Dissecting Performance Overheads of *Confidential Computing in GPU-based Systems*

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Executive Summary

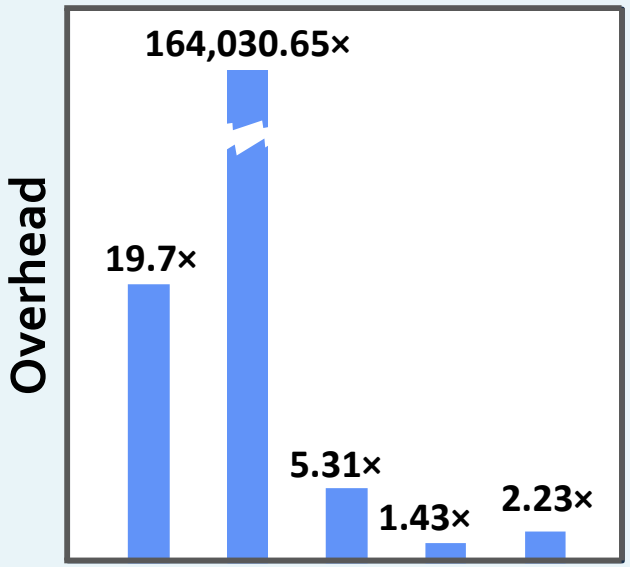
Problem:

- Confidential Computing **with GPU** is emerging
- Existing work lacks **detailed** performance **dissection**
- **Optimization insights** remain unclear due to limited characterization

Goal: Dissect the **performance overheads** of GPU-based confidential computing that can motivate various optimizations to address them.

Our results on real hardware show that GPU-based CC comes with:

- **Data Movement** Overhead (up to 19.7×)
- Low **Encryption** Throughput (3.36 GB/s)
- Kernel **Execution** Time (up to 164,030.65× with **UVM**)
- Kernel **Launch** Overhead (up to 5.31×)
- **Queueing** (1.43× and 2.23× on average)
- **Fusion**, **overlapping** and **quantization**

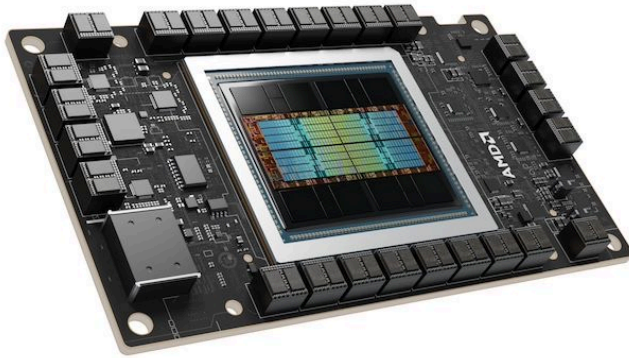


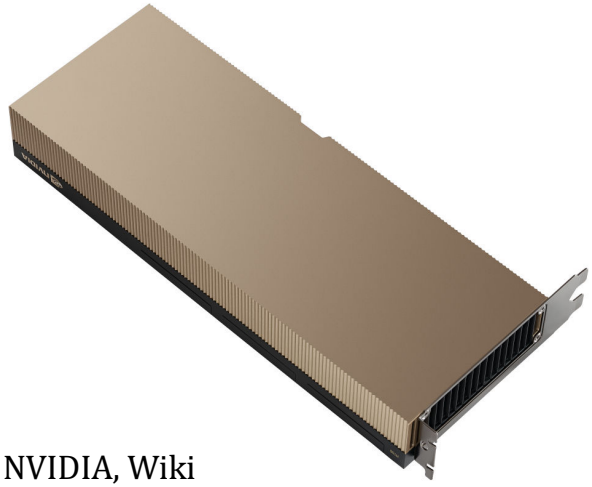
https://github.com/insight-cal-uva/hcc-ispass25-artifact

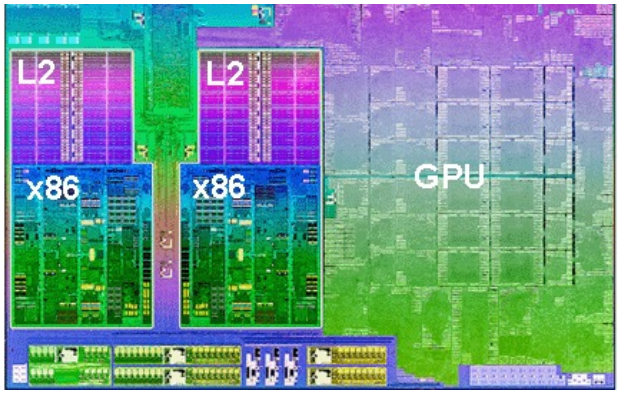
Graphics Processing Units (GPUs)

DL/ML/AI | Graphics | HPC | Crypto | Graphs | Genomics

Abundant Data and Task-level Parallelism







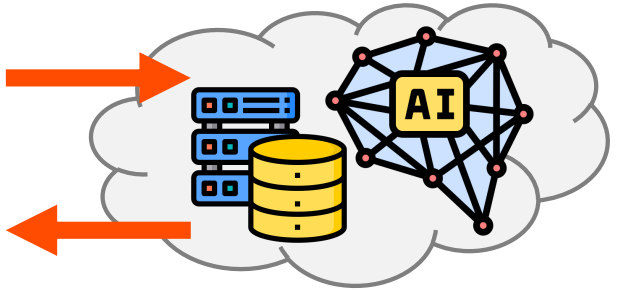
Credit/Source: AMD, NVIDIA, Wiki

High Throughput + Energy Efficiency

Needs for Security and Privacy

- ***Data is Private***
  - Client privacy (chat bot, …)
  - Regulated (GDPR, PII, …)

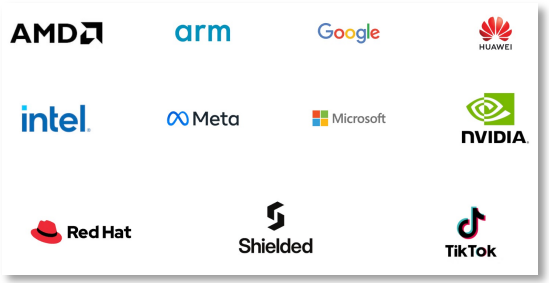
GDPR.EU

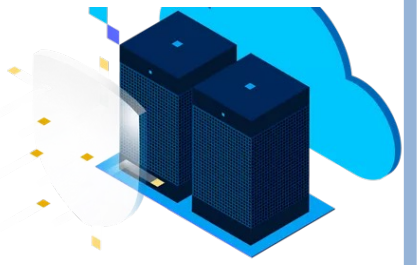


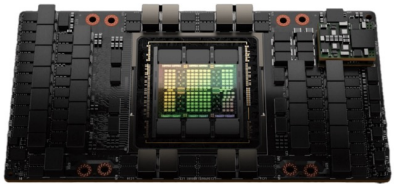
- ***Data is Massive***
  - Outsource compute & data to public cloud Infra.

Can cloud service providers be trusted?

