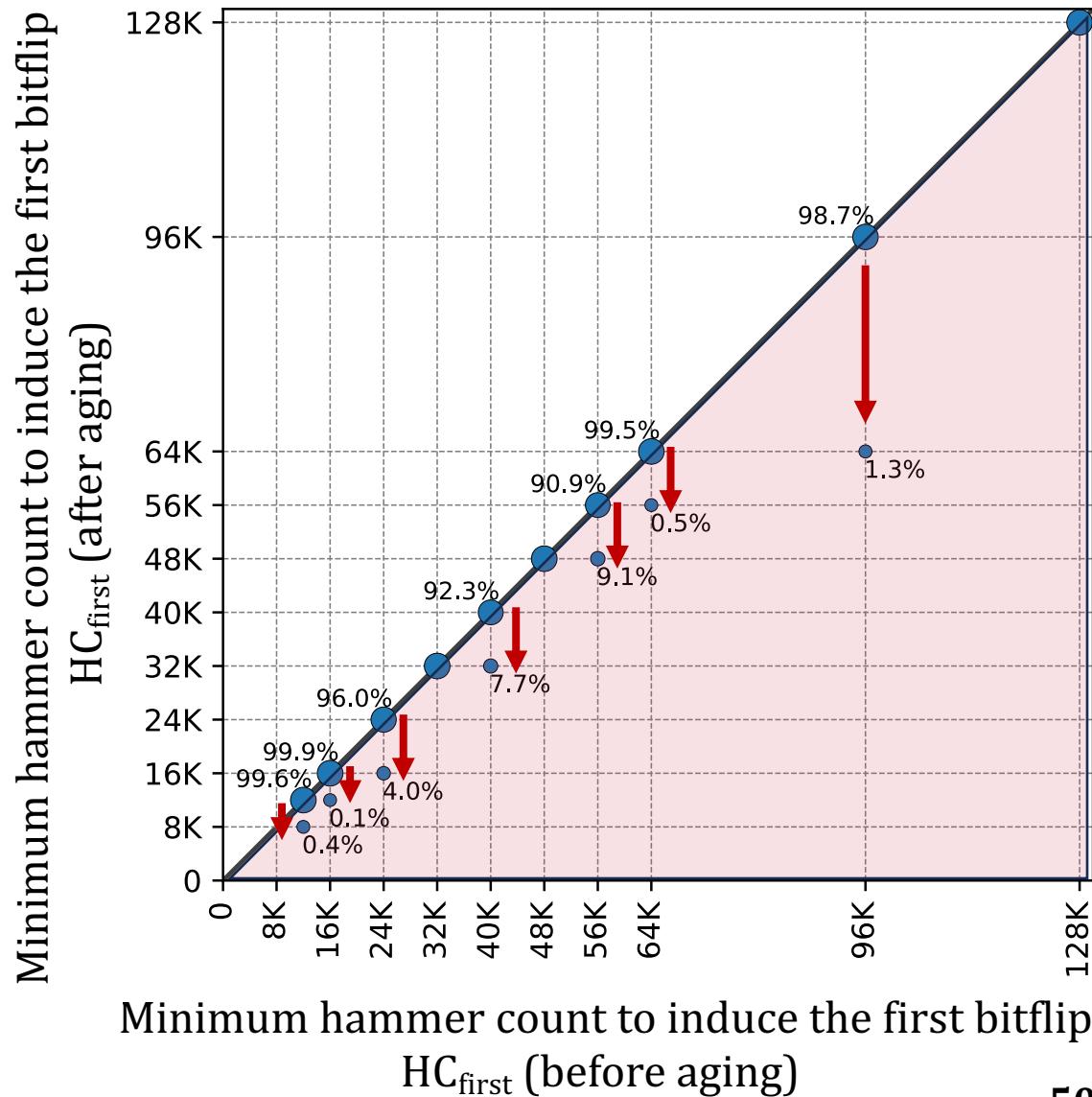


Cross-Layer  
Communication

# Deeper Understanding of Physics and Vulnerabilities

- The effect of **aging**  
Preliminary data on aging via 68-day of continuous hammering

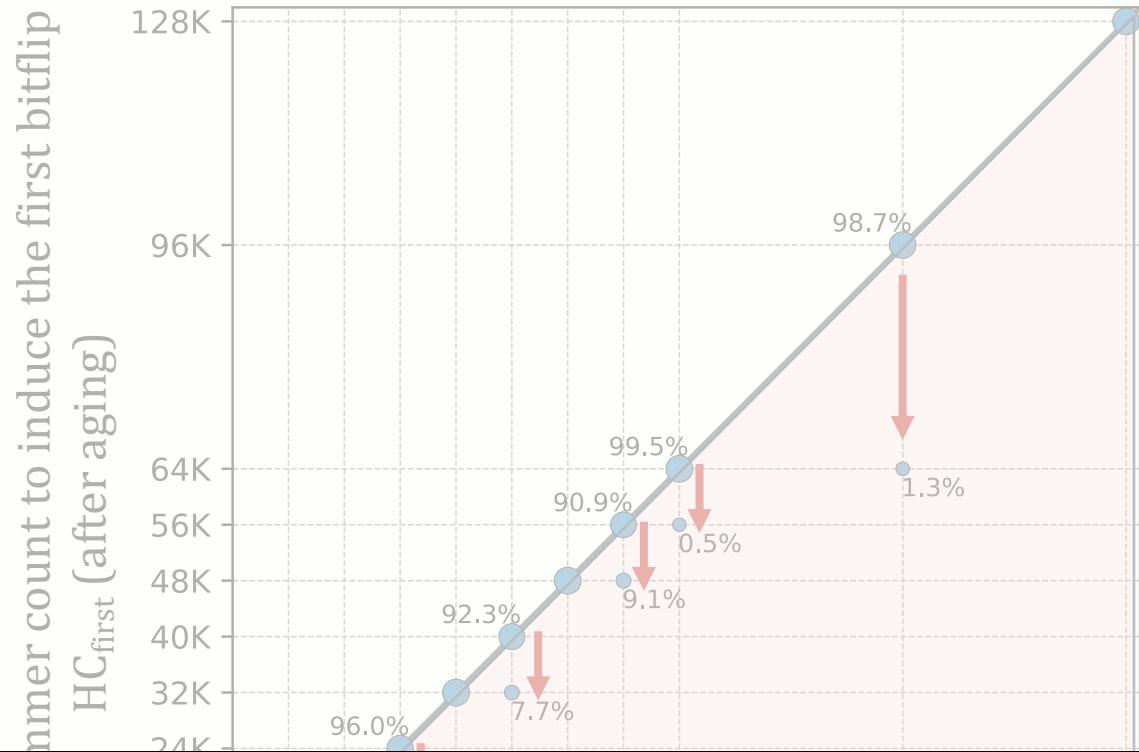
Aging can lead to read disturbance bitflips at **smaller** hammer counts



# Deeper Understanding of Physics and Vulnerabilities

- The effect of **aging**  
Preliminary data on aging via 68-day of continuous hammering

Aging can lead to read disturbance bitflips at smaller hammer counts



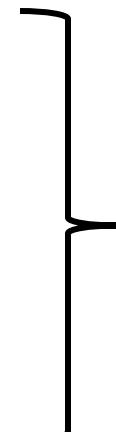
Future work:  
**rigorous aging characterization**  
and **online profiling of read disturbance vulnerability**

Minimum hammer count to induce the first bitflip  
HC<sub>first</sub> (before aging)

# Deeper Understanding of Physics and Vulnerabilities

- The effect of **aging**
- **Interactions** across different error mechanisms
  - RowHammer
  - RowPress
  - Data retention time errors
  - Variable retention time
  - ...

# Deeper Understanding of Physics and Vulnerabilities

- The effect of **aging**
  - **Interactions** across different error mechanisms
  - What is **the worst-case**?
    - Temperature
    - Data pattern
    - Memory access pattern
    - Spatial variation
    - Voltage
- 
- What is **the worst-case** considering all **these sensitivities**?
- What is **the minimum hammer count** to induce a read disturbance bitflip?

# Deeper Understanding of Physics and Vulnerabilities

- The effect of **aging**
- **Interactions** across different error mechanisms
- What is **the worst-case?**

How reliable are our DRAM chips?

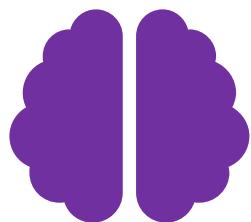
How reliable will our DRAM chips be tomorrow?

We **do not** know! This is an **open research problem**

# Future Research for Better Memory Systems



Deeper Understanding of  
Physics and Vulnerabilities



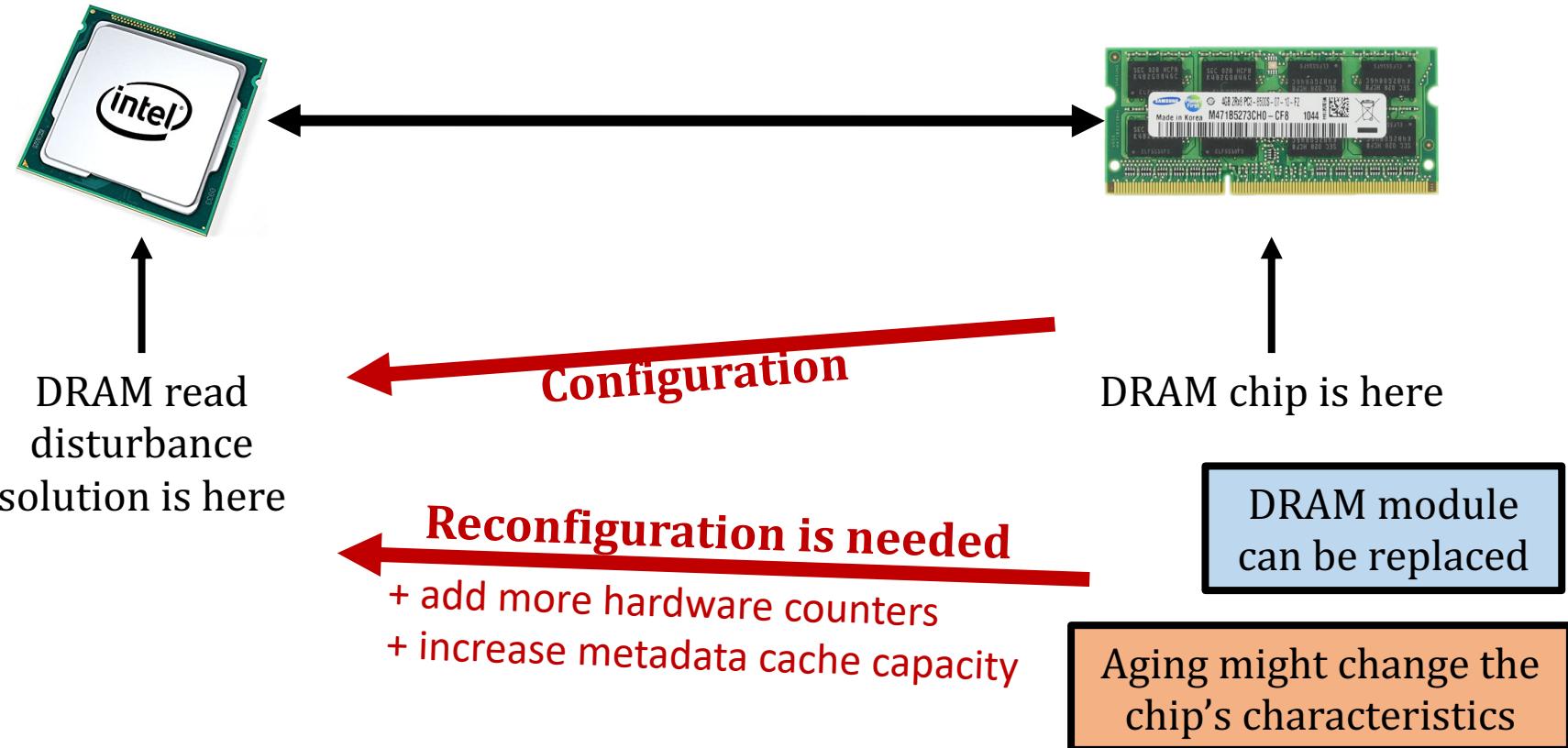
Flexible and Intelligent Memory  
Chips, Interfaces, Controllers



Cross-Layer  
Communication

# Flexible and Intelligent Chips, Interfaces, Controllers

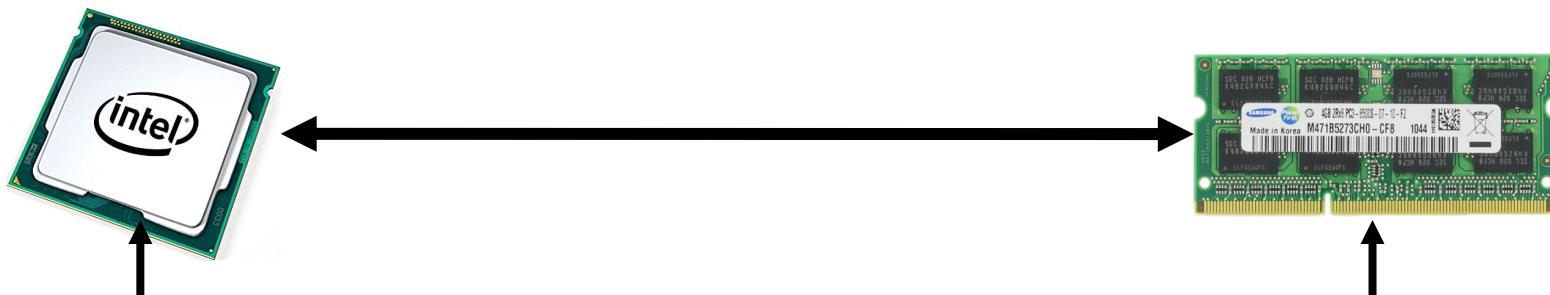
- In-field patching is necessary



Deployed solutions should be patchable in field

# Flexible and Intelligent Chips, Interfaces, Controllers

- In-field patching is necessary
- Interfaces should be **more flexible**



Memory controller  
decides what should  
be done when

DRAM chip has read  
disturbance solution inside  
(tracking+prevention)

- The memory controller should provide the DRAM chip with **necessary time window** to perform **preventive actions (e.g., refreshing rows)**
- The memory controller **does not have** the tracking information
- Communicating is **not straightforward** due to strict communication protocol

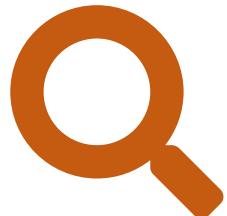
A more flexible interface is necessary

# Flexible and Intelligent Chips, Interfaces, Controllers

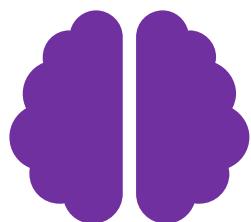
- In-field patching is necessary
- Interfaces should be more flexible
- Memory controllers should be more intelligent in detecting malicious activity
- DRAM chips become more and more vulnerable to RowHammer and RowPress
- Key Insight:
  - A thousand activations are enough to induce bitflips
  - Benign applications perform as many activations
- Problem: DRAM read disturbance solutions are getting prohibitively expensive
- Research Question: How to identify malicious threads/processes/users?
- More intelligent detection mechanisms are needed → AI can play an important role
- The memory controller observes all memory accesses → has the ground truth data

More intelligent memory controllers can help

# Future Research for Better Memory Systems



Deeper Understanding of  
Physics and Vulnerabilities

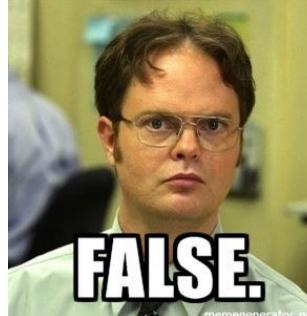


Flexible and Intelligent Memory  
Chips, Interfaces, Controllers

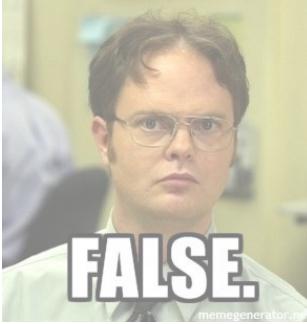


Cross-Layer  
Communication

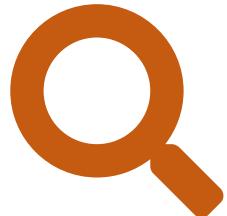
# Cross-Layer Communication

	Detection	Mitigation
Software	<ul style="list-style-type: none"><li>• Memory allocations</li><li>• Memory access patterns</li><li>• Control flow patterns</li><li>• Time / power measurements</li></ul>	
uArch	<ul style="list-style-type: none"><li>• Memory request scheduling</li><li>• Speculative execution</li><li>• Prefetching, branch prediction</li><li>• Power management</li></ul>	 
Device	<ul style="list-style-type: none"><li>• Bitflips occur</li><li>• Memory isolation is broken</li></ul>	 

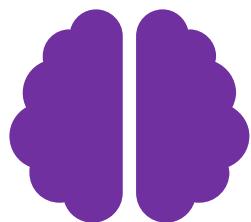
# Cross-Layer Communication

	Detection	Mitigation
Software	<ul style="list-style-type: none"><li>• Memory allocations</li><li>• Memory access patterns</li><li>• Control flow patterns</li><li>• Time / power measurements</li></ul>	 + +
Cross-layer communication is crucial going forward		
Device	<ul style="list-style-type: none"><li>• Bitflips occur</li><li>• Memory isolation is broken</li></ul>	+ + ~

# Future Research for Better Memory Systems



Deeper Understanding of  
Physics and Vulnerabilities



Flexible and Intelligent Memory  
Chips, Interfaces, Controllers



Cross-Layer  
Communication

# Enabling Efficient and Scalable Read Disturbance Mitigation via New Experimental Insights into Modern Memory Chips



[agyaglikci.github.io](https://agyaglikci.github.io)