Trusted Computing





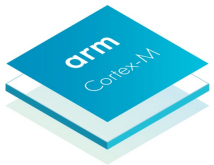


The first commercial GPU TEE

NVIDIA HCC **2023**

CPUs With TDX

Intel SPR **2023** Intel EMR **2023**



CONFIDENTIAL COMPUTING CONSORTIUM

ARM TrustZone **2002**

Intel SGX **2015**

AMD SEV **2016**

CC Consortium **2019**

Intel TDX **2020**

AMD SEV-SNP **2020**

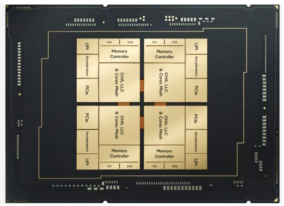
ARM CCA **2021**

VM-based Isolation

RISC-V KeyStone **2019**

RISC-V Penglai **2020**

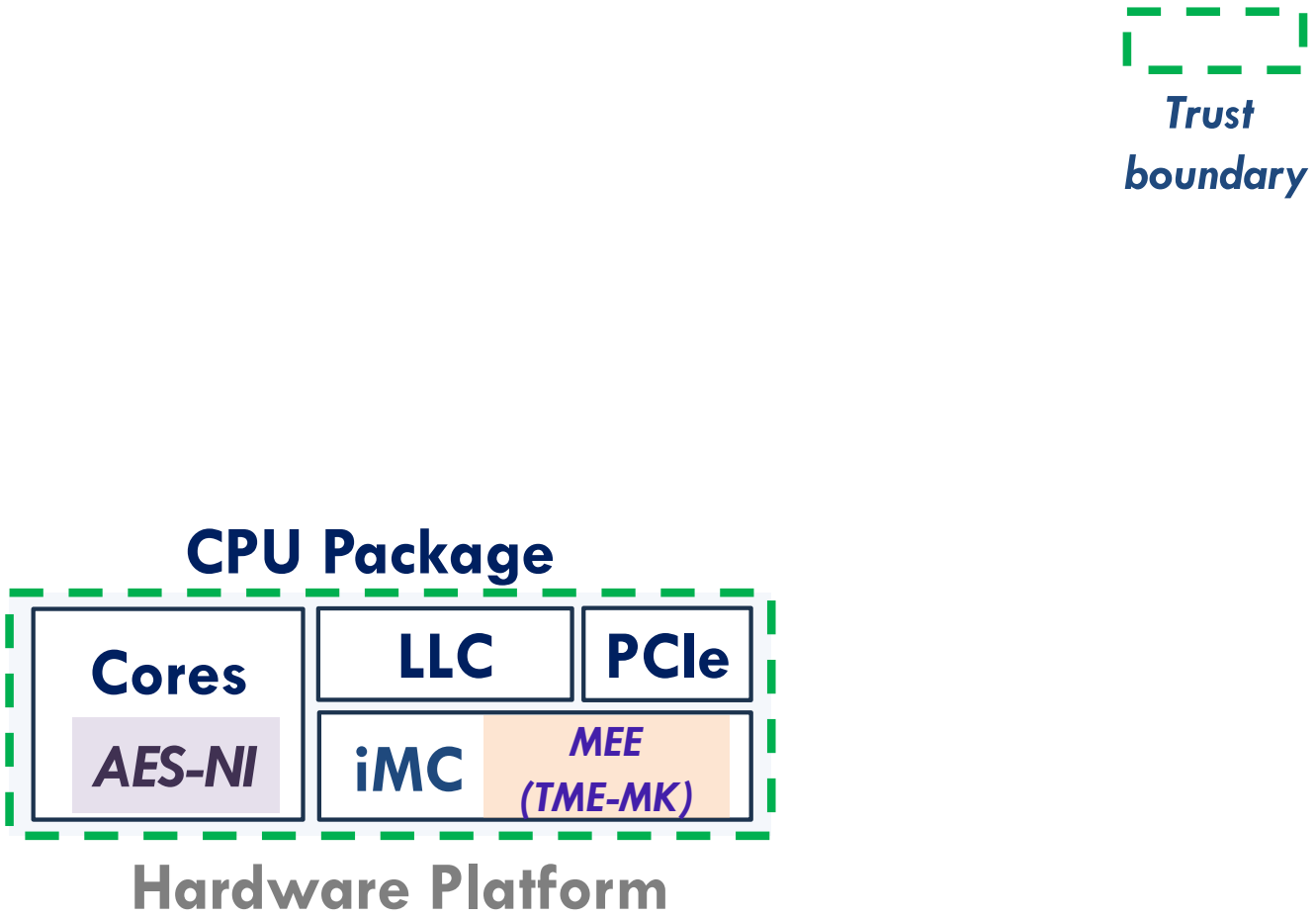
RISC-V®



GPU-based CC

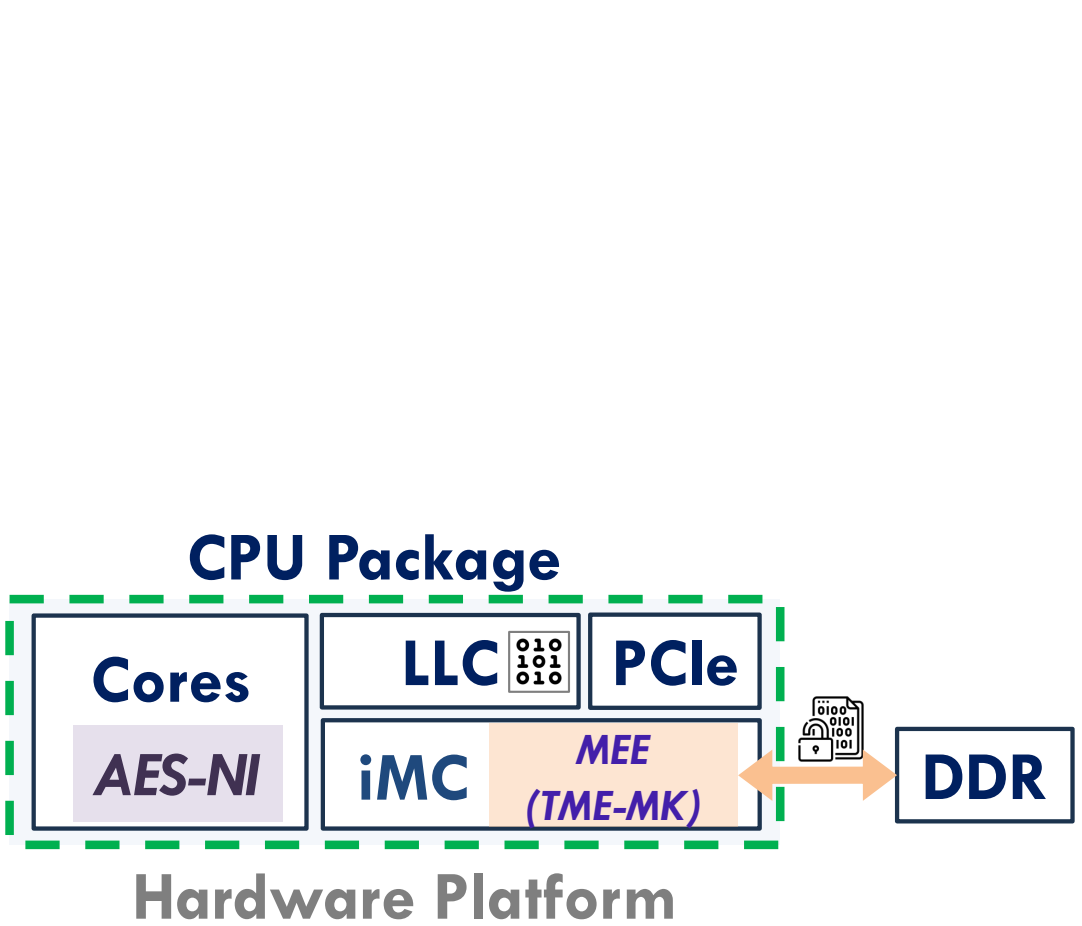
Credit/Source: ARM/INTEL/AMD/CCC/RISC-V/NVIDIA/Wiki

Confidential Computing



MEE: Memory Encryption Engine

Confidential Computing



MEE: Memory Encryption Engine

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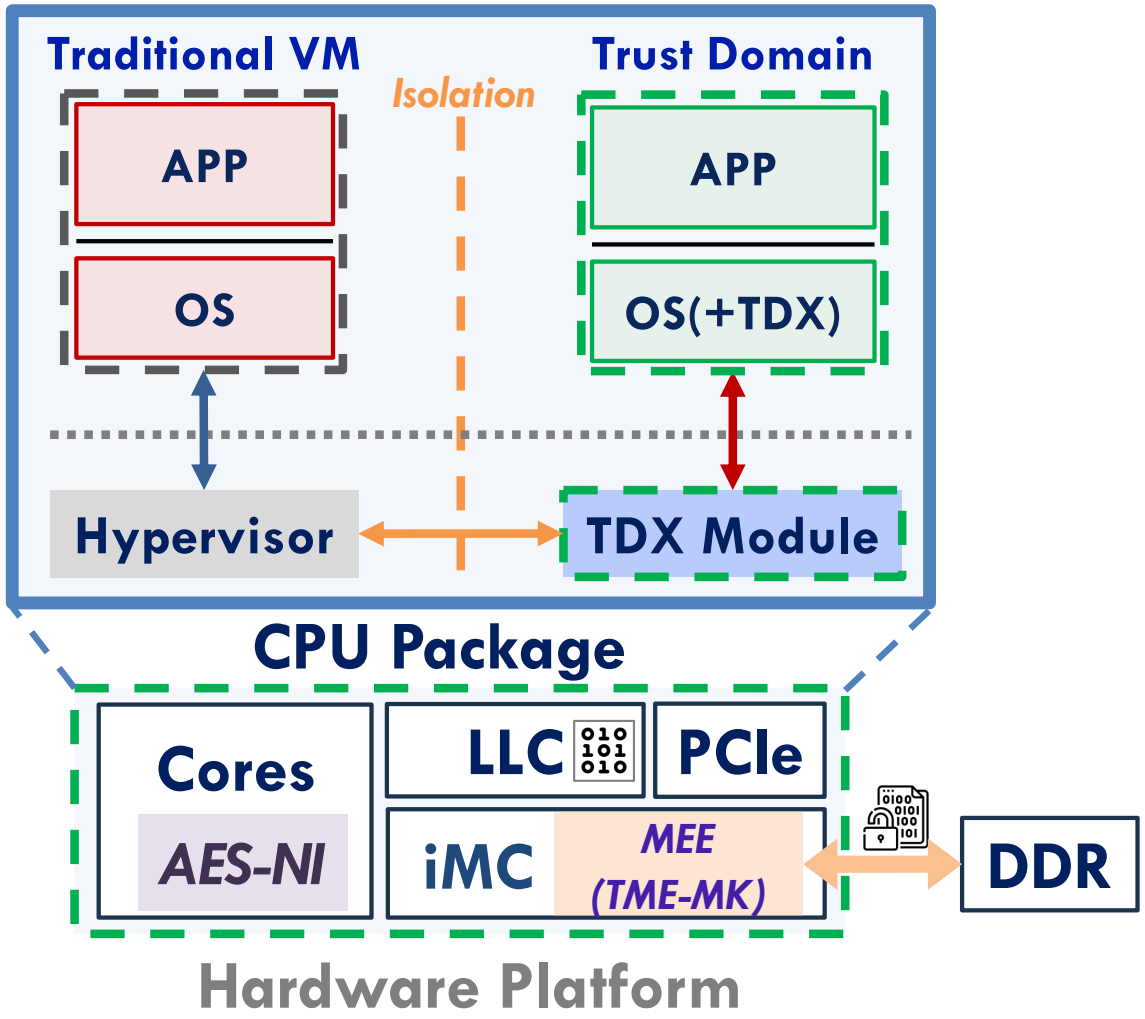
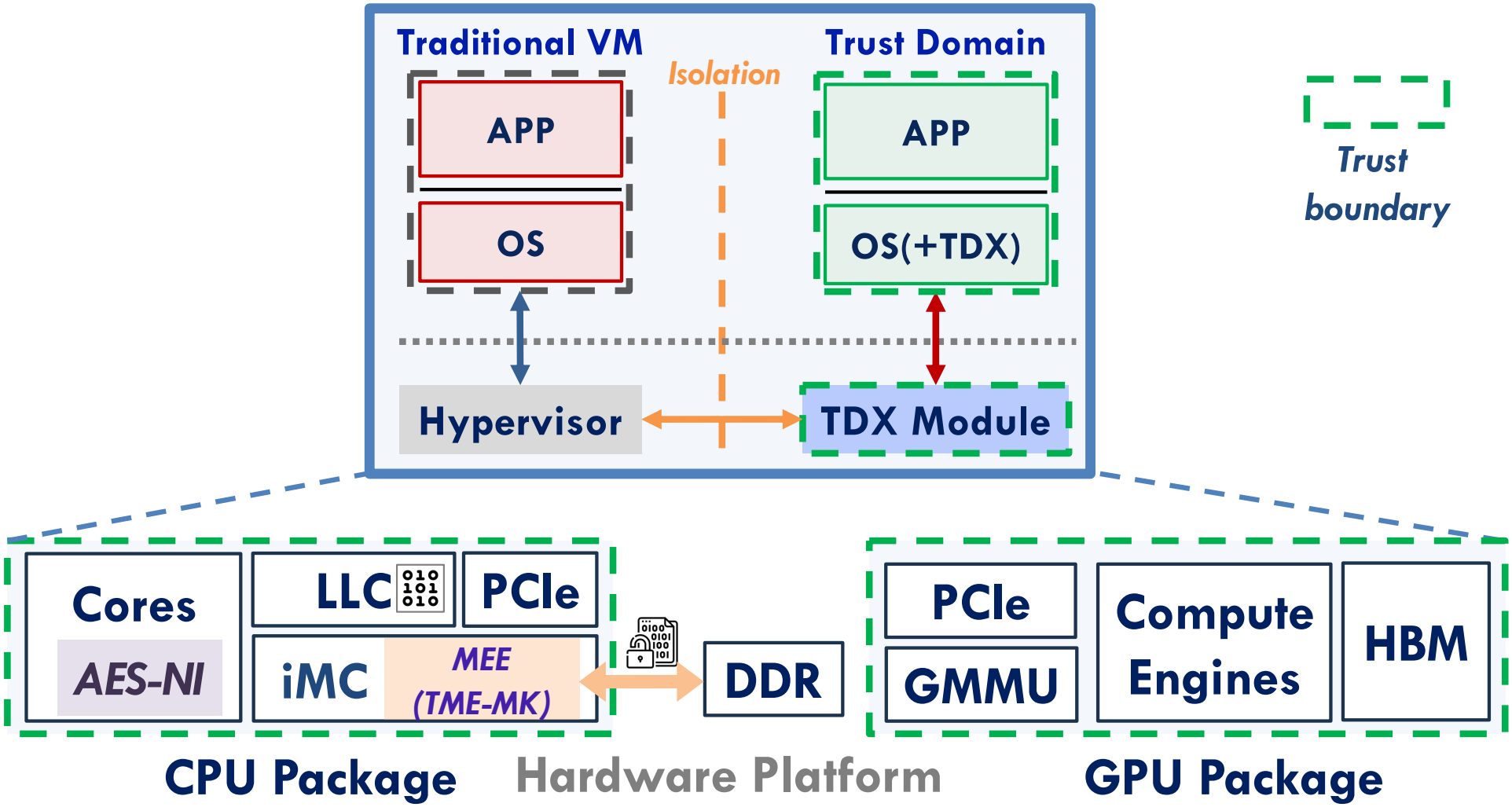


MEE: Memory Encryption Engine

Confidential Computing with GPU



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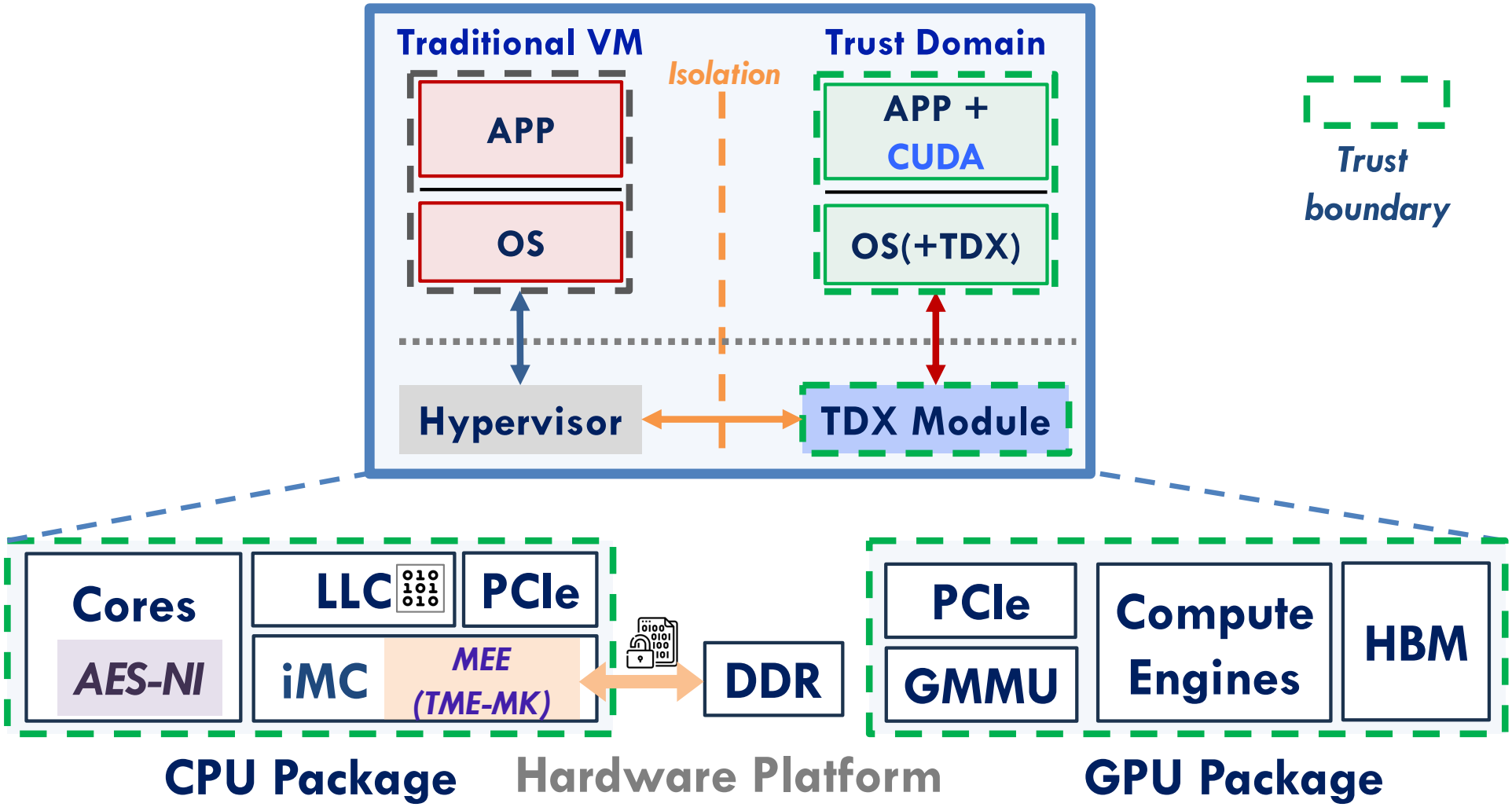