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7 March 2024

University of Glasgow



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**SAFARI**

**ETH zürich**

# A Deeper Look into DRAM Read Disturbance

SAFARI Live Seminars in Computer Architecture



## A Deeper Look into RowHammer's Characteristics in Real Modern DRAM Chips

- A deeper look into RowHammer's characteristics



Temperature



Memory access patterns



Victim cell's physical location



Voltage



### SPEAKER

Abdullah Giray Yağlıkçı

SAFARI Research Group, ETH Zurich

JAN 17, 2024 5:00PM CET

[https://www.youtube.com/live/CRtm1es4n3o?si=8N5zB6e\\_RUc5Ejl8](https://www.youtube.com/live/CRtm1es4n3o?si=8N5zB6e_RUc5Ejl8)

# Solutions to DRAM Read Disturbance

SAFARI Live Seminars in Computer Architecture

Efficiently and Scalably Mitigating  
RowHammer in Modern and Future  
DRAM-Based Memory Systems



Leveraging  
Heterogeneity



Throttling Unsafe  
Accesses



Parallelizing  
Preventive Actions



SPEAKER

Abdullah Giray Yağlıkçı  
SAFARI Research Group, ETH Zurich

**ETH** zürich

**SAFARI**  
SAFARI Research Group

JAN 22. 2024 5:00PM CET

# Enabling Efficient and Scalable Read Disturbance Mitigation via New Experimental Insights into Modern Memory Chips

## Backup Slides



[agyaglikci.github.io](https://agyaglikci.github.io)

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7 March 2024

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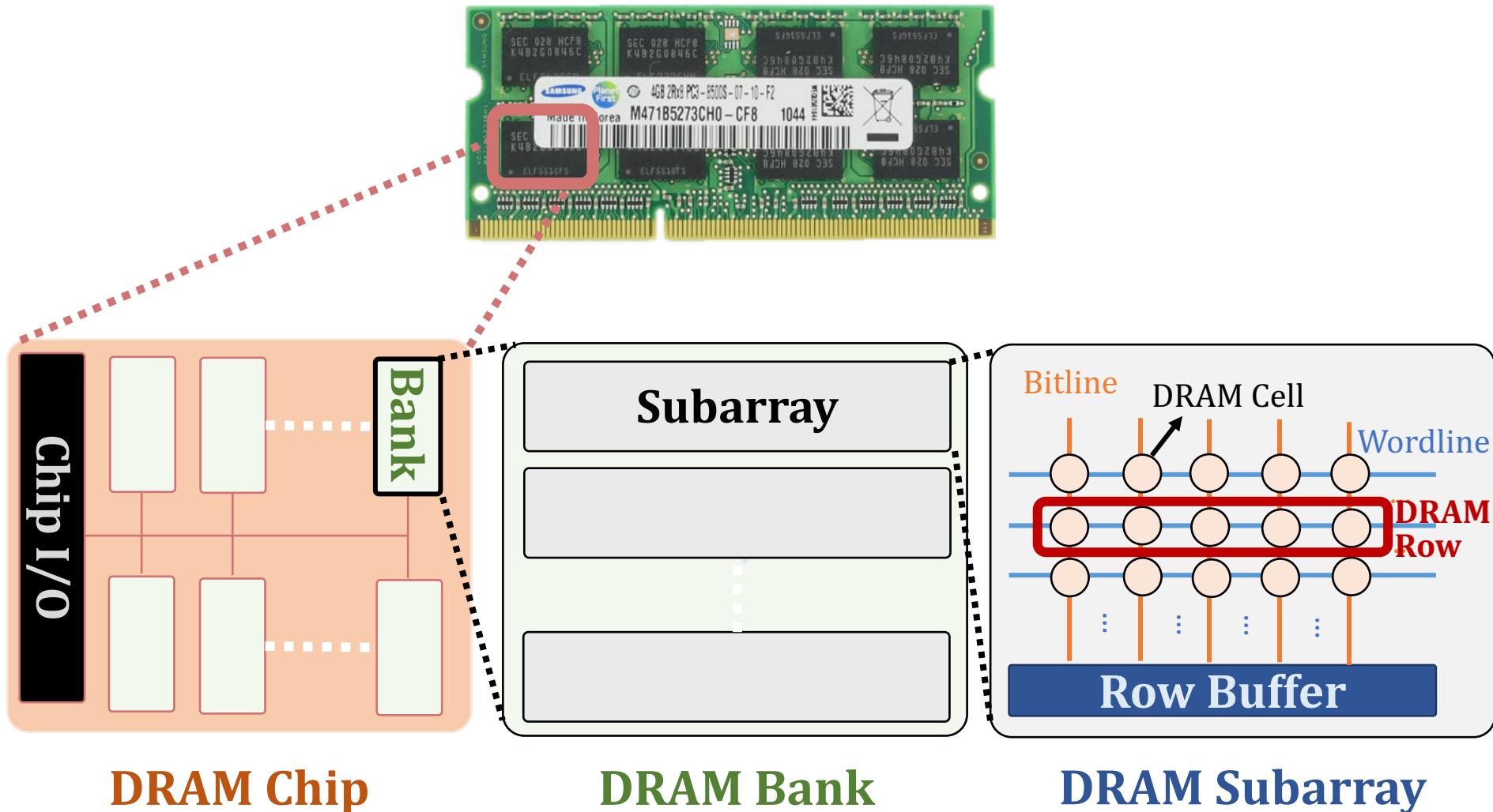
**SAFARI**

**ETH zürich**

# Thesis Statement

Developing  
a deeper understanding of DRAM read disturbance  
and  
revisiting memory controller designs  
enable scientists and engineers to build  
**reliable, secure, and safe DRAM-based systems**

# DRAM Organization



DRAM Chip

DRAM Bank

DRAM Subarray

# DRAM Chips Tested

## A Deeper Look into RowHammer's Sensitivities: Experimental Analysis of Real DRAM Chips and Implications on Future Attacks and Defenses

Lois Orosa\*  
ETH Zürich

A. Giray Yağlıkçı\*  
ETH Zürich

Haocong Luo  
ETH Zürich

Ataberk Olgun  
ETH Zürich, TOBB ETÜ

Jisung Park  
ETH Zürich

Hasan Hassan  
ETH Zürich

Minesh Patel  
ETH Zürich

Jeremie S. Kim  
ETH Zürich

Onur Mutlu  
ETH Zürich

- 272
- Four
- DD
- Dif

Table 4: Characteristics of the tested DDR4 and DDR3 DRAM modules.

Type	Chip Manufacturer	Chip Identifier	Module Vendor	Module Identifier	Freq. (MT/s)	Date Code	Density	Die Rev.	Org.	#Modules	#Chips
DDR4	A: Micron	MT40A2G4WE-083E:B	Micron	MTA18ASF2G72PZ-2G3B1QG [94]	2400	1911	8Gb	B	x4	6	96
	B: Samsung	K4A4G085WF-BCTD [132]	G.SKILL	F4-2400C17S-8GNT [35]	2400	1843				2	32
	C: SK Hynix	DWCW (Partial Marking) †	G.SKILL	F4-2400C17S-8GNT [35]	2400	1844				1	16
	D: Nanya	D1028AN9CPGRK ‡	Kingston	KVR24N17S8/ [75]	2400	2042	4Gb	F	x8	4	32
DDR3	A: Micron	MT41K512M8DA-107:P [22]	Crucial	CT51264BF160BJ.M8FP	1600	1703	4Gb	P	x8	1	8
	B: Samsung	K4B4G0846Q	Samsung	M471B5173QH0-YK0 [131]	1600	1416	4Gb	Q	x8	1	8
	C: SK Hynix	H5TC4G83BFR-PBA	SK Hynix	HMT451S6BFR8A-PB [139]	1600	1535	4Gb	B	x8	1	8

# DRAM Testing Methodology

To characterize our DRAM chips at **worst-case** conditions:

## 1. Prevent sources of interference during core test loop

- **No DRAM refresh**: to avoid refreshing victim row
- **No DRAM calibration events**: to minimize variation in test timing
- **No RowHammer mitigation mechanisms**: to observe circuit-level effects
- Test for **less than a refresh window (32ms)** to avoid retention failures
- **Repeat tests** for ten times

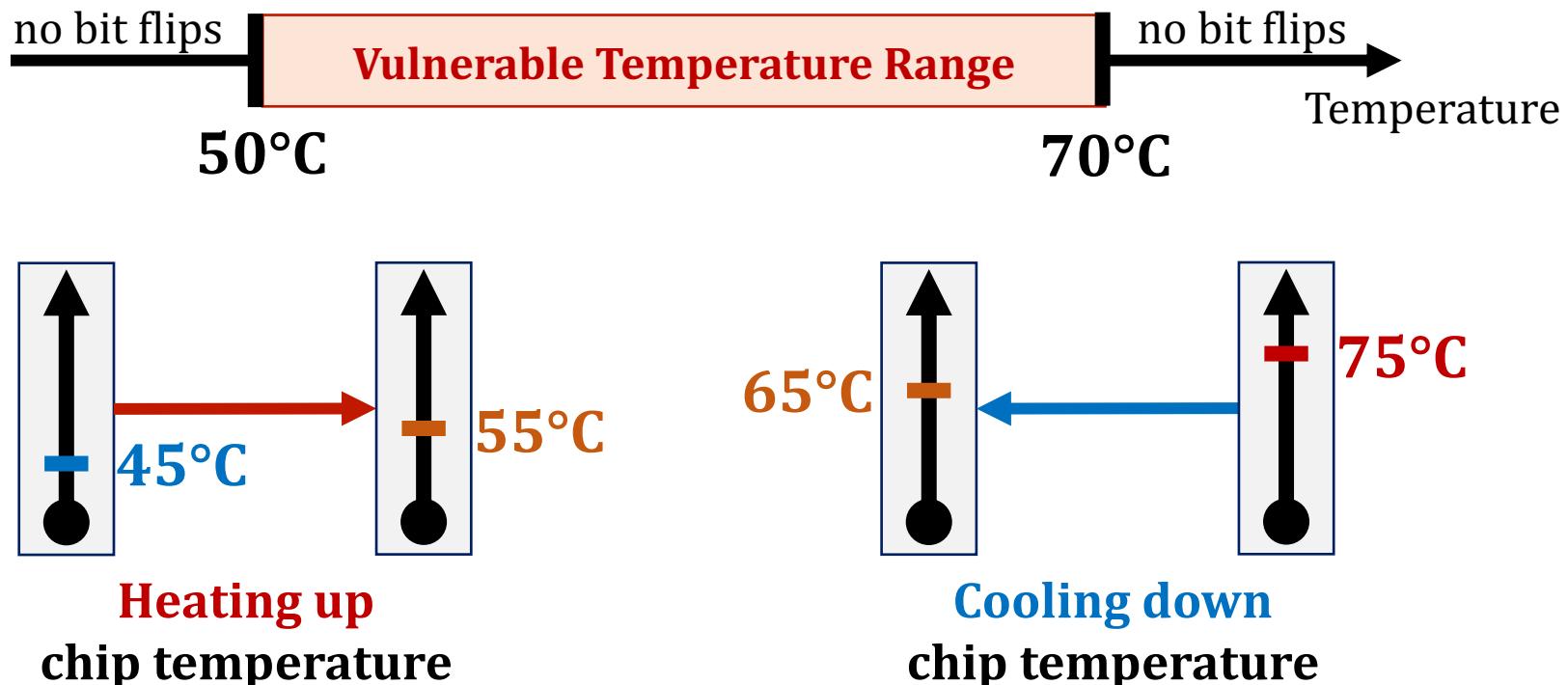
## 2. Worst-case access sequence

- We use **worst-case** access sequence based on prior works' observations
- For each row, **repeatedly access the two physically-adjacent rows as fast as possible**

# Attack Improvement 1: Making DRAM Cells More Vulnerable

An attacker can **manipulate temperature** to make the cells that store sensitive data **more vulnerable**

DRAM cells are vulnerable in a **bounded temperature range**



# Key Takeaways from Spatial Variation Analysis



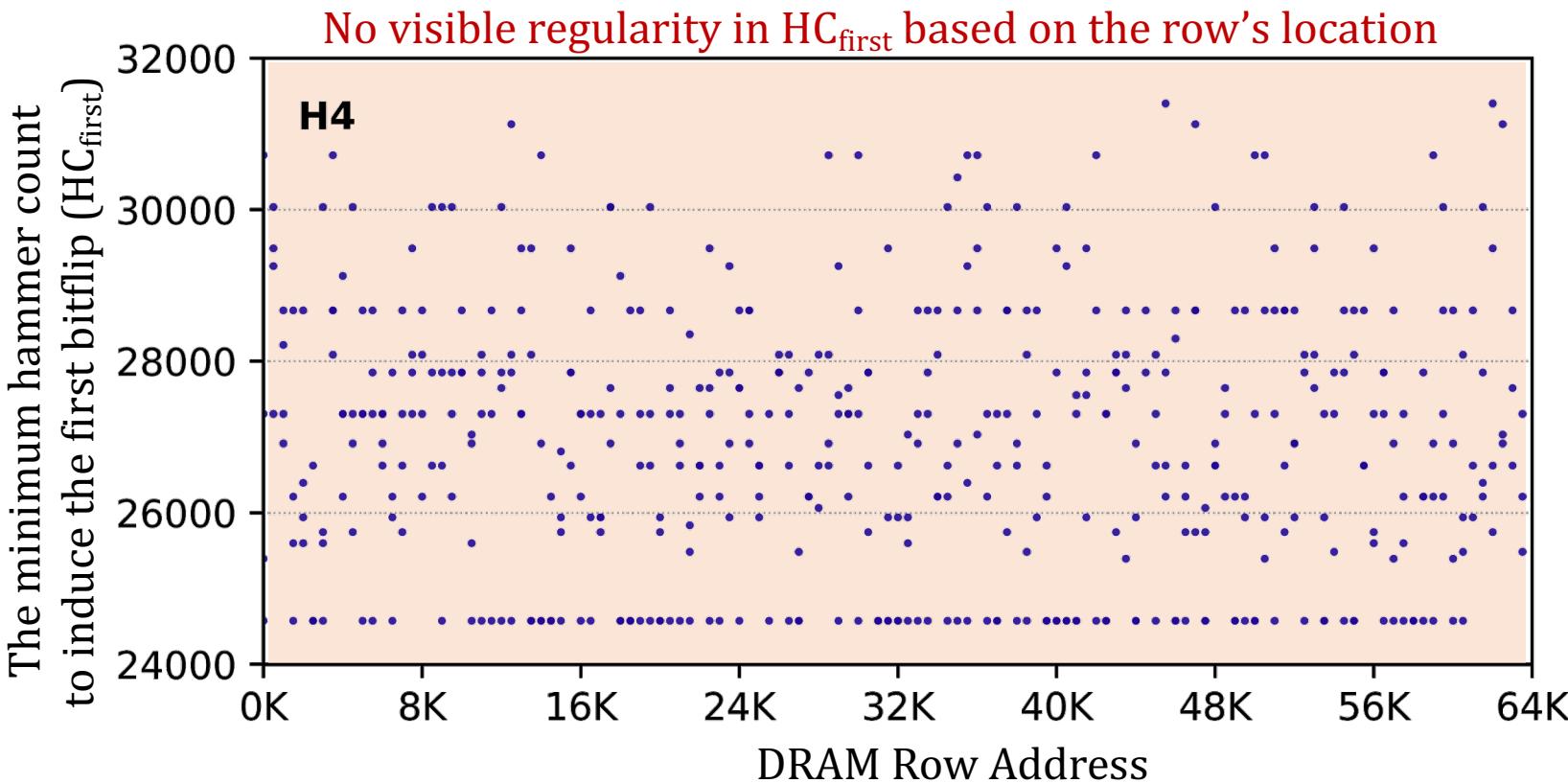
## Key Takeaway 1

RowHammer vulnerability **significantly varies** across DRAM rows and columns due to **design** and **manufacturing-process**