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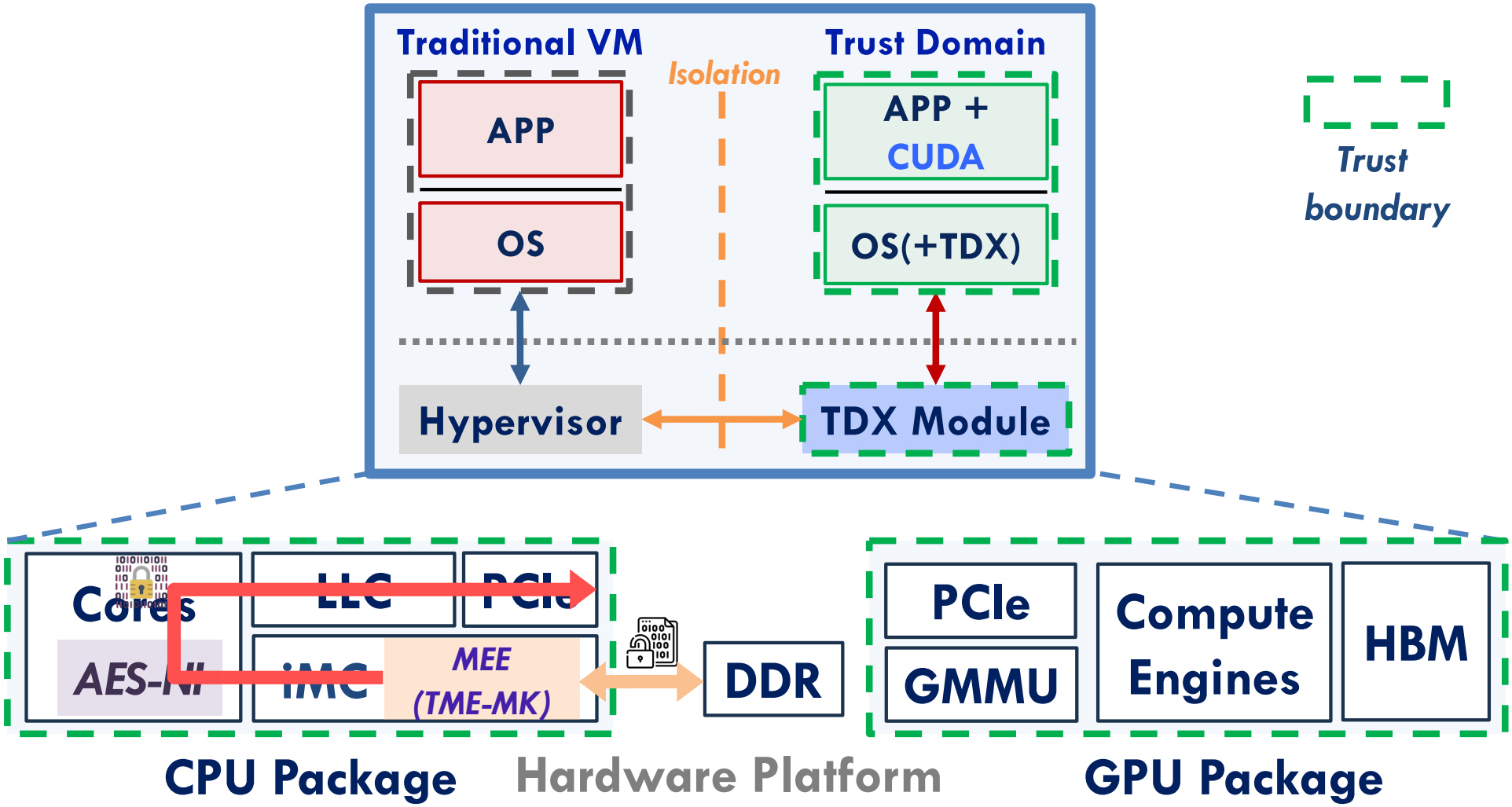
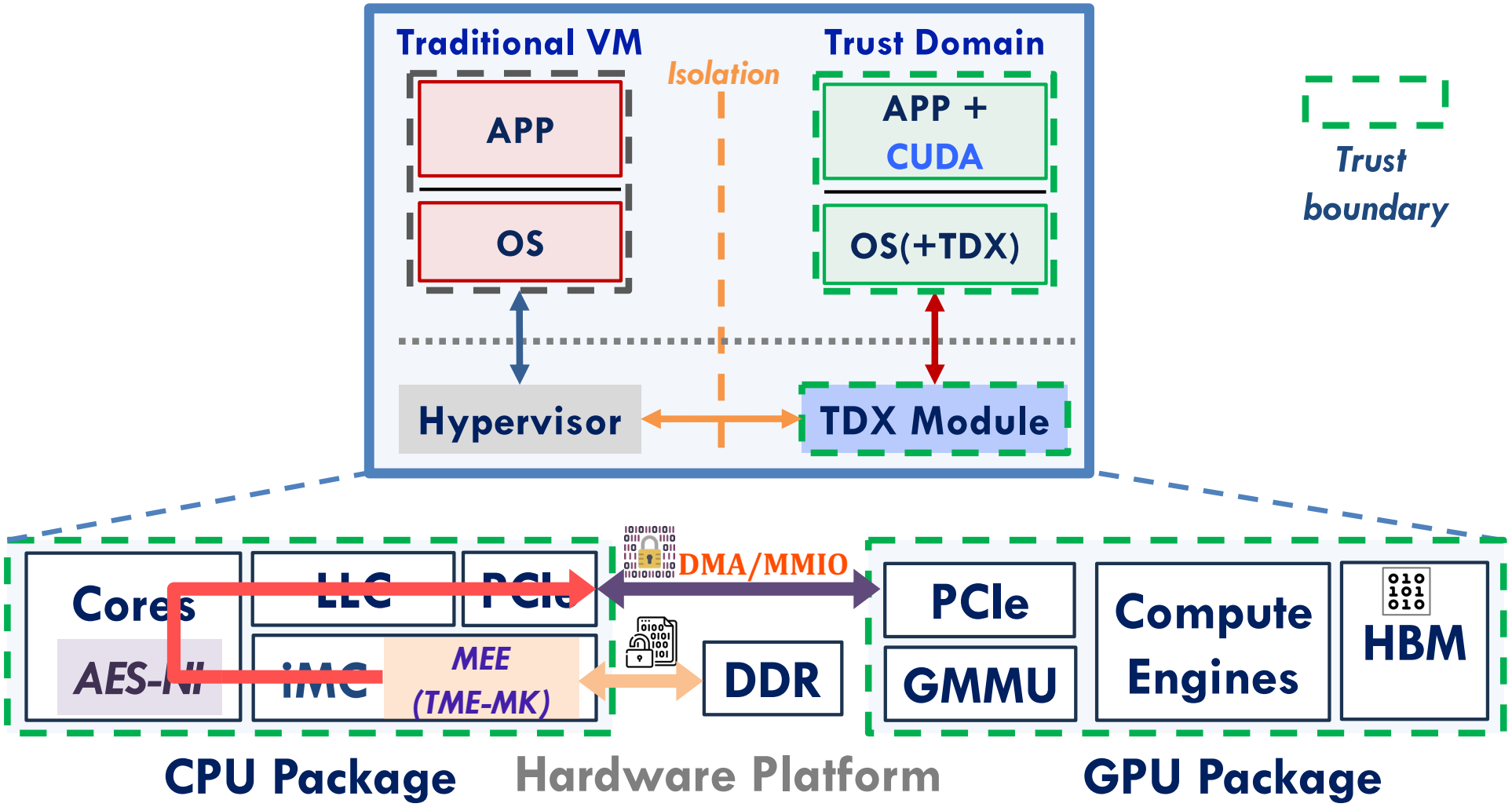


MEE: Memory Encryption Engine

Confidential Computing with GPU

Communication (MMIO/DMA) will trigger #VE, TD will context-switch



MEE: Memory Encryption Engine

Real World Setup

https://github.com/insight-cal-uva/hcc-ispass25-artifact

System Configuration

Configuration	Details
CPU	2× 5th Gen Intel Xeon 6530 Gold @2.1GHz, 32 cores
TME-MK	Auto bypass enabled
OS	Ubuntu 22.04.5 LTS (Linux 6.2.0, tdx patched)
Hypervisor	QEMU 7.2.0 (tdx patched)
TDX Tools	TDX 1.5 (tag 2023ww15)
GPU	NVIDIA H100 NVL, 94GB HBM3, PCIe 5.0 ×16 CUDA 12.4, Driver 550.127.05

CC-capable CPUs: support TDX or SEV-SNP

H100 is the first GPU that supports CC.

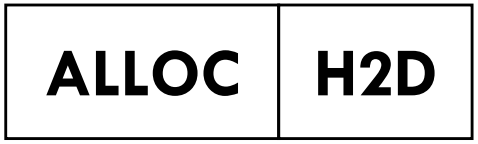
Problem:

- Confidential Computing **with GPU** is emerging
- Existing work lacks **detailed** performance **dissection**
- **Optimization insights** remain unclear due to limited characterization

Performance Model

ALLOC

Performance Model



H2D: host (CPU) to device (GPU) copy

Performance Model

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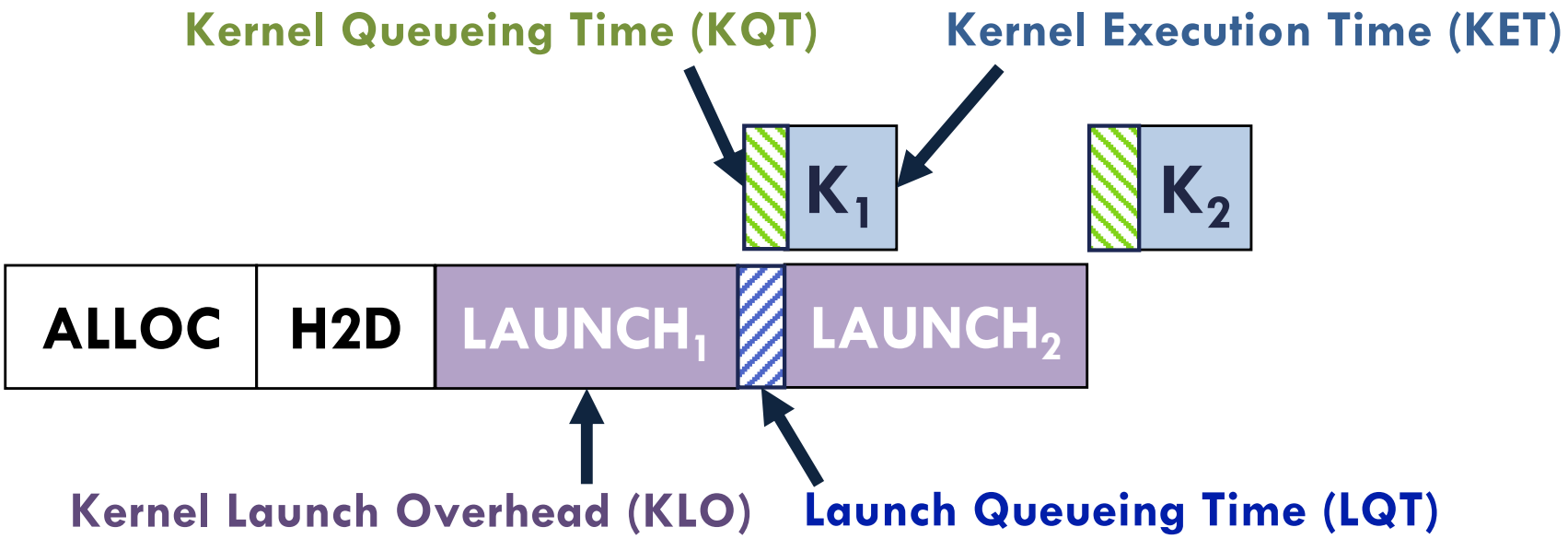
Performance Model



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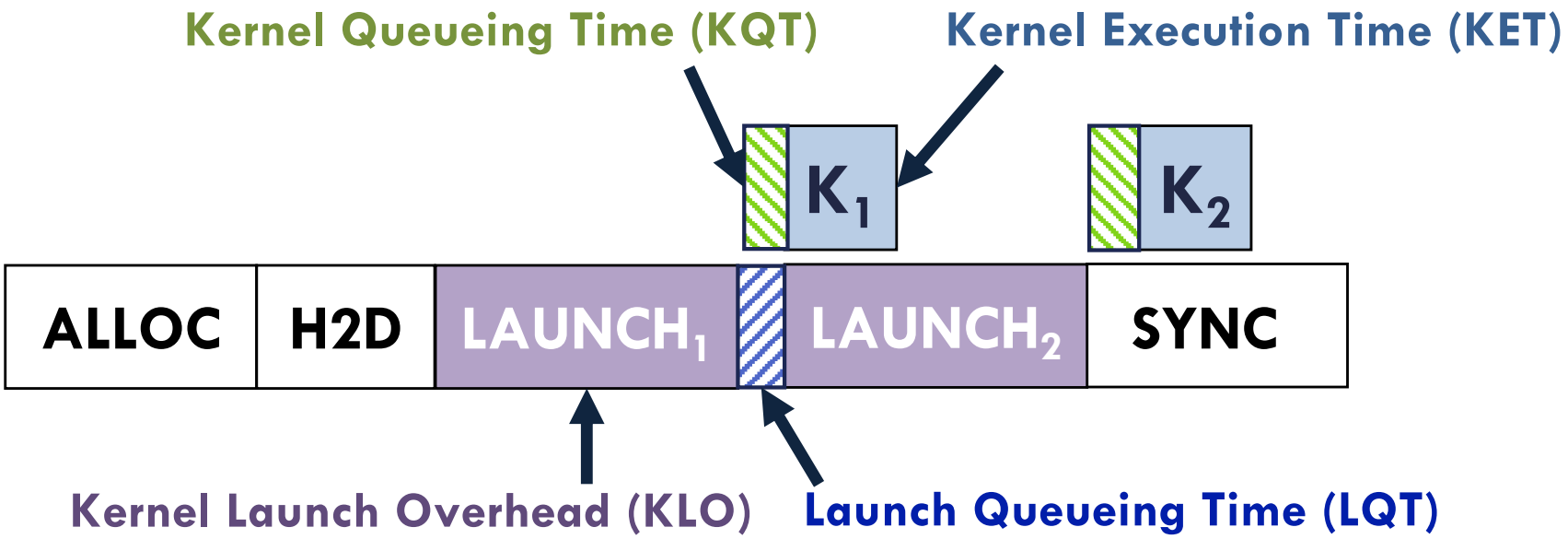

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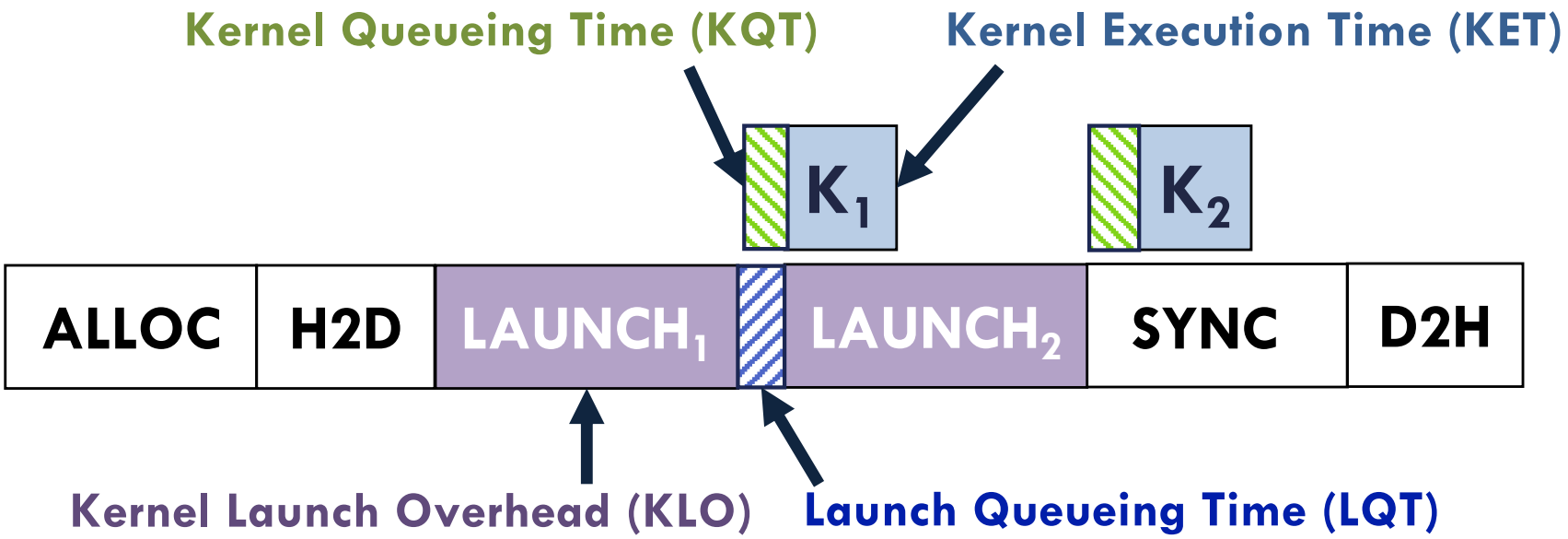
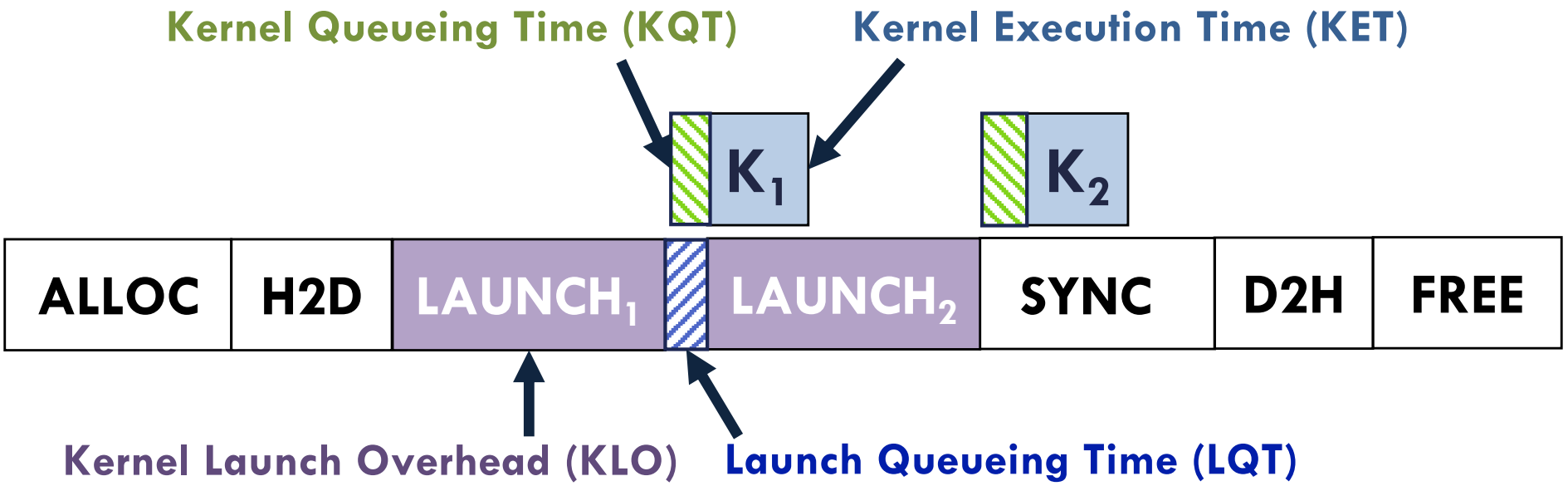