## Key Takeaway 2

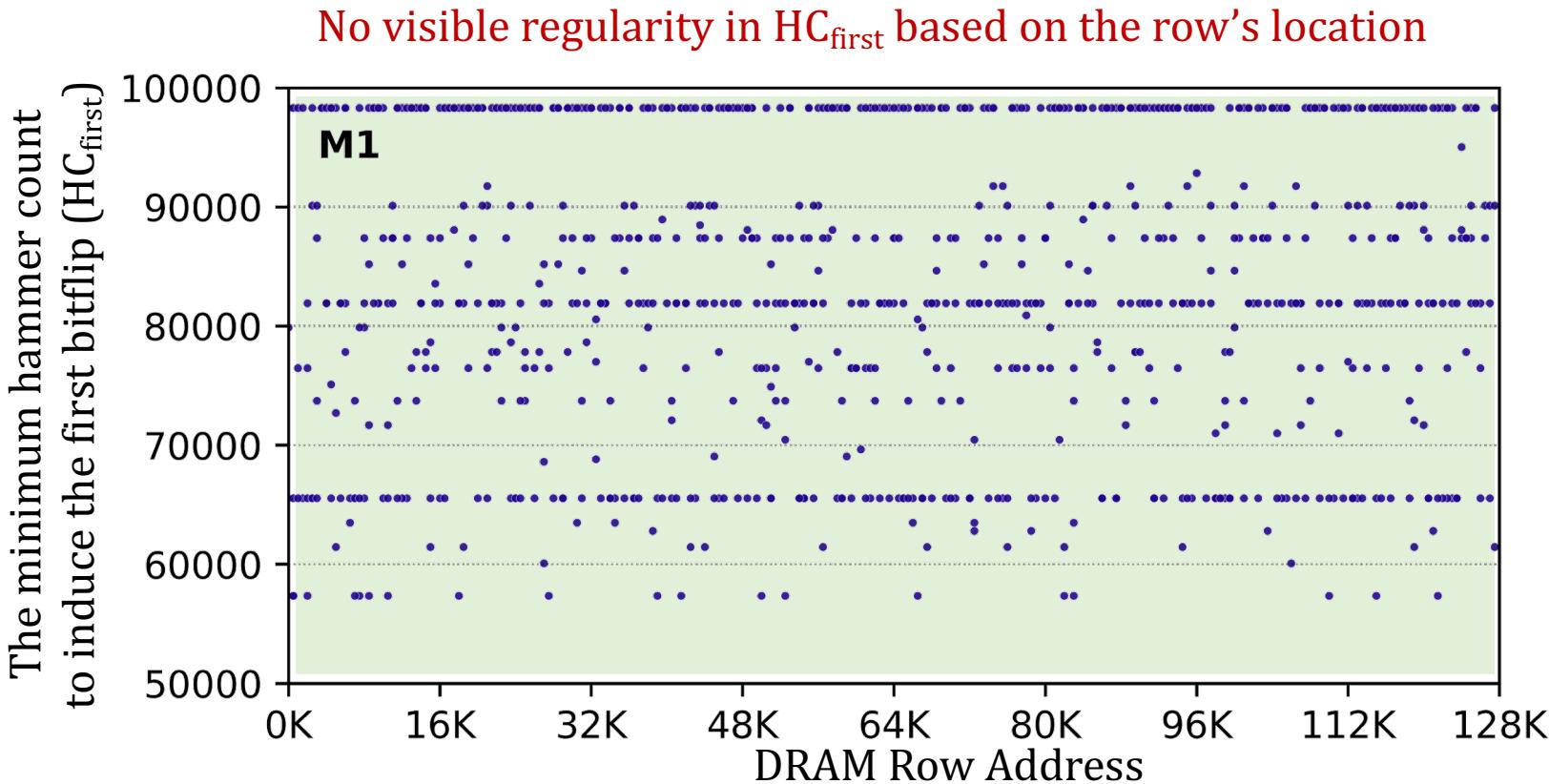
Minimum hammer count to induce the first bitflip ( $HC_{first}$ ) significantly varies **across rows in a subarray** but **not as much across subarrays**

# Regularity in Spatial Variation of Read Disturbance across DRAM Rows



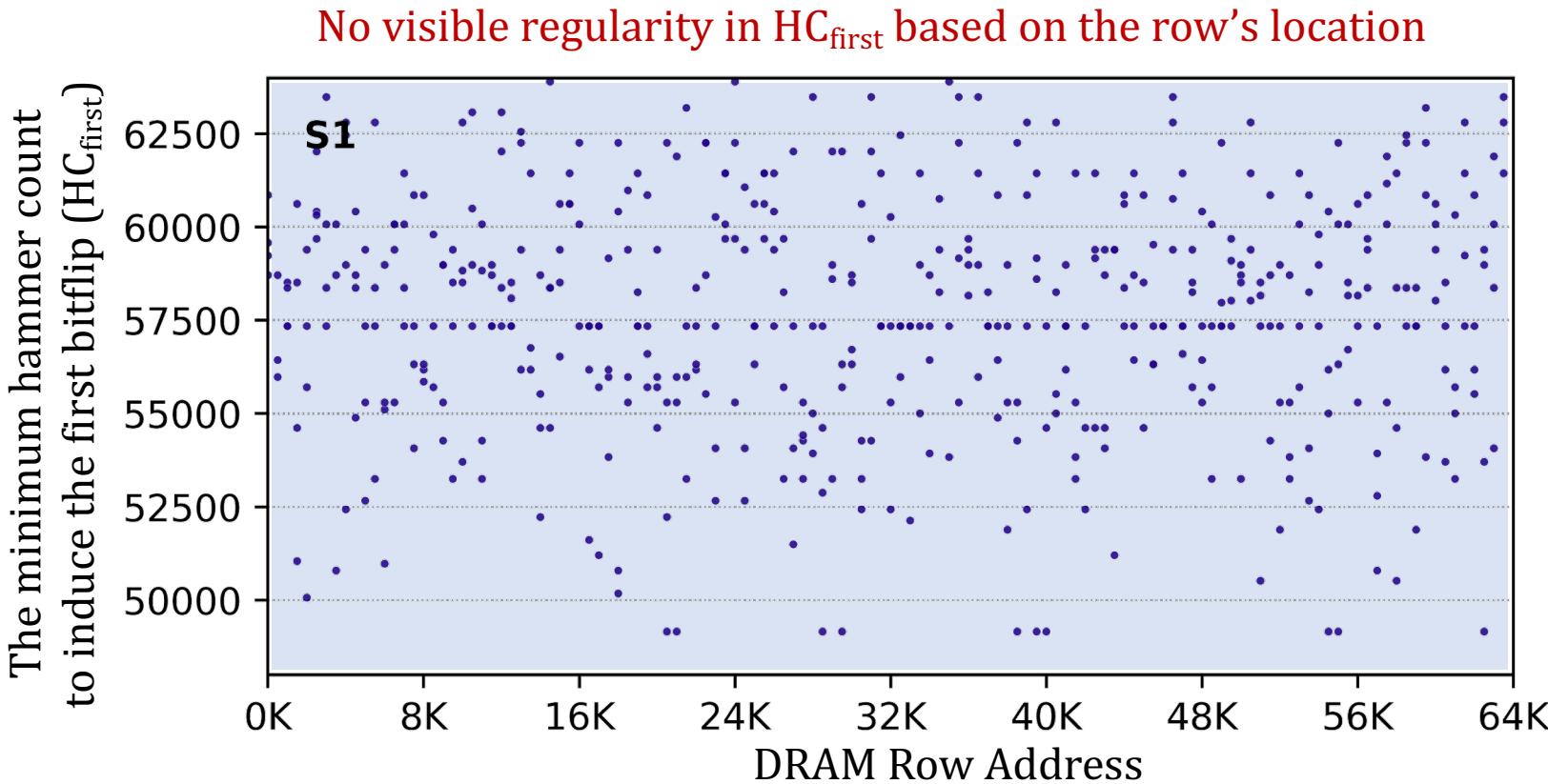
The minimum hammer count to induce the first bitflip **irregularly varies** with respect to row's location in DRAM bank

# Regularity in Spatial Variation of Read Disturbance across DRAM Rows



The minimum hammer count to induce the first bitflip **irregularly varies** with respect to row's location in DRAM bank

# Regularity in Spatial Variation of Read Disturbance across DRAM Rows



The minimum hammer count to induce the first bitflip **irregularly varies** with respect to row's location in DRAM bank

# Predictability of Read Disturbance Vulnerability

**Predictability of** a DRAM row's read disturbance vulnerability based on the row's spatial features

- bank address bits
- subarray address bits
- row address bits
- row's distance to local row buffer

## Methodology

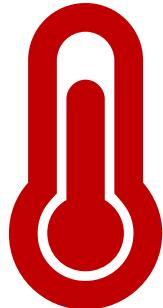
- Cluster DRAM rows into 15 bins based on each row's minimum hammer count to induce the first bitflip ( $HC_{first}$ )
- Predict whether a row is in a cluster, based on each spatial feature
- Measure the F1 score for these predictions

**Key Result:** Only a few spatial features have F1 scores  $> 0.7$  only for Mfr. S

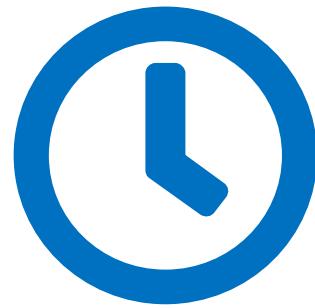
A row's **spatial features** are weak predictors for the row's **read disturbance vulnerability**

# My Dissertation Works

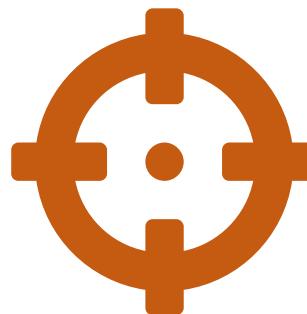
- A deeper look into DRAM read disturbance



Temperature



Memory Access Patterns



In-Chip Variations



Voltage

- Solutions to DRAM read disturbance



Throttling Unsafe  
Accesses



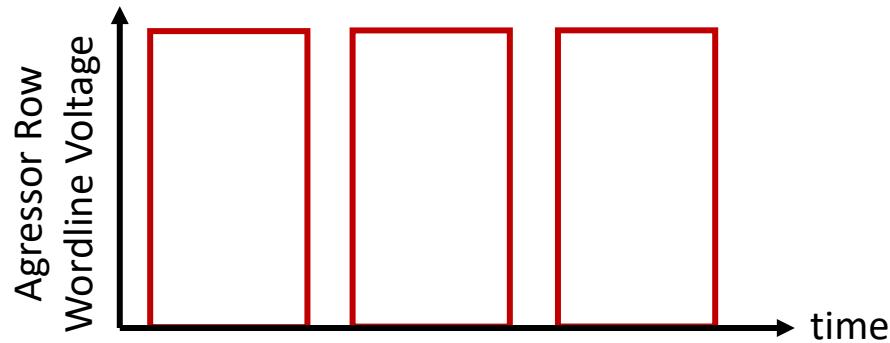
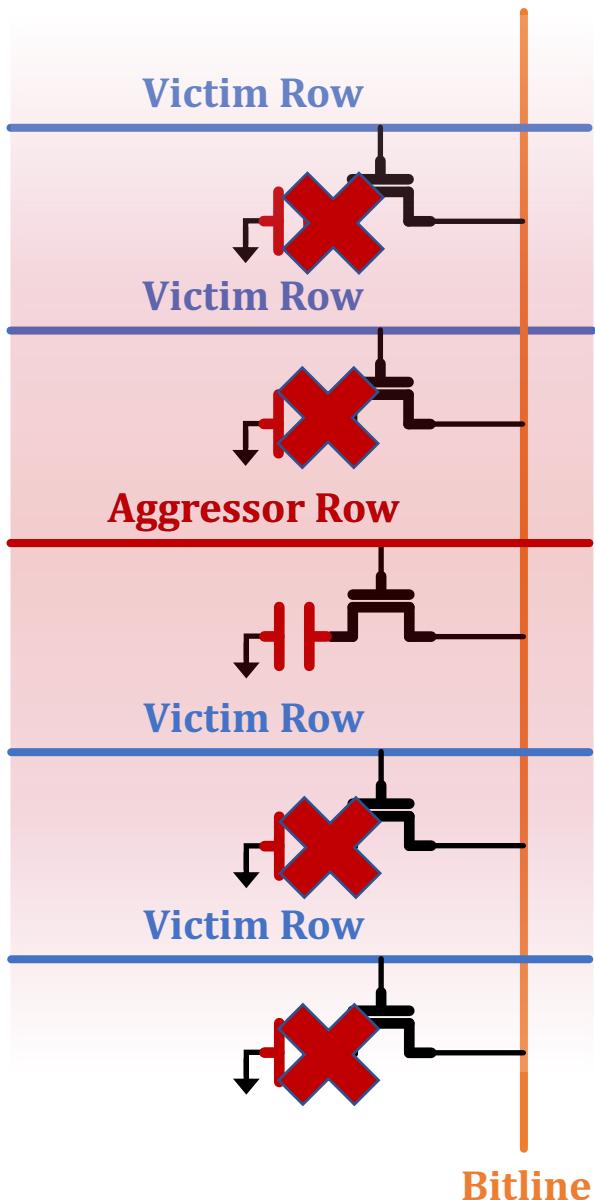
Parallelizing  
Preventive Measures



Leveraging  
Heterogeneity

# A Closer Look into RowHammer

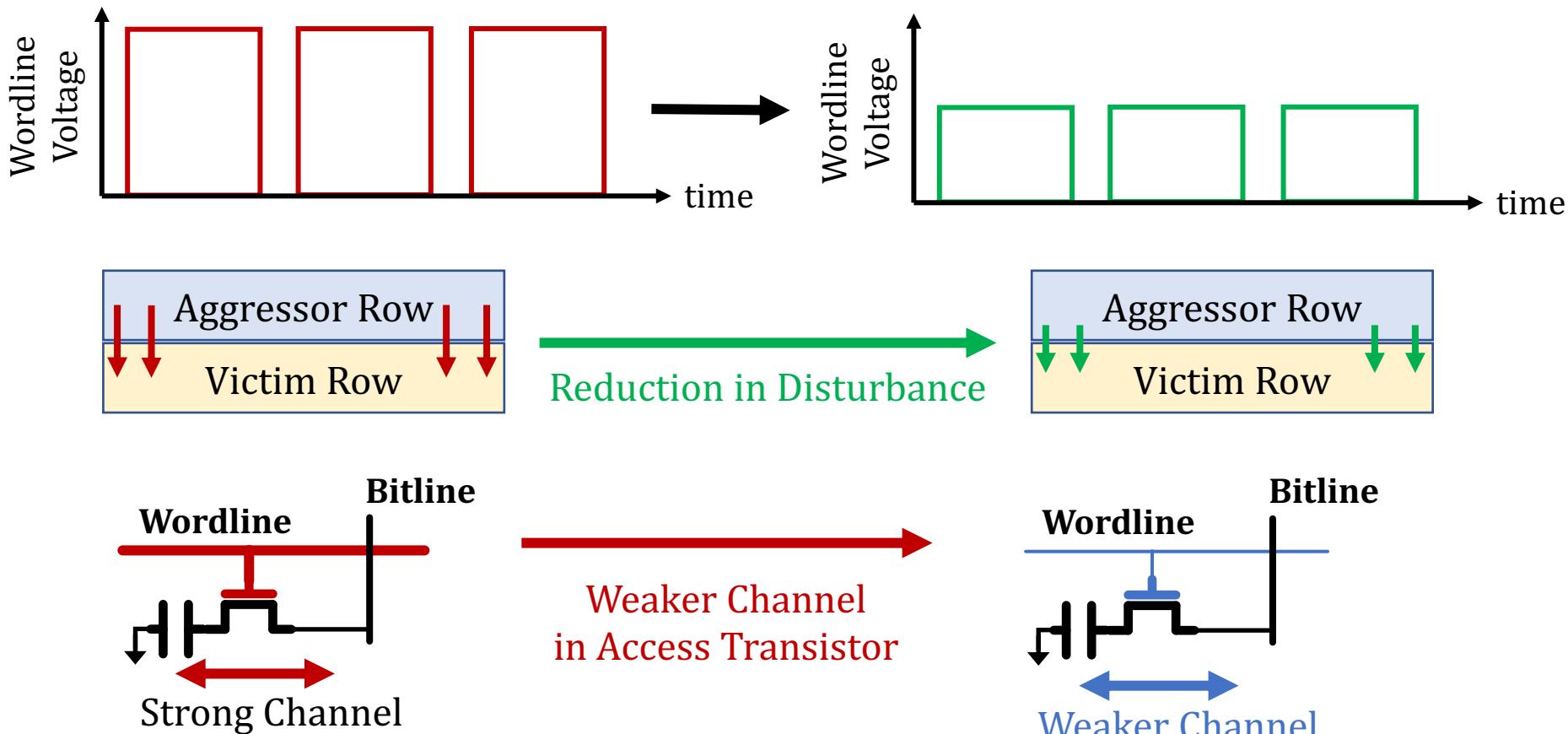
Low Voltage  
Low Voltage  
High Voltage  
Low Voltage  
Low Voltage



Repeatedly toggling wordline voltage is the *key* to inducing **RowHammer bitflips**

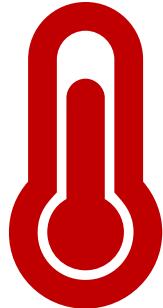
# Our Key Finding

Reducing wordline voltage  
reduces RowHammer vulnerability  
*without significantly affecting reliable DRAM operation*



# My Dissertation Works

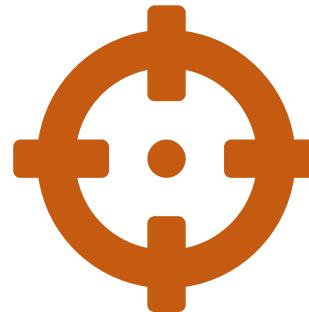
- A deeper look into DRAM read disturbance



Temperature



Memory Access Patterns



In-Chip Variations



Voltage

- Solutions to DRAM read disturbance



Throttling Unsafe  
Accesses



Parallelizing  
Preventive Measures

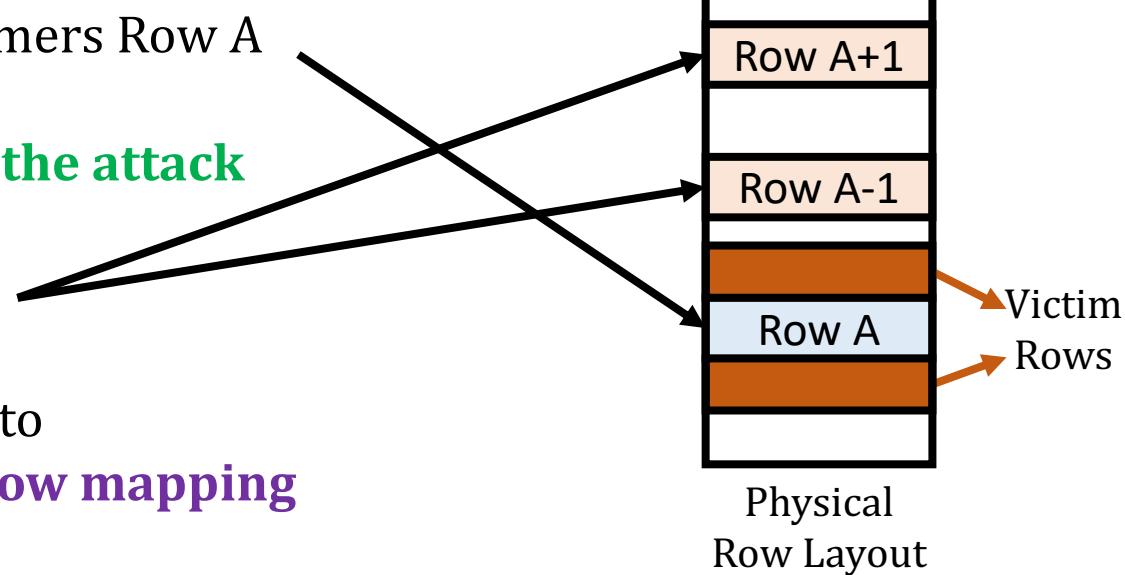


Leveraging  
Heterogeneity

# Compatibility with Commodity DRAM Chips



- A **RowHammer attack** hammers Row A
- Existing mechanisms **detect the attack**
- Refresh rows **A+1** and **A-1**
- Bit flips **still may occur** due to **unknown DRAM-internal row mapping**



Existing **read disturbance mitigation** mechanisms  
need to know **proprietary DRAM-internal row address mapping**

# BlockHammer – HPCA 2021

- A. Giray Yaglikci, Minesh Patel, Jeremie S. Kim, Roknoddin Azizi, Ataberk Olgun, Lois Orosa, Hasan Hassan, Jisung Park, Konstantinos Kanellopoulos, Taha Shahroodi, Saugata Ghose, and Onur Mutlu,  
[\*\*"BlockHammer: Preventing RowHammer at Low Cost by Blacklisting Rapidly-Accessed DRAM Rows"\*\*](#)  
*Proceedings of the 27th International Symposium on High-Performance Computer Architecture (HPCA)*,  
Virtual, February–March 2021.

[[Slides \(pptx\)](#) ([pdf](#))]

[[Short Talk Slides \(pptx\)](#) ([pdf](#))]

[[Intel Hardware Security Academic Awards](#)

[[Short Talk Slides \(pptx\)](#) ([pdf](#))]

[[Talk Video](#) (22 minutes)]

[[Short Talk Video](#) (7 minutes)]

[[Intel Hardware Security Academic Awards](#)

[[Short Talk Video](#) (2 minutes)]

[[BlockHammer Source Code](#)]

**Intel Hardware Security Academic Award Finalist  
(one of 4 finalists out of 34 nominations)**

Congratulations to A. Giray Yaglikci & Team!

Finalists – 2022 Intel Hardware Security Academic Award for

"BlockHammer: Preventing RowHammer at Low Cost by  
Blacklisting Rapidly-Accessed DRAM Rows"



## BlockHammer: Preventing RowHammer at Low Cost by Blacklisting Rapidly-Accessed DRAM Rows

A. Giray Yağlıkçı<sup>1</sup> Minesh Patel<sup>1</sup> Jeremie S. Kim<sup>1</sup> Roknoddin Azizi<sup>1</sup> Ataberk Olgun<sup>1</sup> Lois Orosa<sup>1</sup>

Hasan Hassan<sup>1</sup> Jisung Park<sup>1</sup> Konstantinos Kanellopoulos<sup>1</sup> Taha Shahroodi<sup>1</sup> Saugata Ghose<sup>2</sup> Onur Mutlu<sup>1</sup>

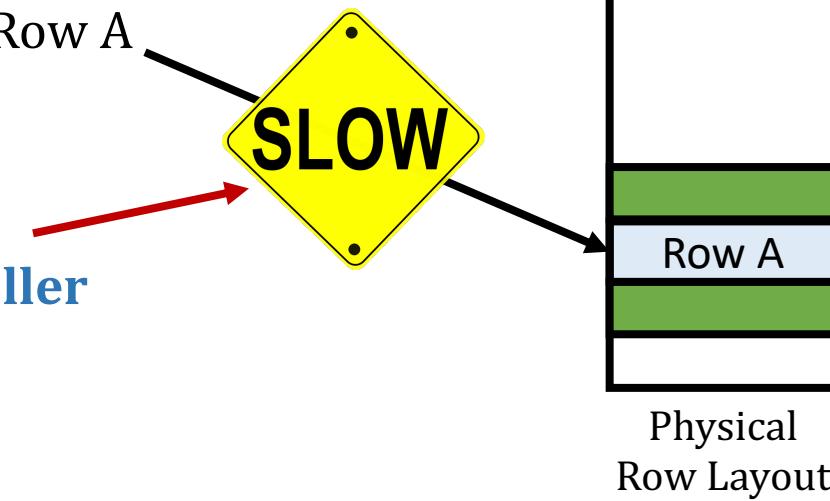
<sup>1</sup>ETH Zürich

<sup>2</sup>University of Illinois at Urbana–Champaign

# BlockHammer: Throttling Unsafe Accesses



- A RowHammer attack hammers Row A
- BlockHammer detects and **selectively throttles accesses** from within **the memory controller**
- Bit flips **do not** occur
- BlockHammer can *optionally inform the system software* about the attack



BlockHammer is compatible with commodity DRAM chips  
No need for proprietary info or modifications to DRAM chips

# Spatial Variation-Aware Read Disturbance Defenses: Experimental Analysis of Real DRAM Chips and Implications on Future Solutions

Aging Slides



Full Paper  
[arXiv \[cs.CR\] 2402.18652](https://arxiv.org/abs/2402.18652)

**Abdullah Giray Yağlıkçı**

Yahya Can Tuğrul   Geraldo F. Oliveira   İsmail Emir Yüksel

Ataberk Olgun   Haocong Luo   Onur Mutlu

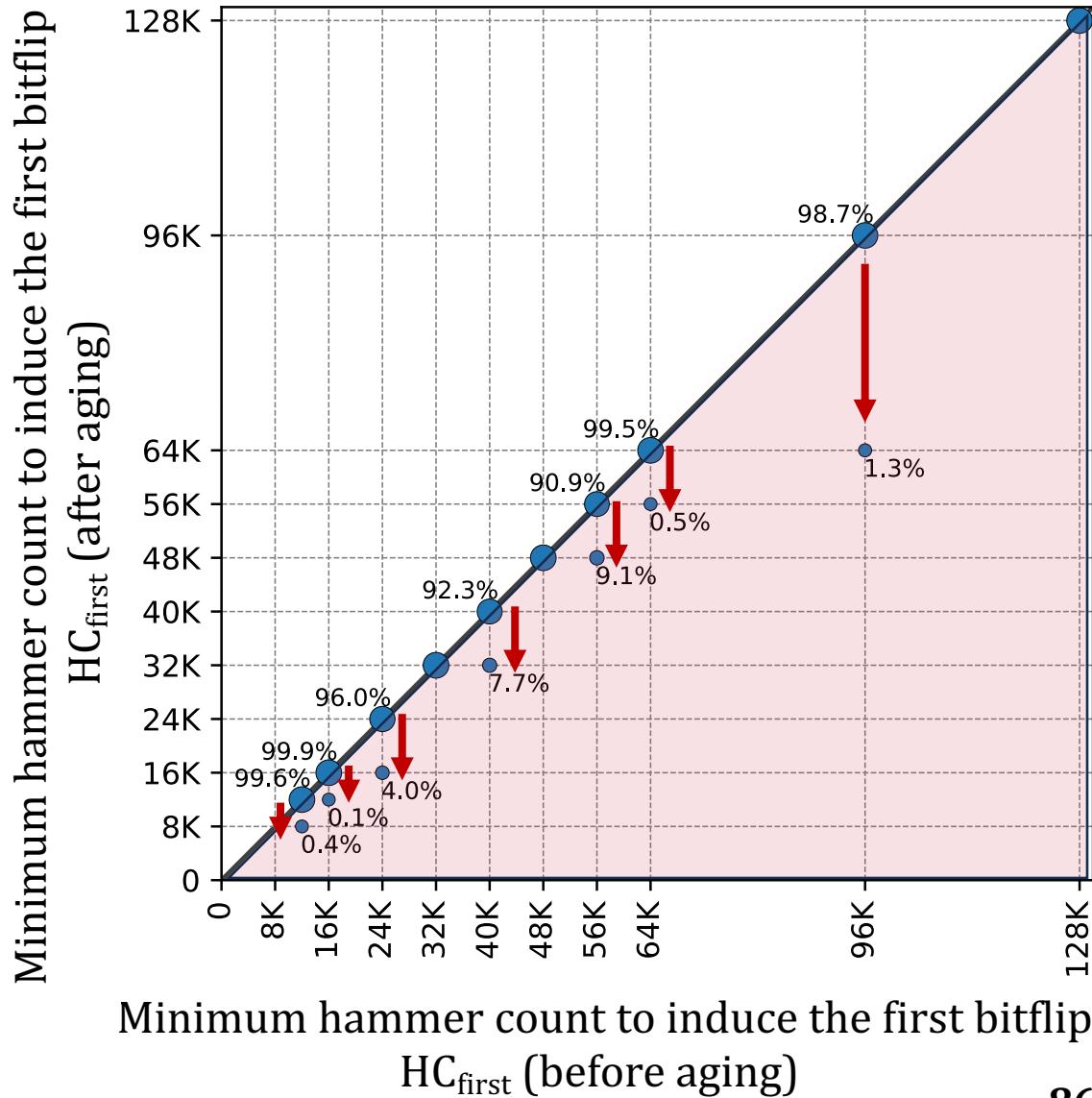
**SAFARI**

**ETH zürich**

# More in the Paper (2/2): Aging Study

Preliminary data on aging via 68-day of continuous hammering

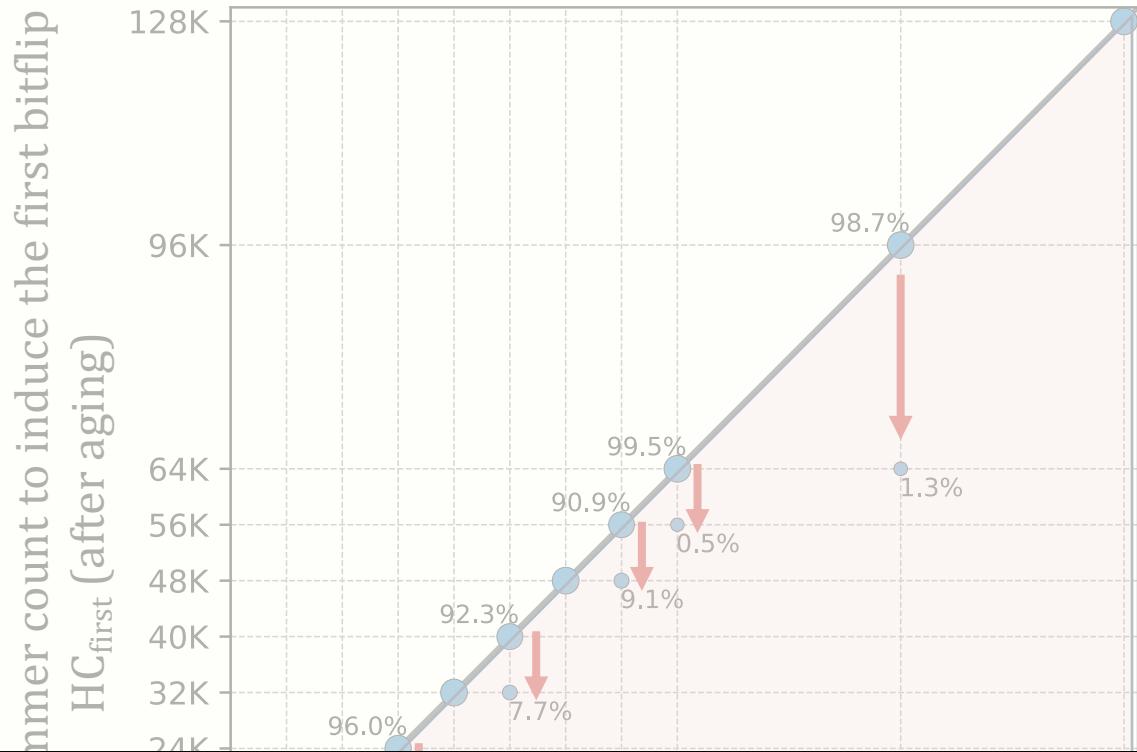
Aging can lead to read disturbance bitflips at smaller hammer counts



# More in the Paper (2/2): Aging Study

Preliminary data on aging via 68-day of continuous hammering

Aging can lead to read disturbance bitflips at smaller hammer counts



Future work:  
rigorous aging characterization  
and online profiling of read disturbance vulnerability

Minimum hammer count to induce the first bitflip  
HC<sub>first</sub> (before aging)

# Spatial Variation-Aware Read Disturbance Defenses: Experimental Analysis of Real DRAM Chips and Implications on Future Solutions

Hydra's Performance



Full Paper  
[arXiv \[cs.CR\] 2402.18652](https://arxiv.org/abs/2402.18652)

**Abdullah Giray Yağlıkçı**

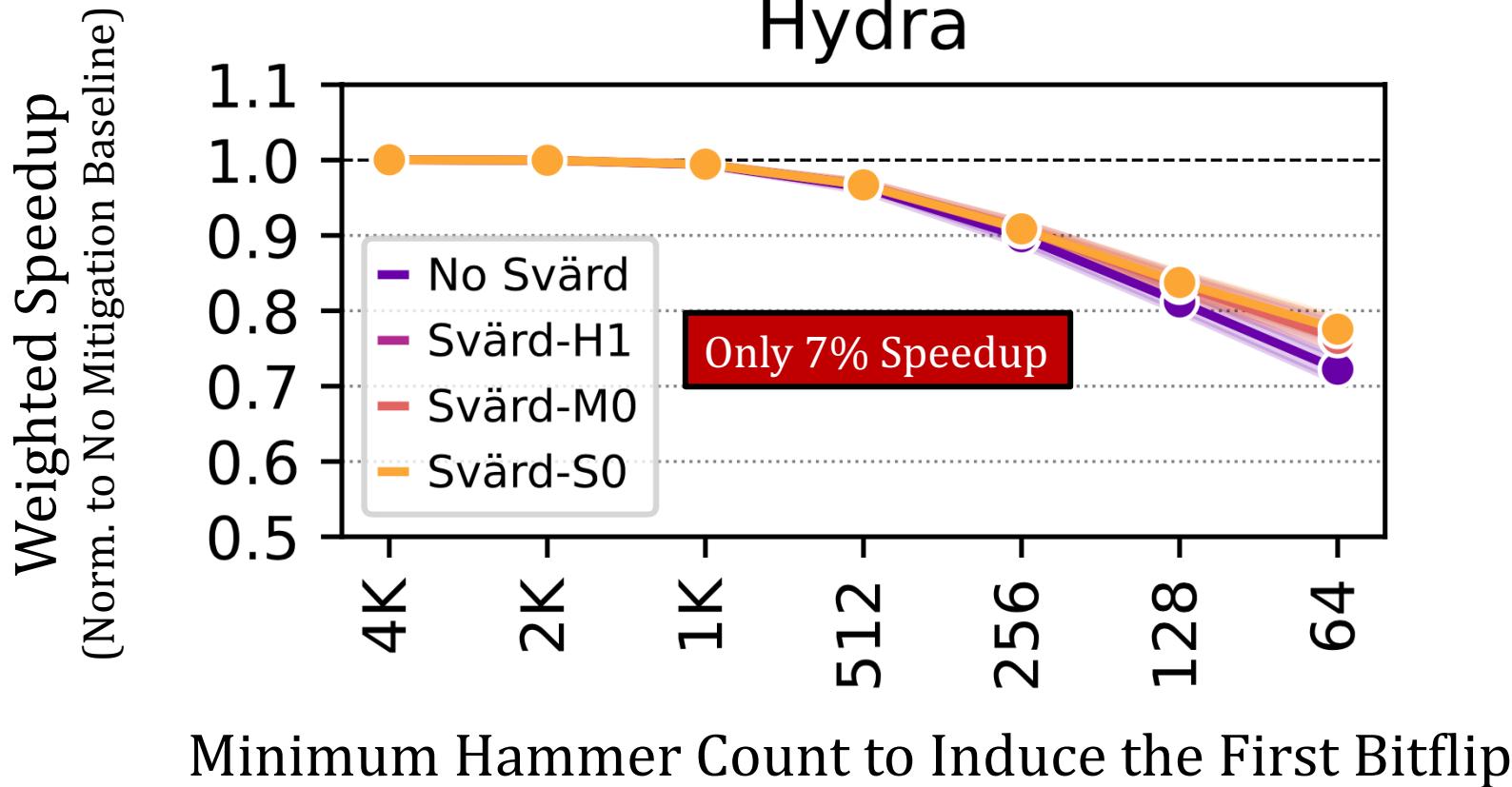
Yahya Can Tuğrul   Geraldo F. Oliveira   İsmail Emir Yüksel