D2H: device (GPU) to host (CPU) copy

H2D: host (CPU) to device (GPU) copy

Performance Model



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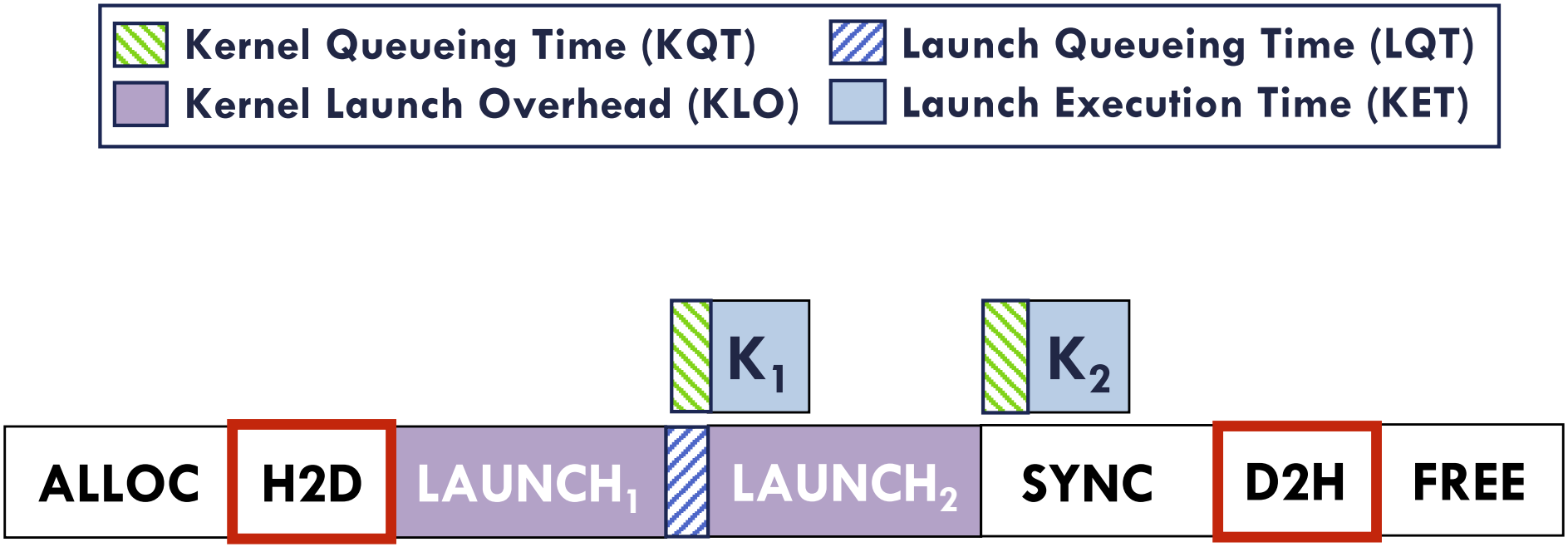
Performance Model



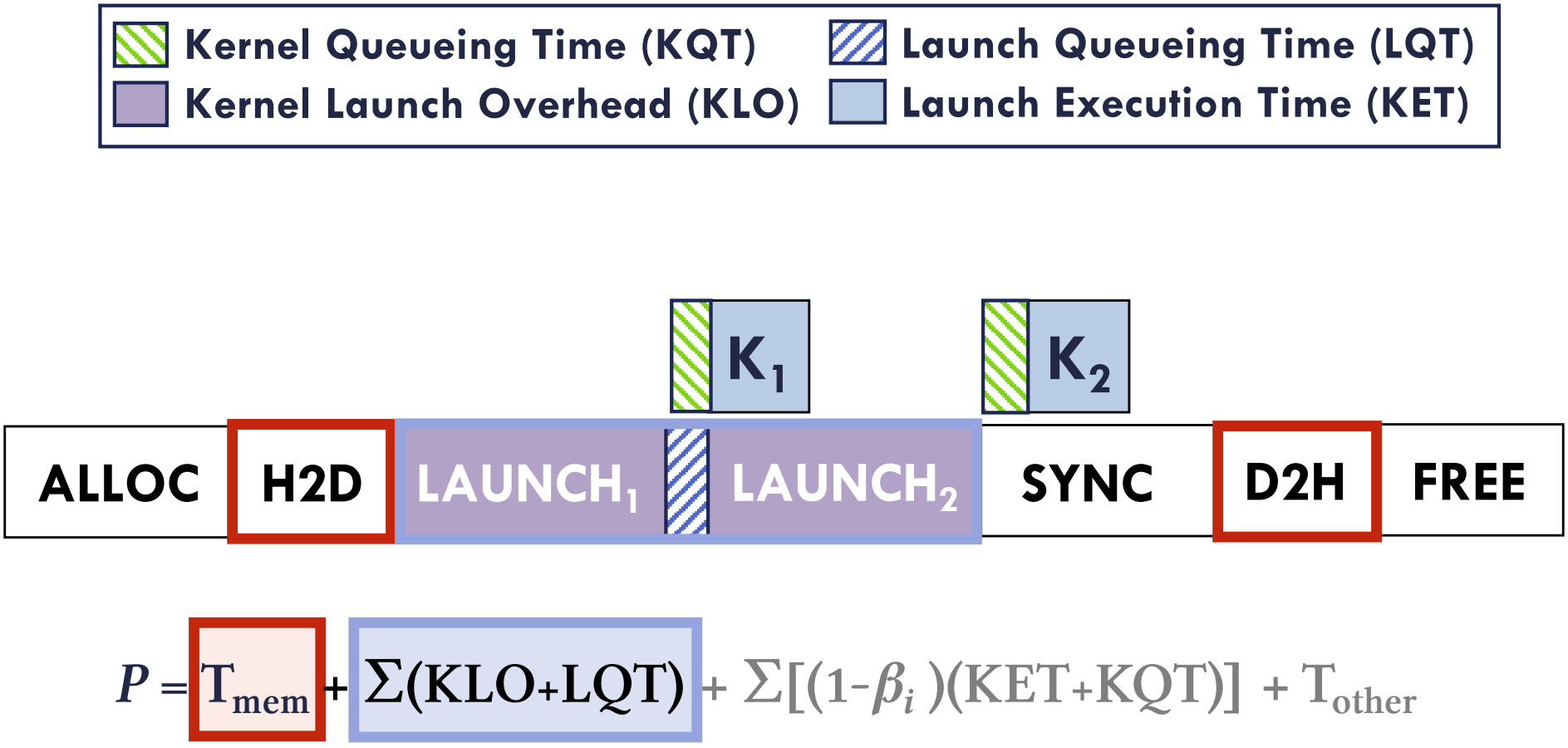
$$P = T_{mem} + \Sigma(KLO+LQT) + \Sigma[(1-\beta_i)(KET+KQT)] + T_{other}$$