Ataberk Olgun   Haocong Luo   Onur Mutlu

**SAFARI**

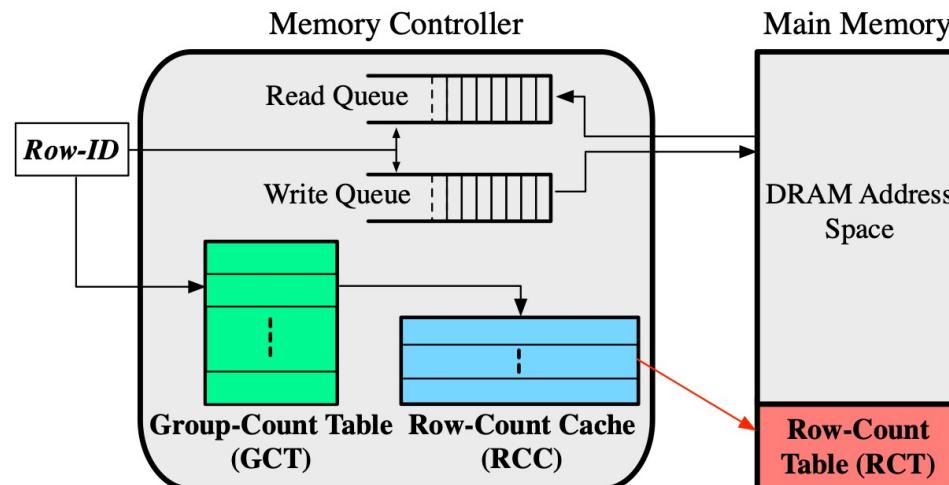
**ETH zürich**

# An Outlier Solution: Hydra



# Hydra Mitigation Mechanism

- Hydra maintains a **row activation counter** for each DRAM row
- Stores these activation counters in the DRAM array
- Caches the counters of hot rows in the memory controller
- At low  $HC_{first}$  configurations, **many rows are hot**
- Fetching / evicting counters dominate the performance overhead
- Svärd needs **further customizations** for Hydra



# Spatial Variation-Aware Read Disturbance Defenses: Experimental Analysis of Real DRAM Chips and Implications on Future Solutions

HC<sub>first</sub> across Rows



Full Paper  
[arXiv \[cs.CR\] 2402.18652](https://arxiv.org/abs/2402.18652)

**Abdullah Giray Yağlıkçı**

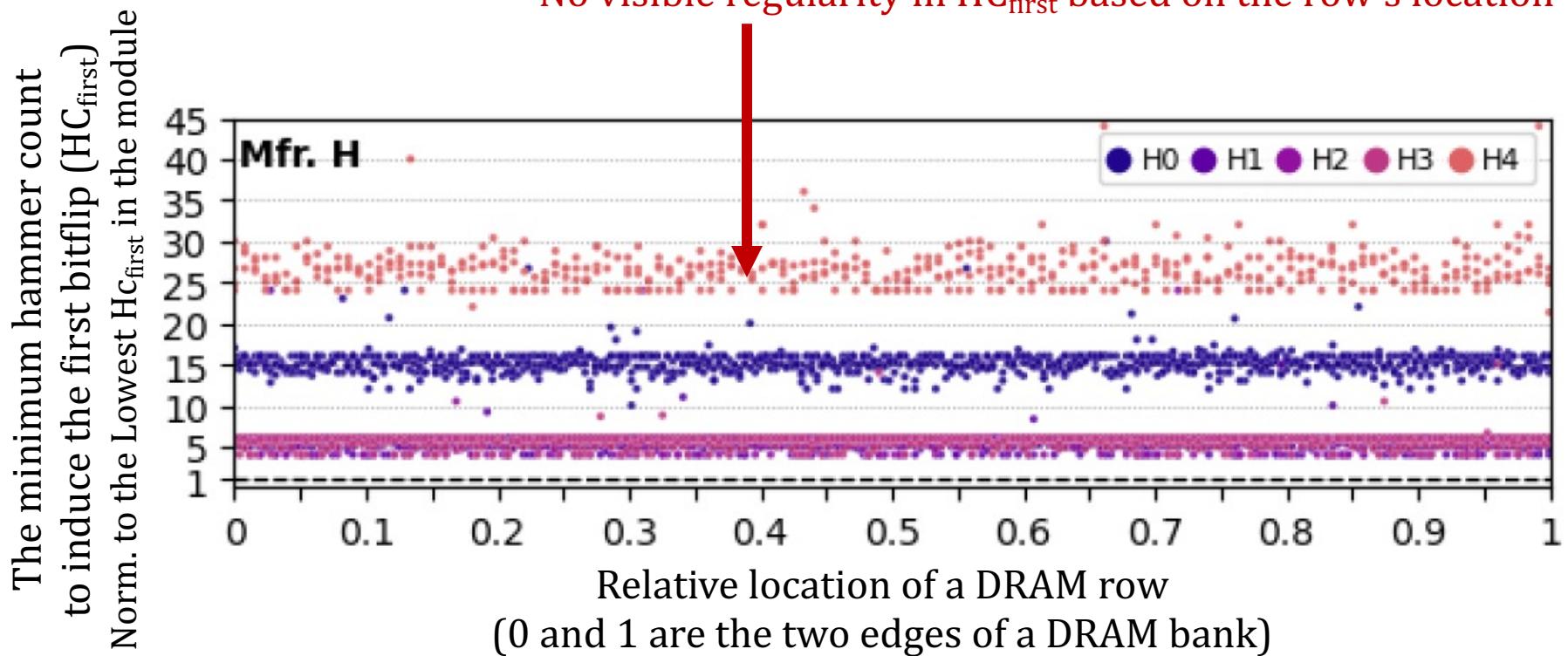
Yahya Can Tuğrul   Geraldo F. Oliveira   İsmail Emir Yüksel

Ataberk Olgun   Haocong Luo   Onur Mutlu

**SAFARI**

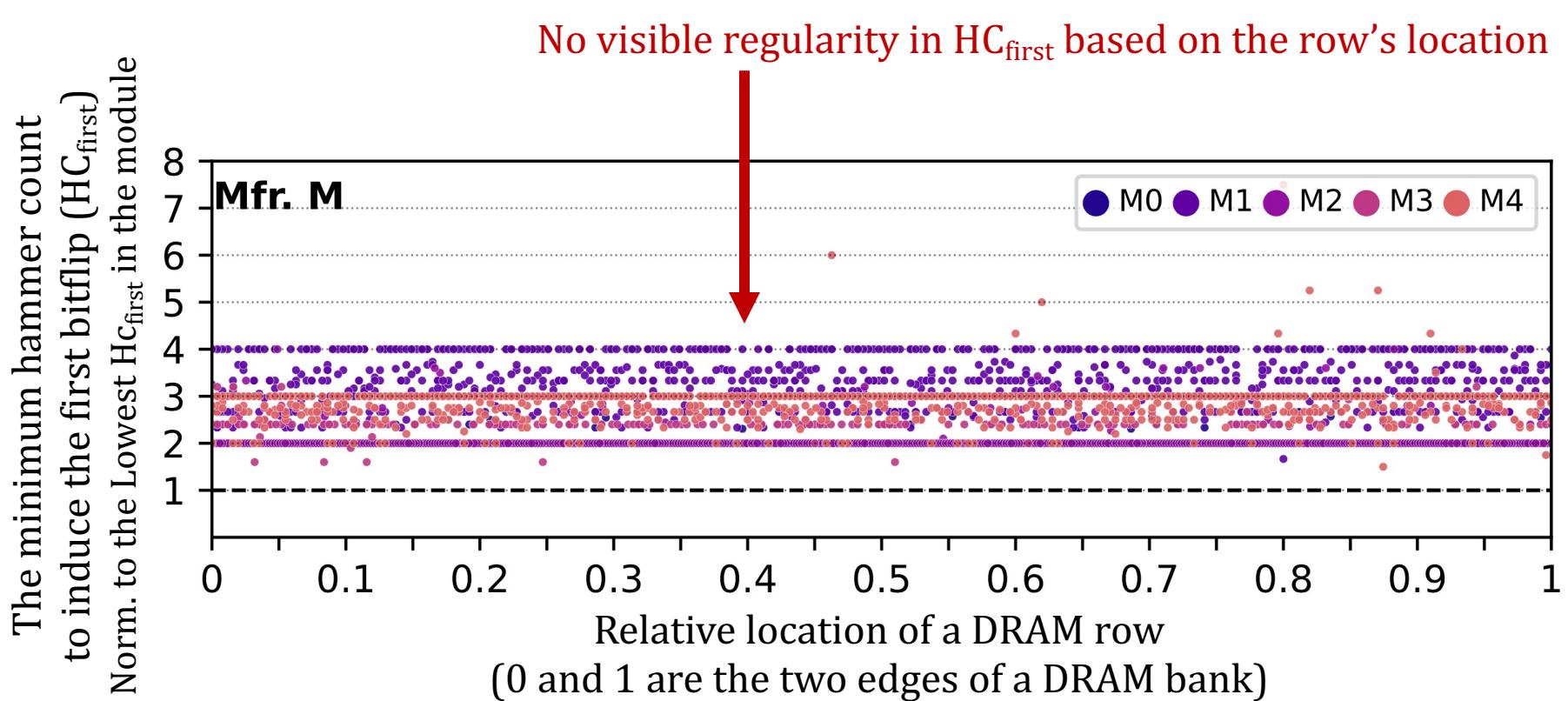
**ETH zürich**

# The Minimum Hammer Count to Induce the First Bitflip across DRAM Rows



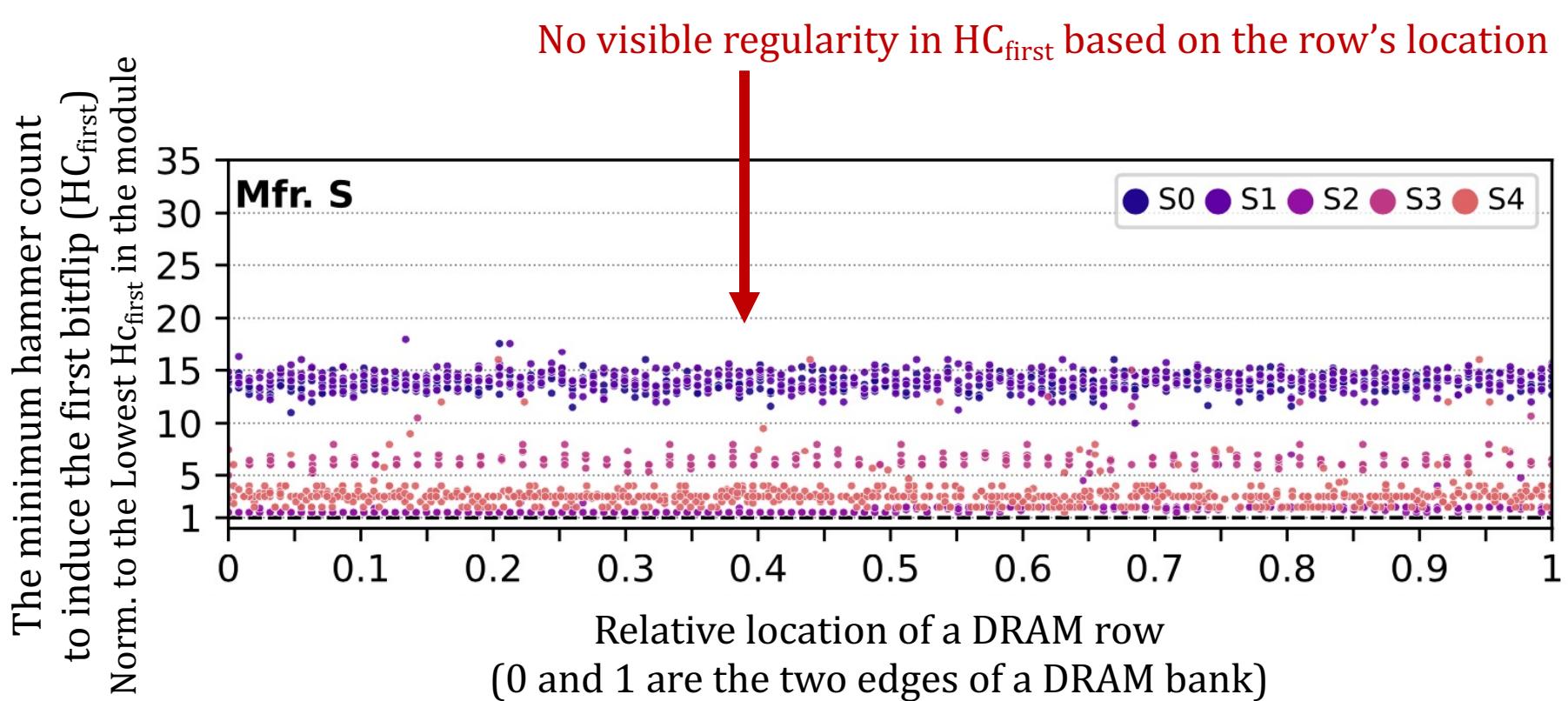
The minimum hammer count to induce the first bitflip **irregularly varies** with respect to row's location in DRAM bank

# The Minimum Hammer Count to Induce the First Bitflip across DRAM Rows



The minimum hammer count to induce the first bitflip **irregularly varies** with respect to row's location in DRAM bank

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The minimum hammer count to induce the first bitflip **irregularly varies** with respect to row's location in DRAM bank

# Spatial Variation-Aware Read Disturbance Defenses: Experimental Analysis of Real DRAM Chips and Implications on Future Solutions

BER across Rows



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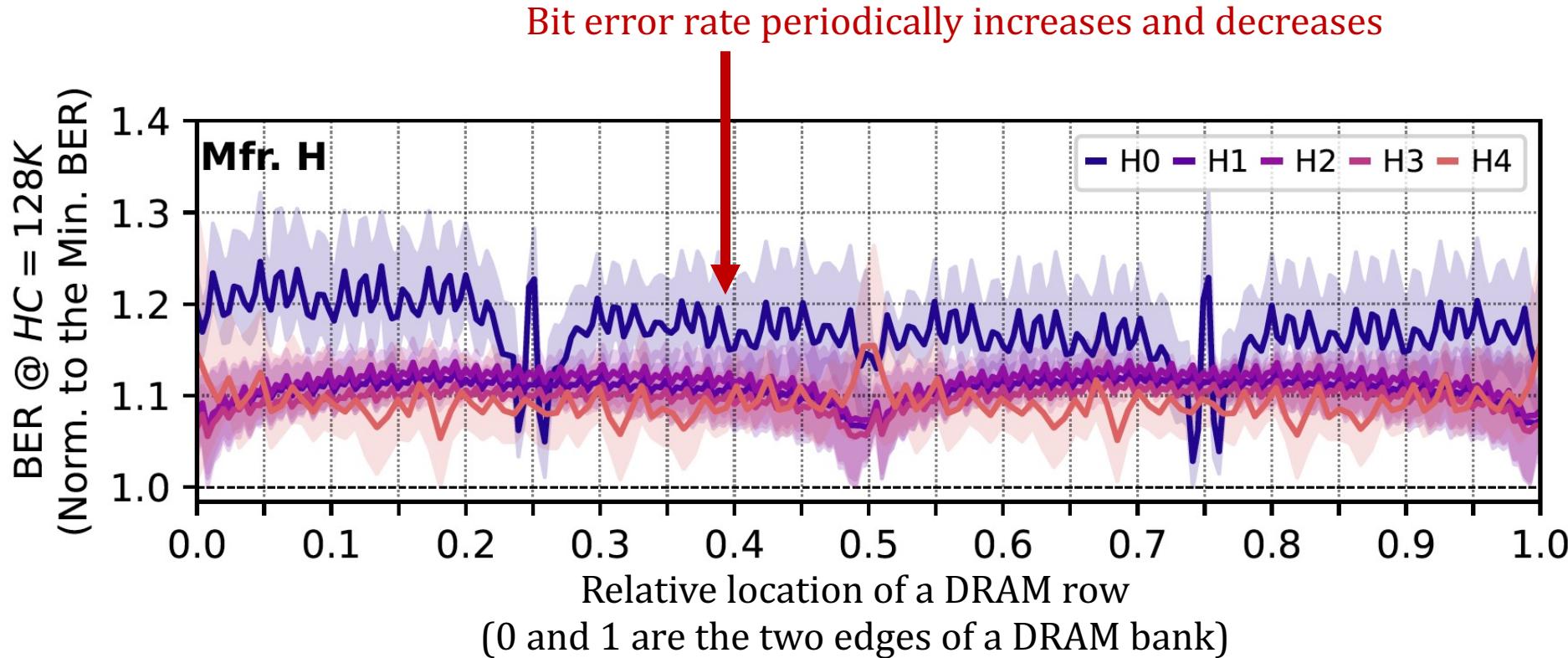
Yahya Can Tuğrul   Geraldo F. Oliveira   İsmail Emir Yüksel

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**SAFARI**

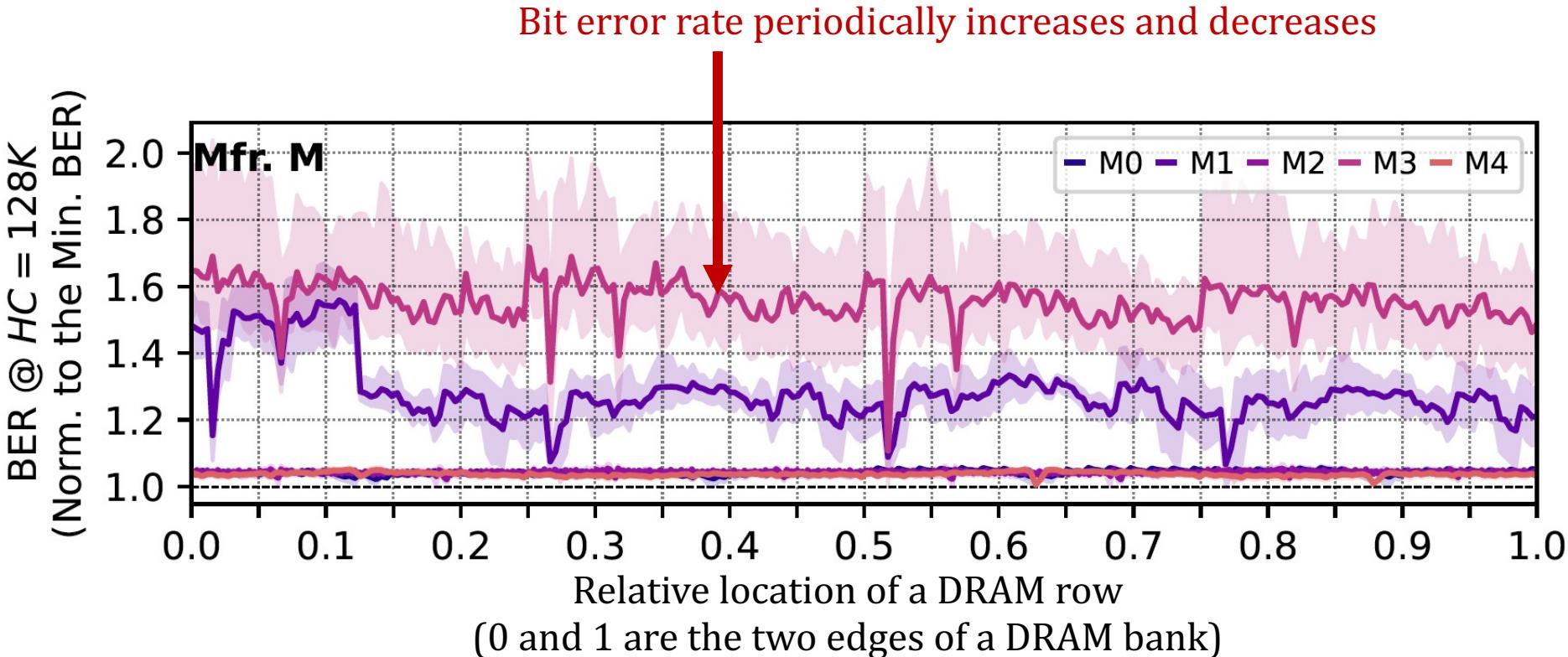
**ETH zürich**

# The Read Disturbance Bit Error Rate across DRAM Rows



The variation in read disturbance bit error rate exhibits a stronger regularity compared to the variation in varies with respect to row's location in DRAM bank

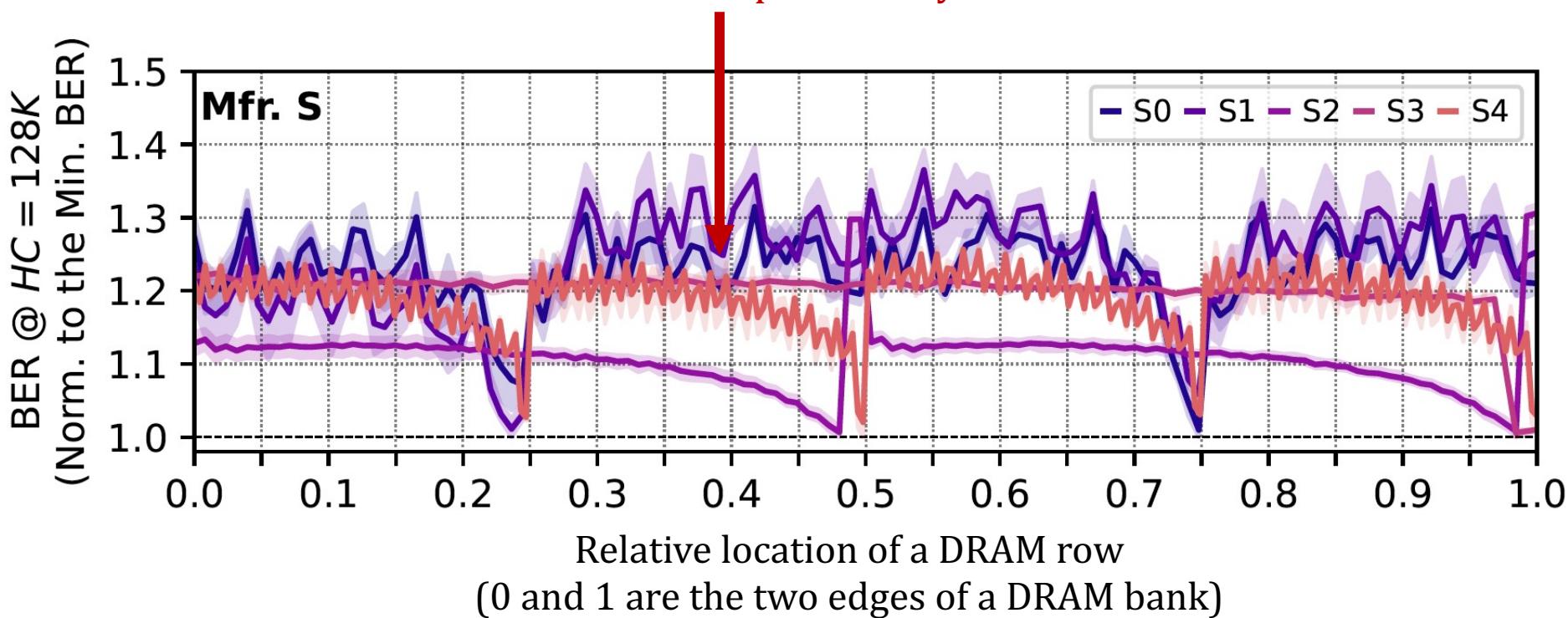
# The Read Disturbance Bit Error Rate across DRAM Rows



The variation in read disturbance bit error rate exhibits a stronger regularity compared to the variation in varies with respect to row's location in DRAM bank

# The Read Disturbance Bit Error Rate across DRAM Rows

Bit error rate periodically increases and decreases



The variation in read disturbance bit error rate exhibits a stronger regularity compared to the variation in varies with respect to row's location in DRAM bank

# Spatial Variation-Aware Read Disturbance Defenses: Experimental Analysis of Real DRAM Chips and Implications on Future Solutions

## Background



Full Paper  
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**Abdullah Giray Yağlıkçı**

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# Two Main Types of DRAM Refresh

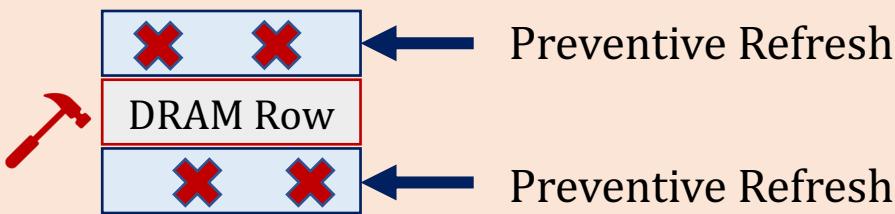
1

Periodic Refresh: Periodically **restores** the charge  
DRAM cells leak **over time**



2

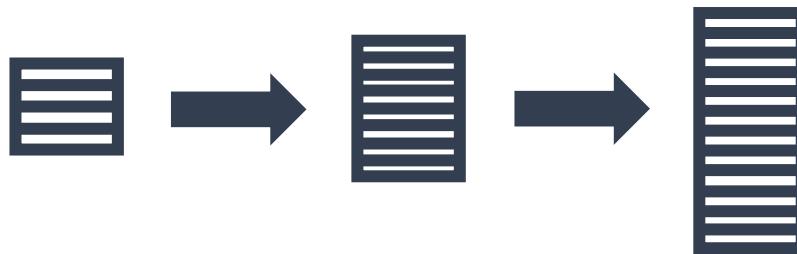
RowHammer: Repeatedly accessing a DRAM row can cause  
**bit flips** in other **physically nearby rows**



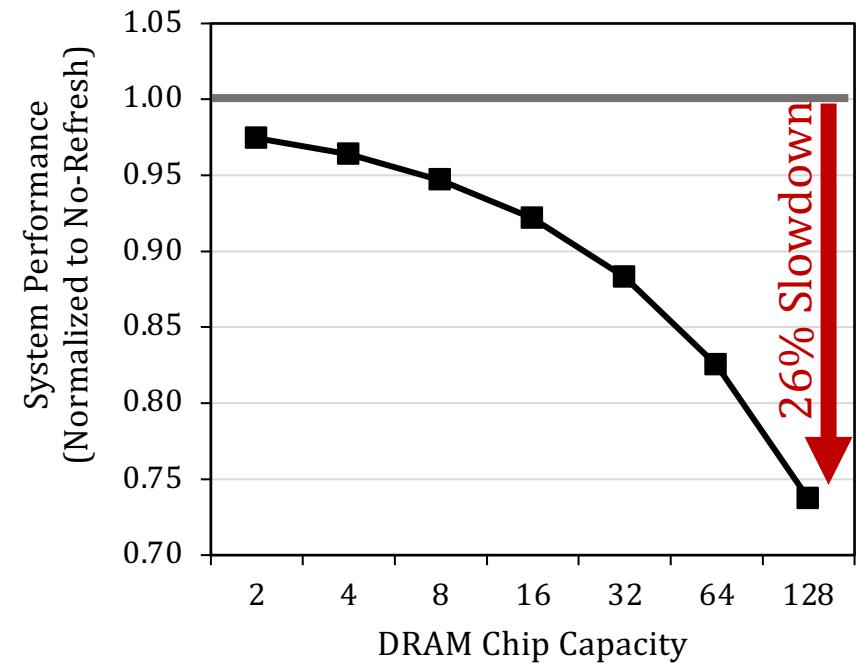
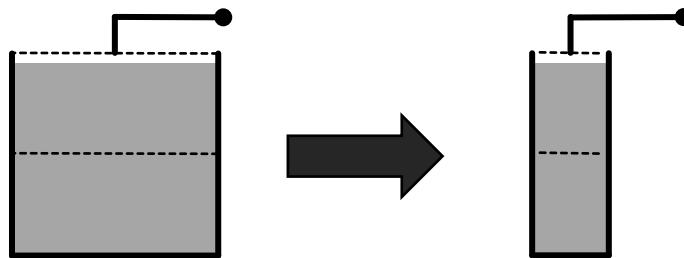
Preventive Refresh: Mitigates RowHammer  
by **refreshing physically nearby rows**  
of a repeatedly accessed row

# Periodic Refresh with Increasing DRAM Chip Density

A **larger capacity** chip has **more rows to be refreshed**



A **smaller** cell stores **less charge**



More periodic refresh operations incur larger performance overhead as DRAM **chip density increases**

# Spatial Variation-Aware Read Disturbance Defenses: Experimental Analysis of Real DRAM Chips and Implications on Future Solutions

RowPress



Full Paper  
[arXiv \[cs.CR\] 2402.18652](https://arxiv.org/abs/2402.18652)

**Abdullah Giray Yağlıkçı**

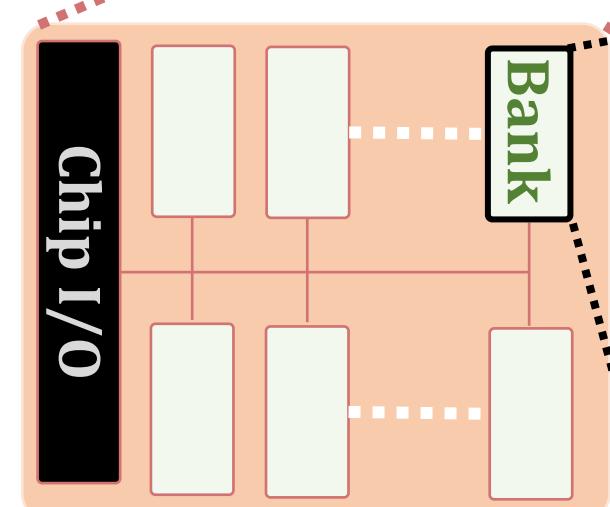
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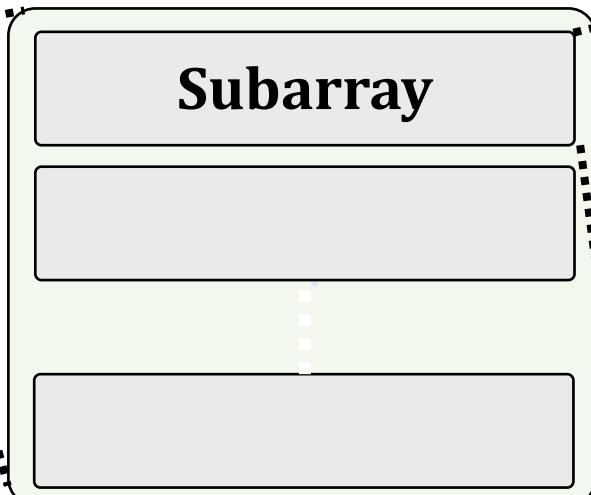
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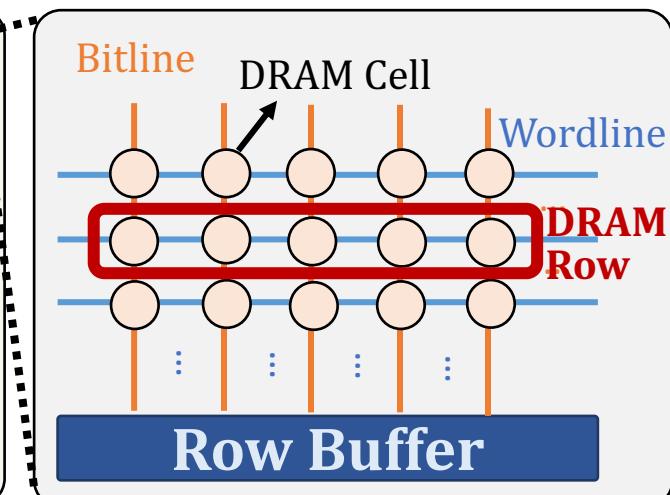
# DRAM Organization



DRAM Chip

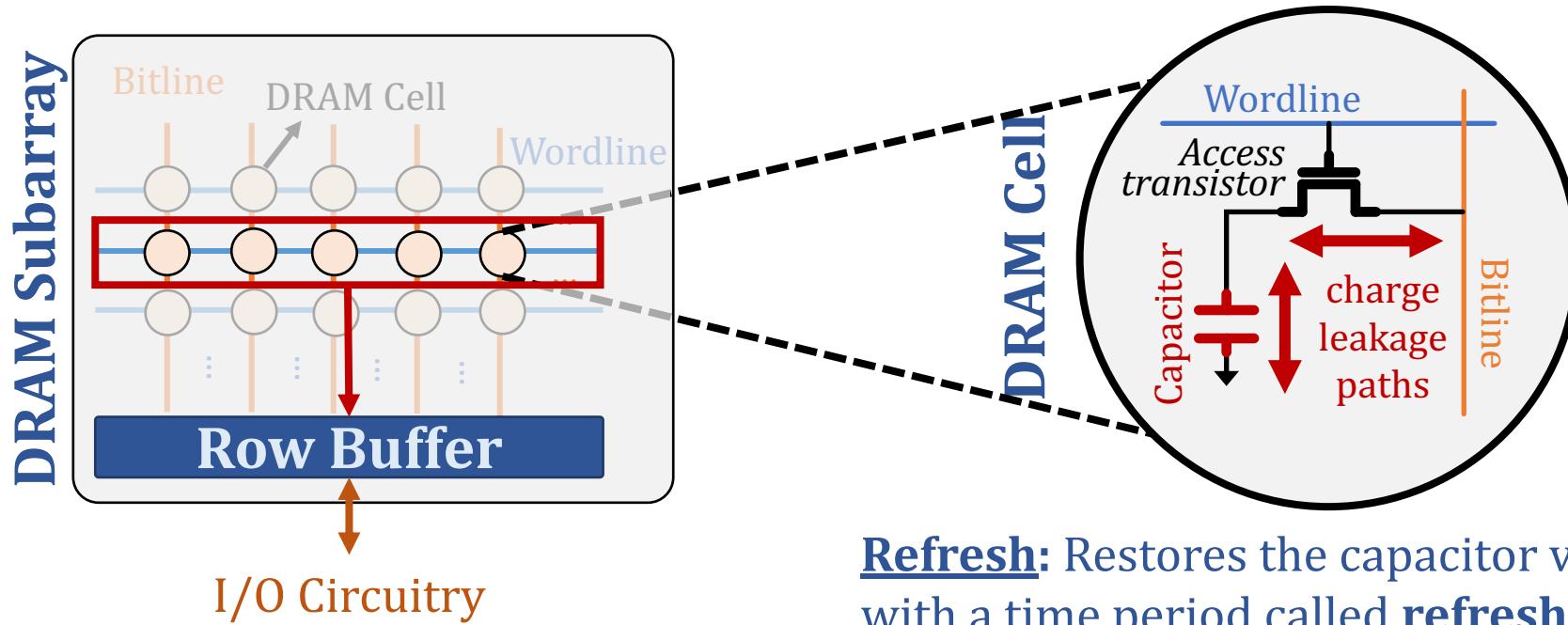


DRAM Bank



DRAM Subarray

# DRAM Operation



**Refresh:** Restores the capacitor voltage with a time period called **refresh window**

1. **Row Activation:** Fetch the row's content into the row buffer
2. **Column Access:** Read/Write a column in the row buffer
3. **Precharge:** Disconnect the row from the row buffer

# Circuit-Level Justification Temperature Analysis

We hypothesize that our observations are caused by the **non-monotonic behavior of charge trapping** characteristics of DRAM cells

## 3D TCAD model [Yang+, EDL'19]

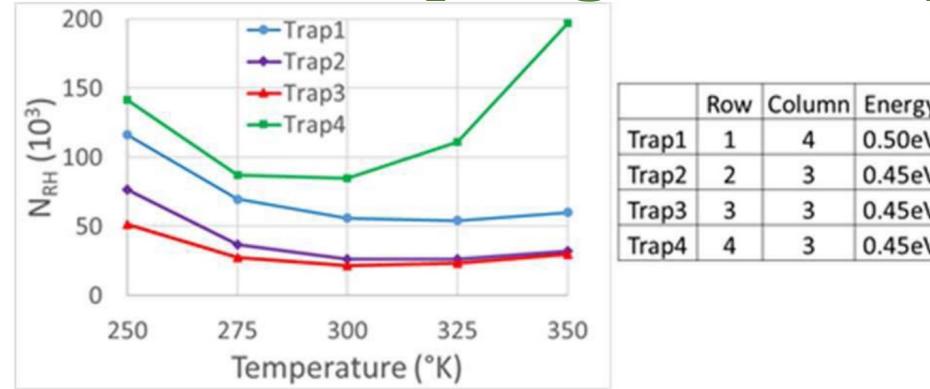


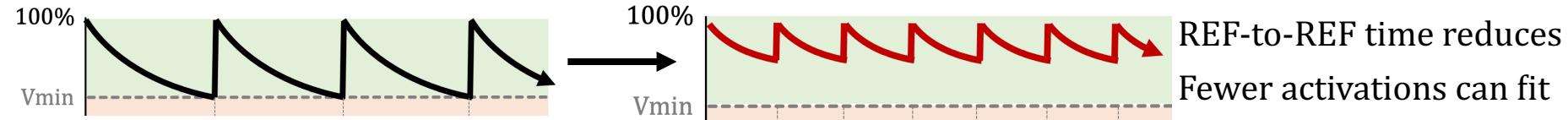
Fig. 6. Hammering threshold  $N_{RH}$  vs. temperature from 250 to 350°K for different traps. Location in row and column refers to matrix in Fig. 2b.