Time on memory copy

D2H: device (GPU) to host (CPU) copy

H2D: host (CPU) to device (GPU) copy

Performance Model



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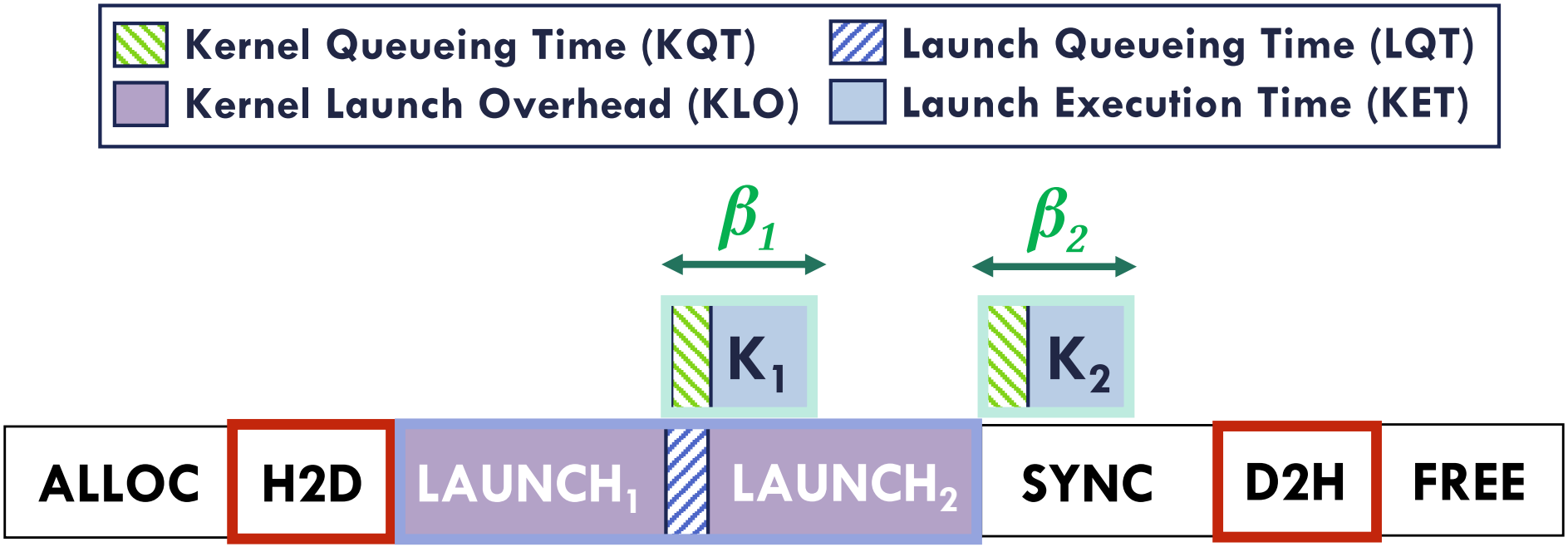

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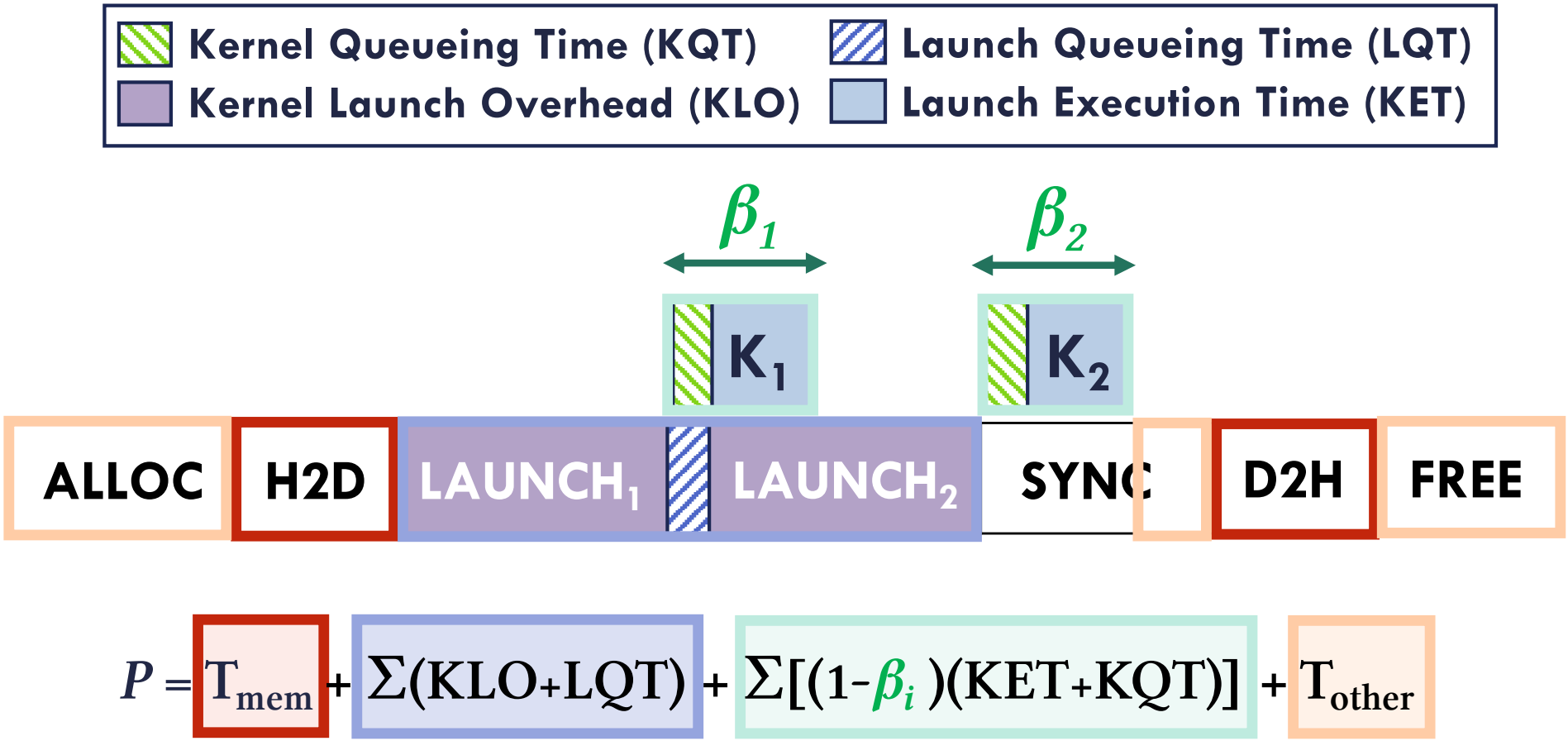

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Performance Model

$$P = T_{mem} + \Sigma(KLO+LQT) + \Sigma[(1-\beta_i)(KET+KQT)] + T_{other}$$

Focus of this presentation

- Data movement (H2D, D2H, page migration)
- Encryption
- Kernel Execution
- Kernel Launch
- Queuing

Transfer Bandwidth

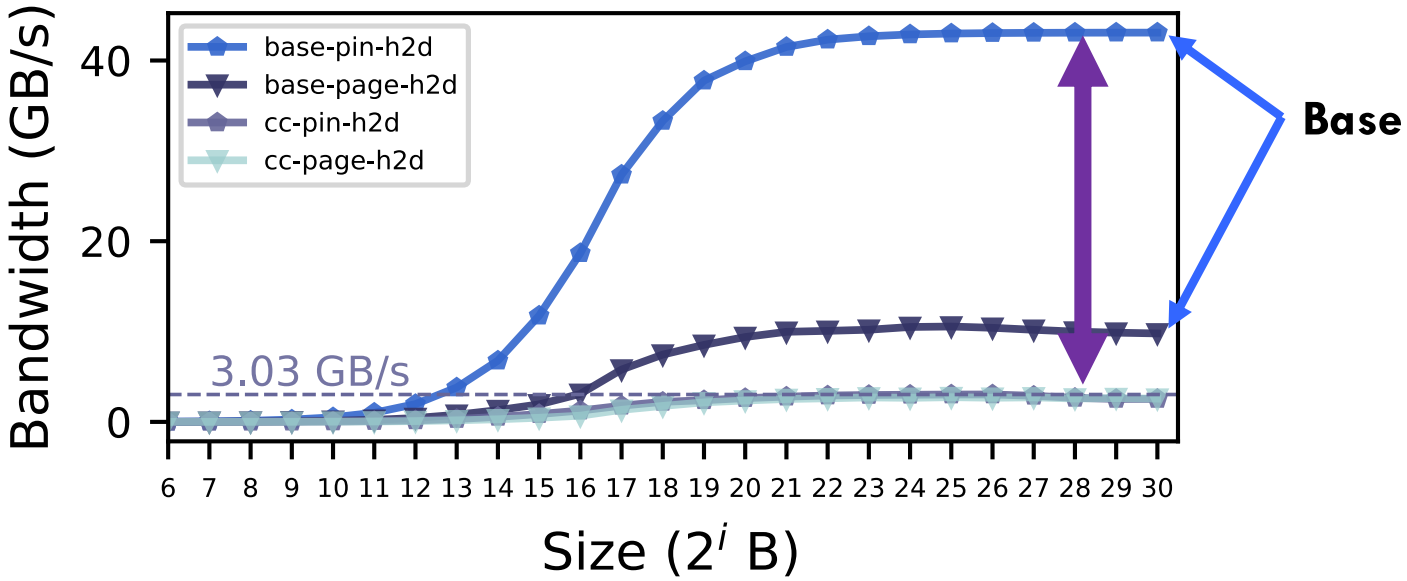


Fig.1 Copy bandwidth

Observation 1.

✓ PCIe bandwidth utilization in CC mode **drops significantly** compared to non-CC.