**$HC_{first}$  decreases as temperature increases**, until a temperature inflection point where  **$HC_{first}$  starts to increase as temperature increases**

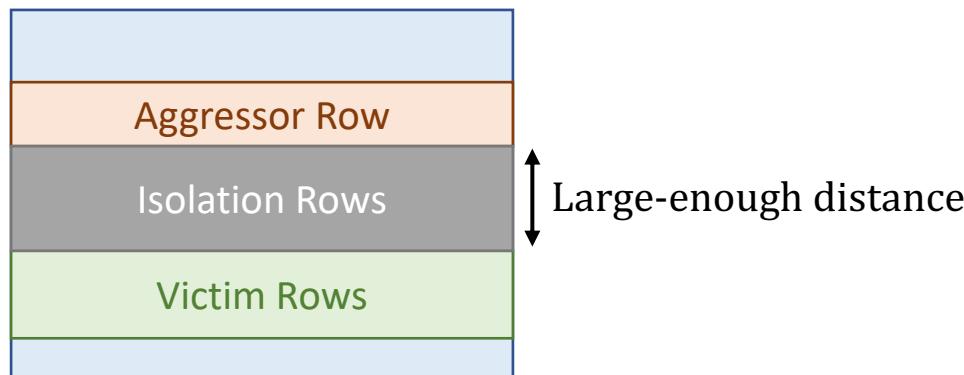
A **cell is more vulnerable** to RowHammer at **temperatures close to its temperature inflection point**

# RowHammer Mitigation Approaches

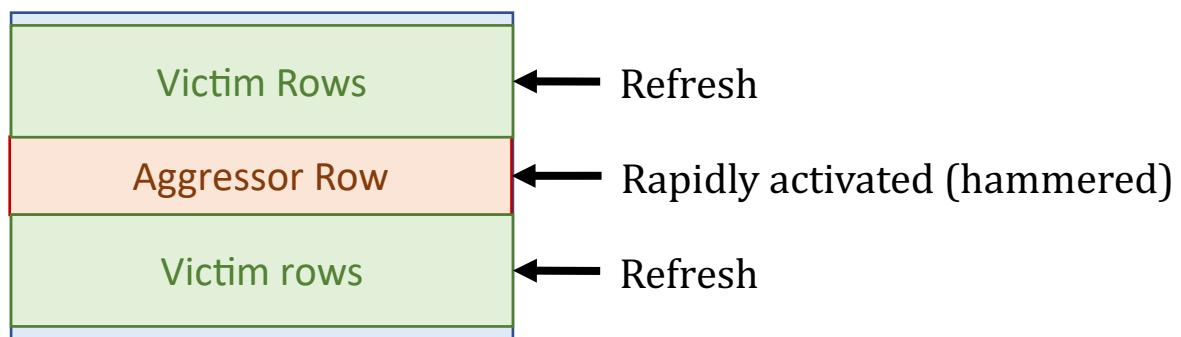
- Increased refresh rate



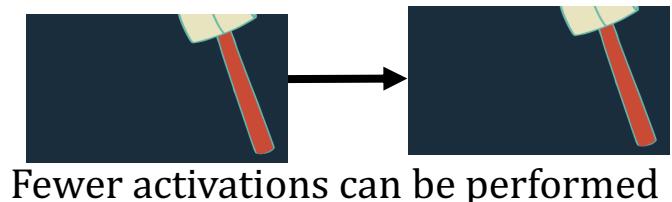
- Physical isolation



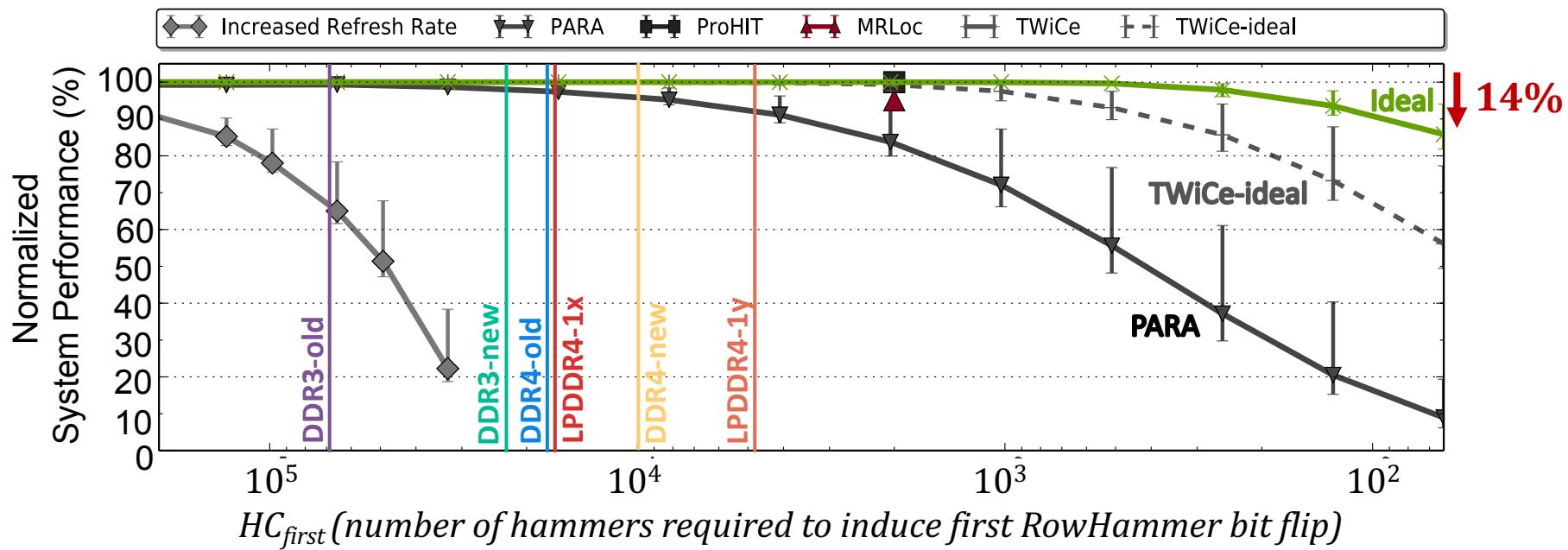
- Reactive refresh



- Proactive throttling



# RowHammer Mitigation across Generations



J. S. Kim, M. Patel, A. G. Yaglikci, H. Hassan, R. Azizi, L. Orosa, and O. Mutlu, "[Revisiting RowHammer: An Experimental Analysis of Modern Devices and Mitigation Techniques](#)," in *ISCA*, 2020.

# RowPress [ISCA 2023]

- Haocong Luo, Ataberk Olgun, Giray Yaglikci, Yahya Can Tugrul, Steve Rhyner, M. Banu Cavlak, Joel Lindegger, Mohammad Sadrosadati, and Onur Mutlu,  
**"RowPress: Amplifying Read Disturbance in Modern DRAM Chips"**  
*Proceedings of the 50th International Symposium on Computer Architecture (ISCA), Orlando, FL, USA, June 2023.*  
[\[Slides \(pptx\) \(pdf\)\]](#)  
[\[Lightning Talk Slides \(pptx\) \(pdf\)\]](#)  
[\[Lightning Talk Video \(3 minutes\)\]](#)  
[\[RowPress Source Code and Datasets \(Officially Artifact Evaluated with All Badges\)\]](#)  
***Officially artifact evaluated as available, reusable and reproducible.***  
***Best artifact award at ISCA 2023.***

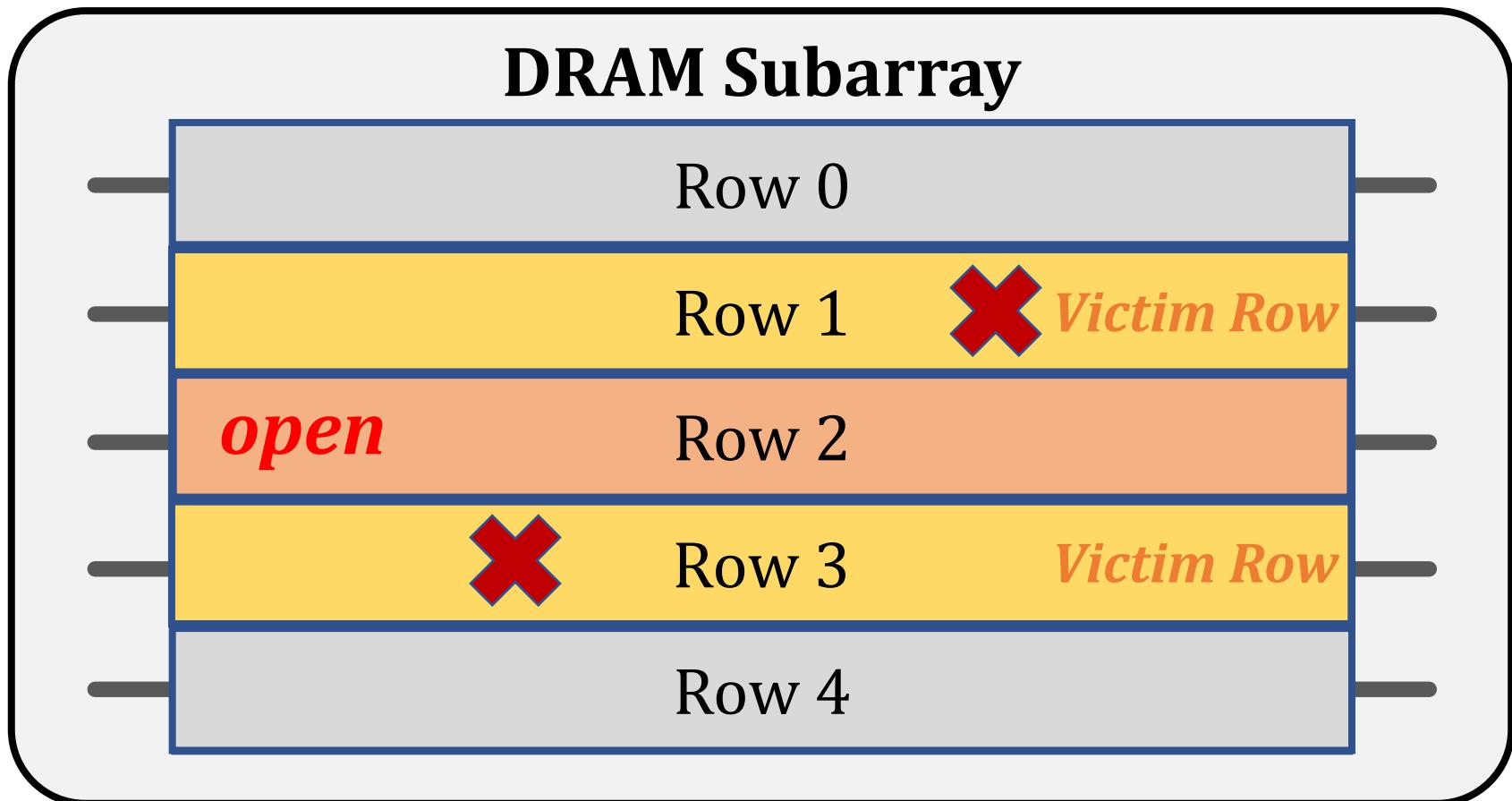


## RowPress: Amplifying Read-Disturbance in Modern DRAM Chips

Haocong Luo   Ataberk Olgun   A. Giray Yağlıkçı   Yahya Can Tuğrul   Steve Rhyner  
Meryem Banu Cavlak   Joël Lindegger   Mohammad Sadrosadati   Onur Mutlu

ETH Zürich

# RowPress A New DRAM Read Disturbance Phenomenon

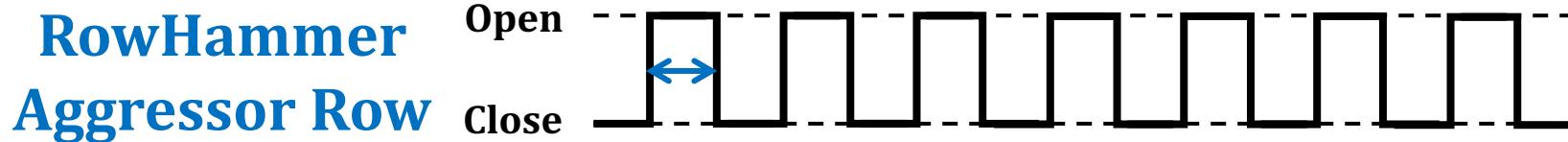


Keeping a DRAM row **open** (activated)  
causes **RowPress bitflips** in nearby cells

# Two Prime Examples of DRAM Read Disturbance: RowHammer and RowPress

Instead of using a high activation count,

- ☛ increase the time that the aggressor row stays open



# RowPress [ISCA 2023]

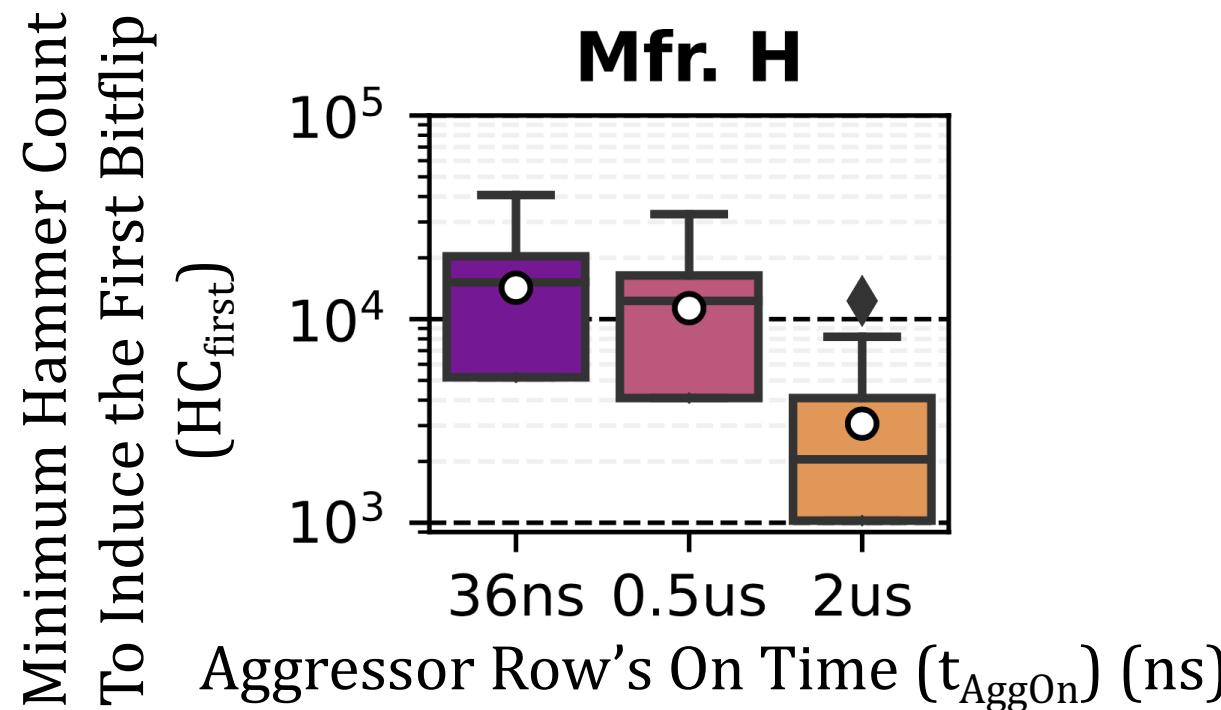
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## RowPress: Amplifying Read-Disturbance in Modern DRAM Chips

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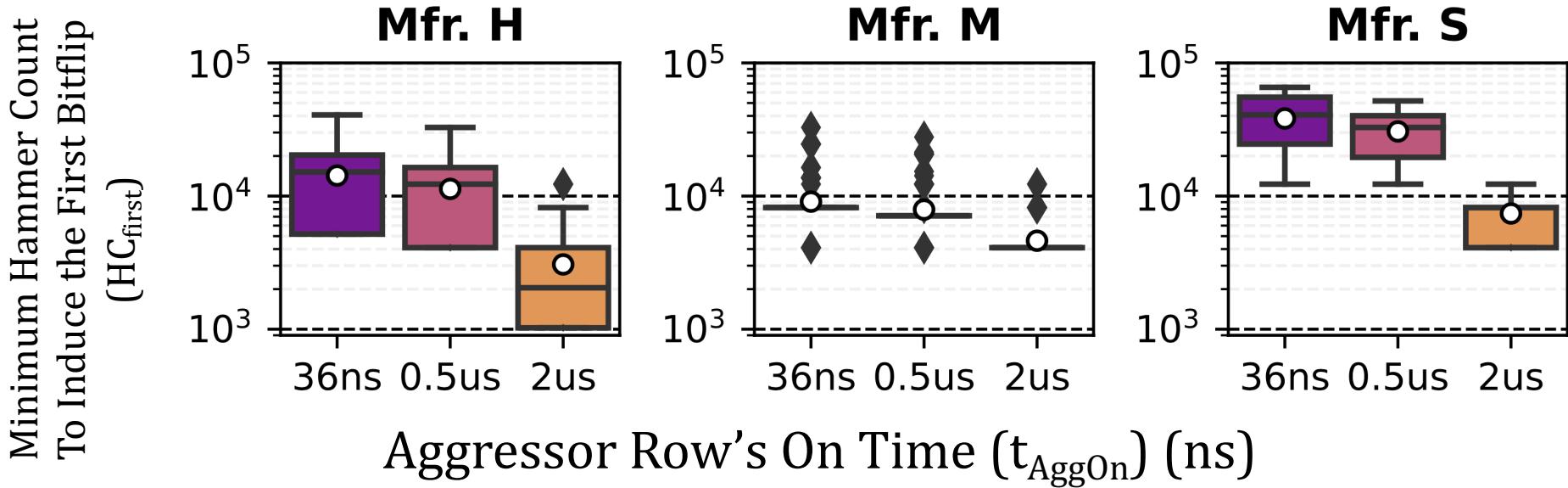
# Effect of RowPress on Spatial Variation of Read Disturbance Vulnerability across Rows



RowPress reduces the mean of the distribution with increased  $t_{\text{AggOn}}$

There is still significant variation in the HC<sub>first</sub> across rows

# Effect of RowPress on the HCfirst Distribution



Bitflips occur at **lower hammer counts** with RowPress and these hammer counts still **significantly vary** across DRAM rows

# Spatial Variation-Aware Read Disturbance Defenses: Experimental Analysis of Real DRAM Chips and Implications on Future Solutions

Predictability



Full Paper  
[arXiv \[cs.CR\] 2402.18652](https://arxiv.org/abs/2402.18652)

**Abdullah Giray Yağlıkçı**

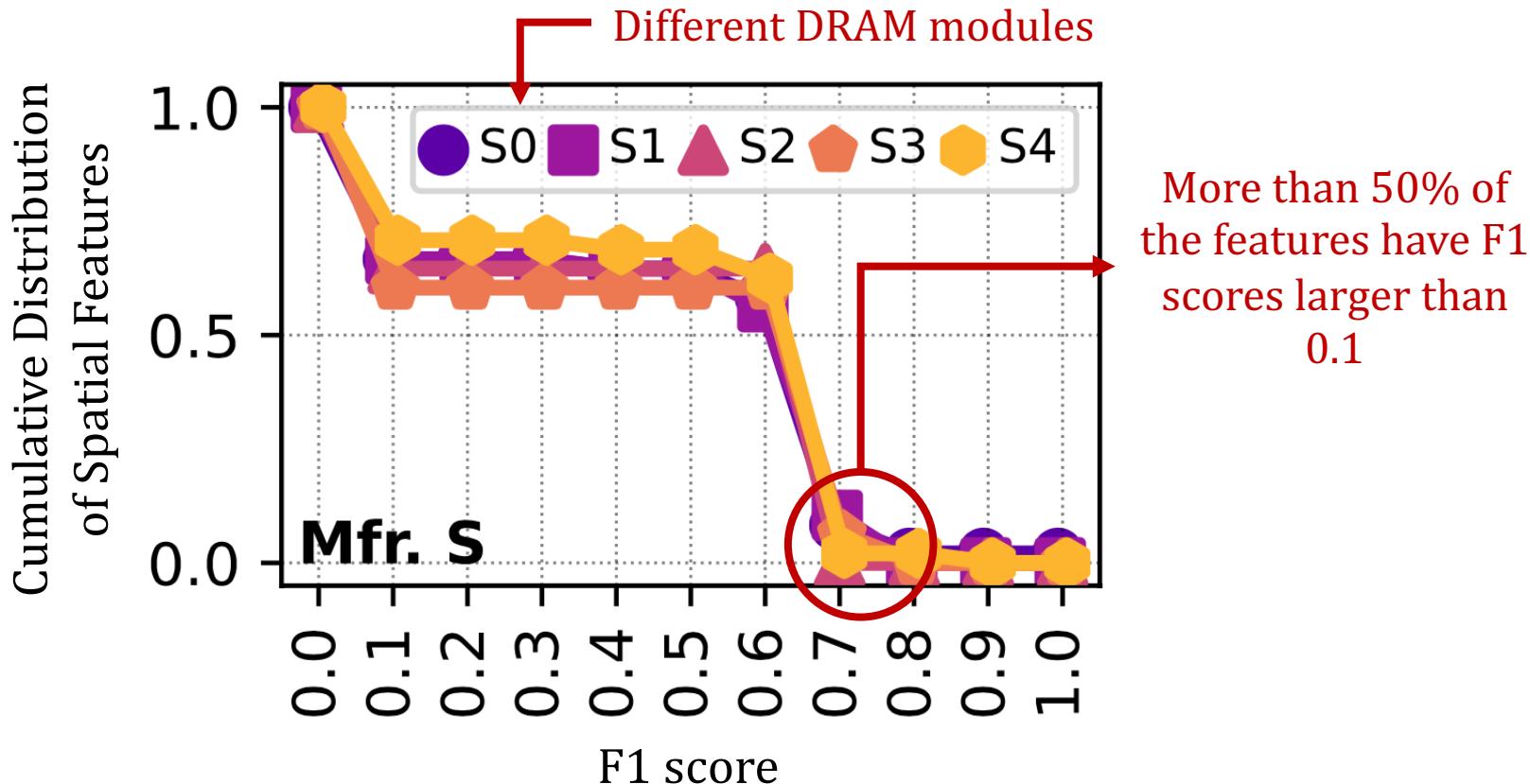
Yahya Can Tuğrul   Geraldo F. Oliveira   İsmail Emir Yüksel

Ataberk Olgun   Haocong Luo   Onur Mutlu

**SAFARI**

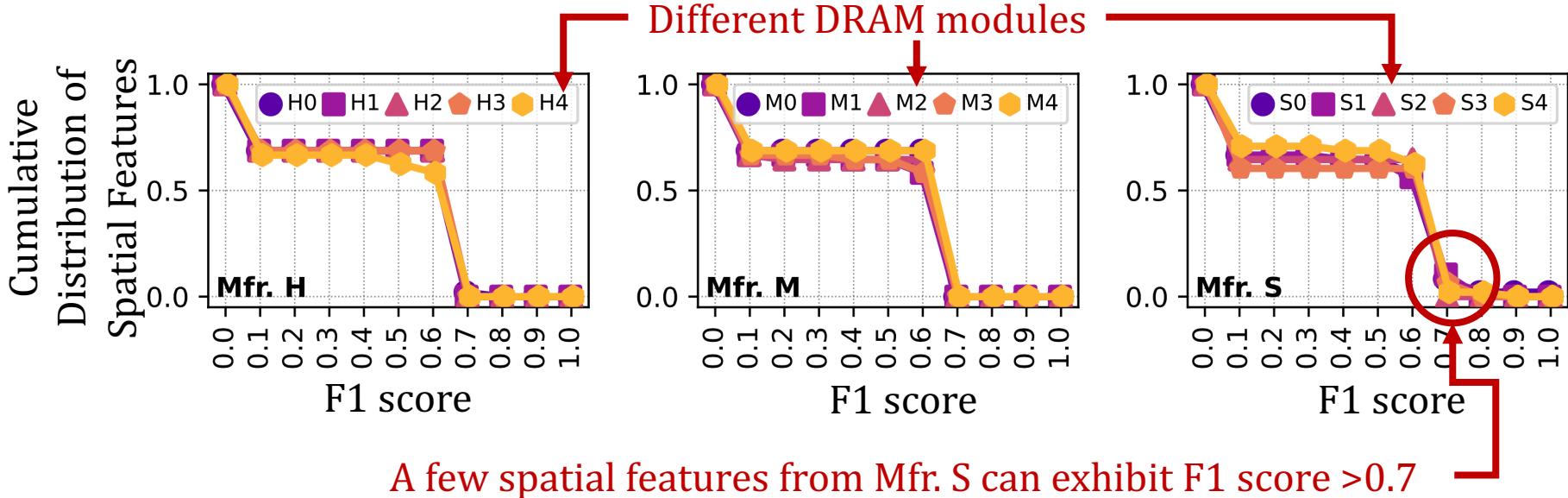
**ETH zürich**

# Cumulative Distribution of Spatial Features based on F1 Score



Weak prediction observed between a row's **spatial features** & read disturbance **vulnerability**

# Cumulative Distribution of Spatial Features based on F1 Score



Weak prediction observed between a row's  
**spatial features** & read disturbance **vulnerability**

# Spatial Variation-Aware Read Disturbance Defenses: Experimental Analysis of Real DRAM Chips and Implications on Future Solutions

Implementation Details



Full Paper  
[arXiv \[cs.CR\] 2402.18652](https://arxiv.org/abs/2402.18652)

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# Svärd: Spatial Variation-Aware Read Disturbance Defenses

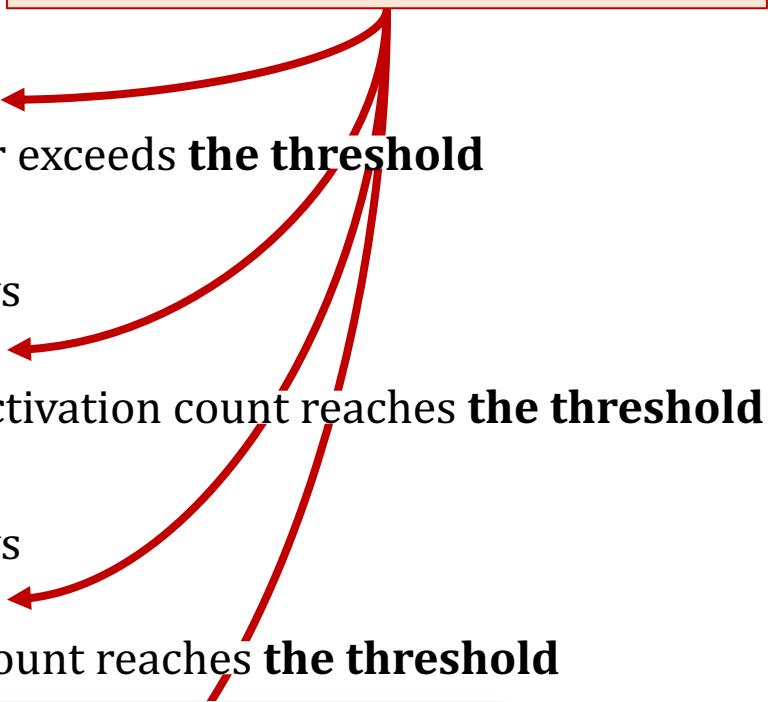
## Integration Examples with Existing Defenses

- Integrate Svärd with five solutions

### 1) PARA [Kim+, ISCA'14]

- Generates **a random number**
- Compares the random number with **a threshold**
- **Refreshes the victim row** if the random number exceeds **the threshold**

Svärd tunes **the threshold** based on the **victim row's vulnerability**



### 2) BlockHammer [Yaglikci+, HPCA'21]

- Counts **the number of activations** of DRAM rows
- Compares the activation count **with a threshold**
- **Throttles accesses** to the aggressor row if the activation count reaches **the threshold**

### 3) Hydra [Qureshi+, ISCA'22]

- Counts **the number of activations** of DRAM rows
- Compares the activation count **with a threshold**
- **Refreshes the victim row** when the activation count reaches **the threshold**

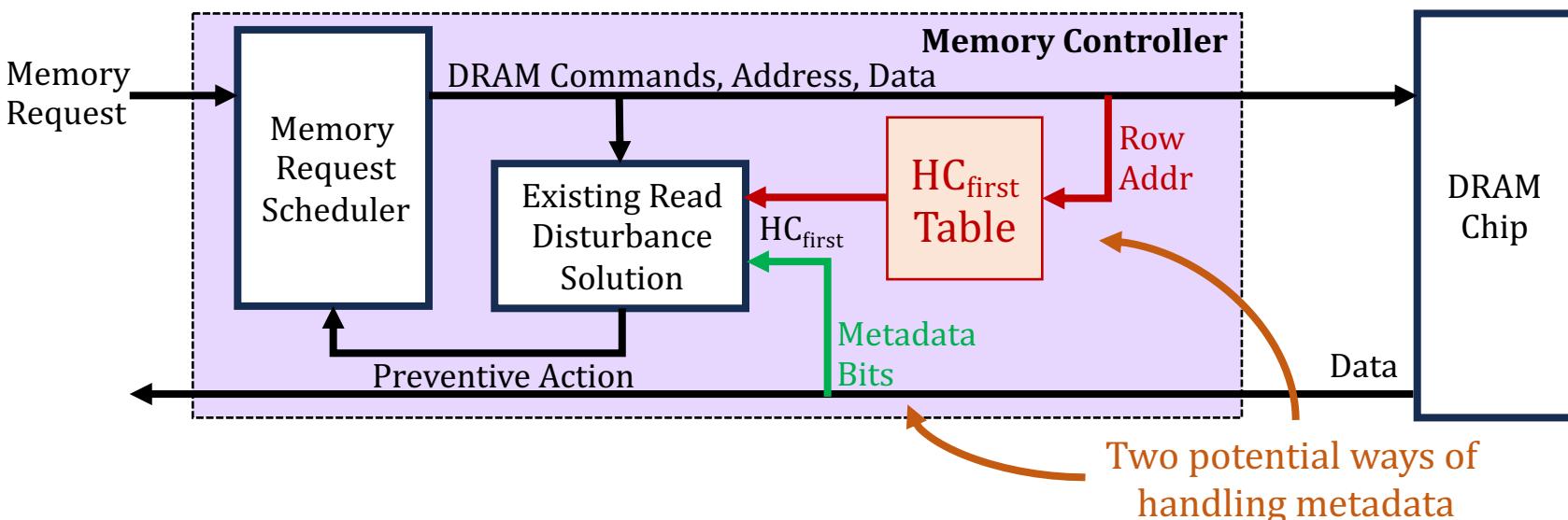
### 4) AQUA [Saxena+, MICRO'22] and 5) RRS [Saileshwar+, ASPLOS'22]

- Counts **the number of activations** of DRAM rows
- Compares the activation count **with a threshold**
- **Relocates the aggressor row** when the activation count reaches **the threshold**

# Svärd: Spatial Variation-Aware Read Disturbance Defenses

## Example Implementation 1

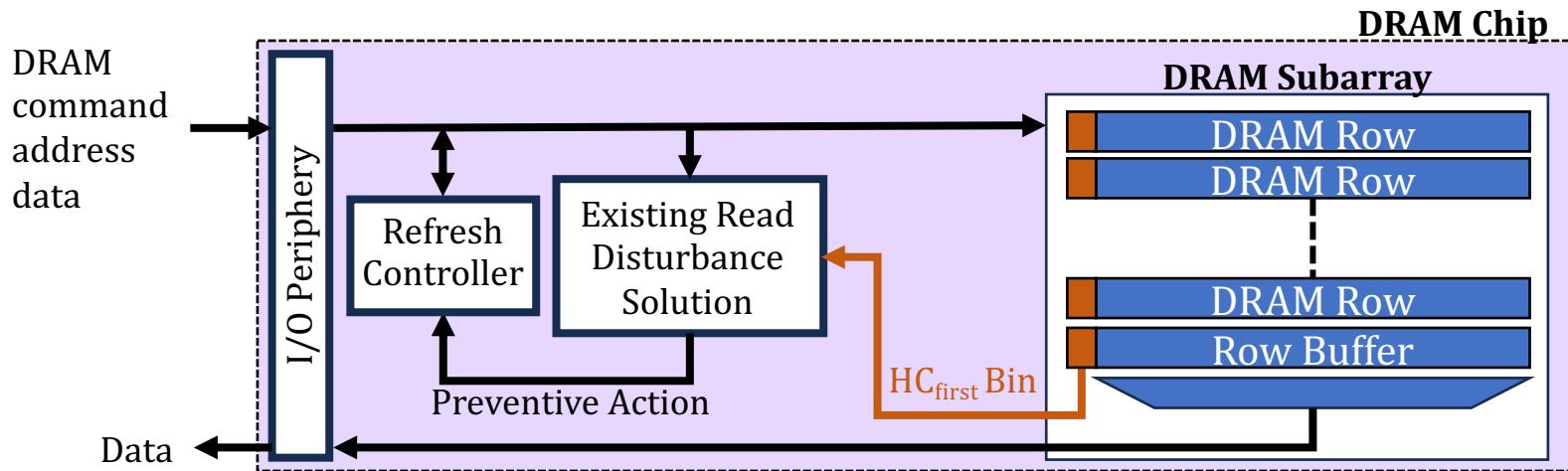
- Classifies DRAM rows into **several vulnerability-level bins**
  - Maintains **a few (e.g., four) bits** per DRAM row
- Implemented in either the memory controller or the DRAM chip
- Two example memory controller-based implementations:



# Svärd: Spatial Variation-Aware Read Disturbance Defenses

## Example Implementation 2

- Classifies DRAM rows into **several vulnerability-level bins**
  - Maintains **a few (e.g., four) bits** per DRAM row
- Implemented in either the memory controller or the DRAM chip
- An example DRAM chip-based implementation:
  - **Additional few (e.g., four) bits** per DRAM row (e.g., 8Kb)



# Spatial Variation-Aware Read Disturbance Defenses: Experimental Analysis of Real DRAM Chips and Implications on Future Solutions

Backup Slides

**Abdullah Giray Yağlıkçı**

Yahya Can Tuğrul   Geraldo F. Oliveira   İsmail Emir Yüksel  
Ataberk Olgun   Haocong Luo   Onur Mutlu

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