Transfer Bandwidth

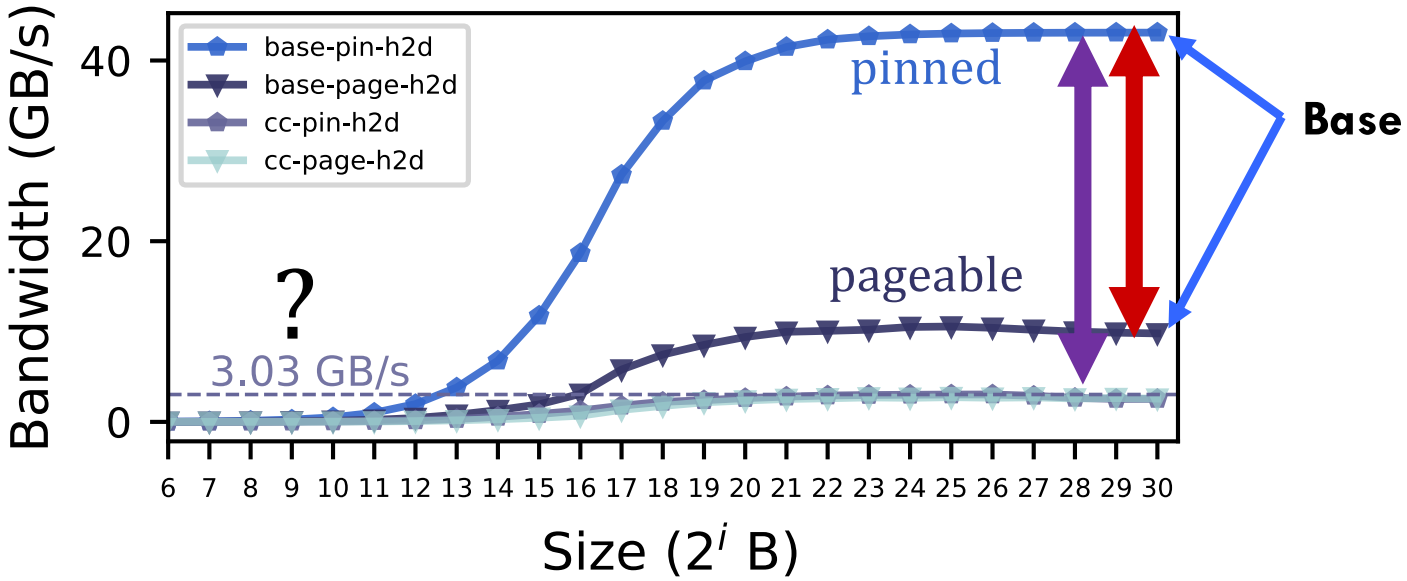


Fig.1 Copy bandwidth

Observation 1.

- ✓ PCIe bandwidth utilization in CC mode **drops significantly** compared to non-CC.
- ✓ Bandwidth **gap** between pageable and pinned memory observed in non-CC mode disappears in CC mode, suggesting that pinned memory relies on pageable mechanisms in CC mode.

Crypto Throughput

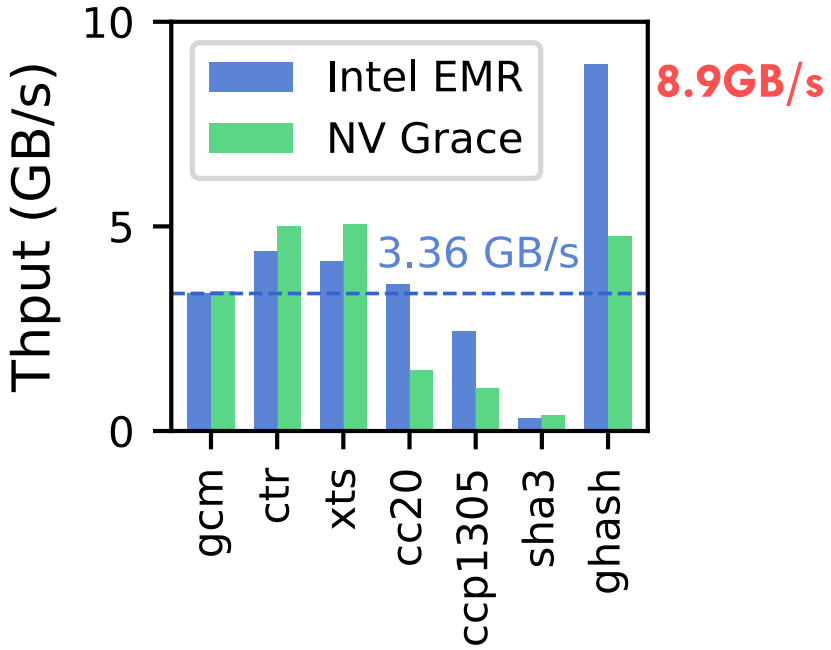


Fig.2 Crypto throughput

Observation 2.

- ✓ The absence of **dedicated hardware AES engines** results in low encryption throughput, even when using **AES-NI** acceleration.
- ✓ While *alternative cryptographic algorithms* may offer higher throughput, they often come at the cost of weaker security guarantees.

AES is on the critical path.

Kernel Execution Time

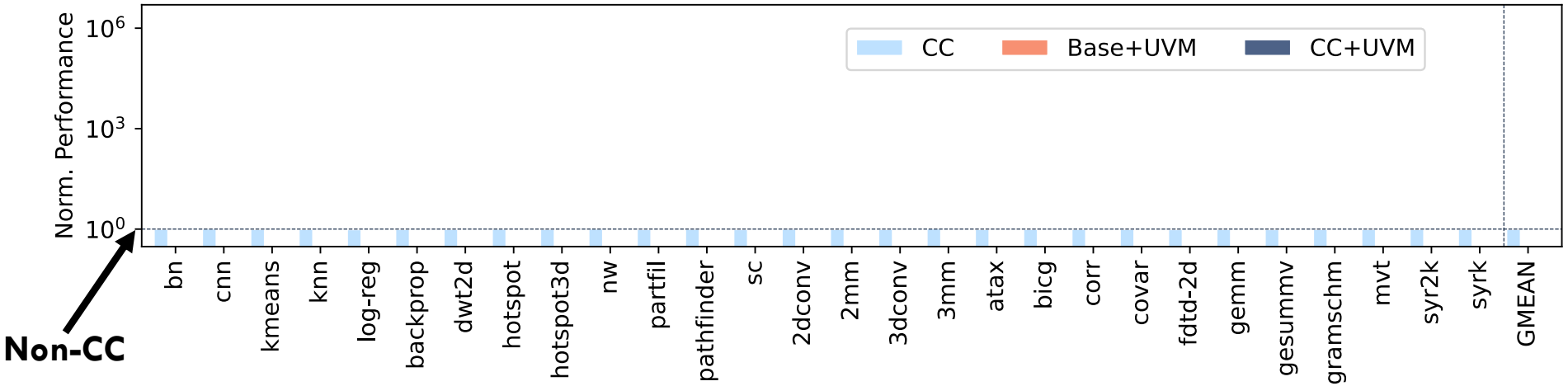


Fig.3 Normalized kernel execution time.

Observation 3.

- CC has **minimal** impact on **non-UVM** kernels (**0.48% increase**).

? **Execution is locked inside GPU, no interaction with CPU**

Kernel Execution Time

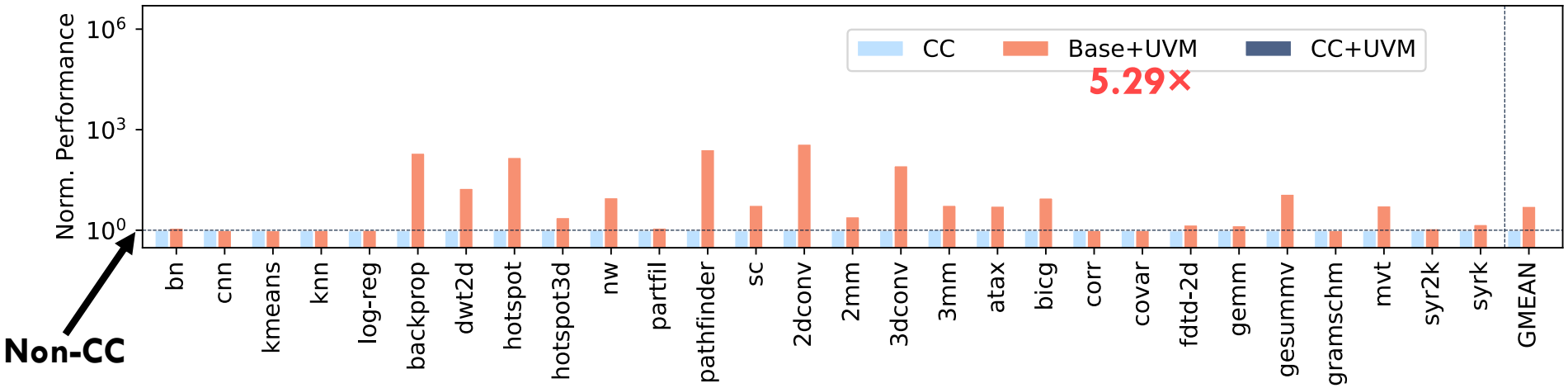
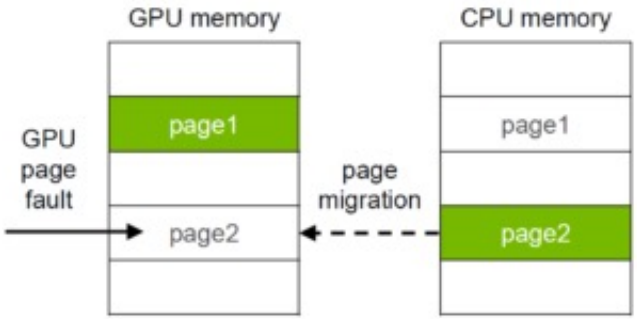


Fig.3 Normalized kernel execution time.

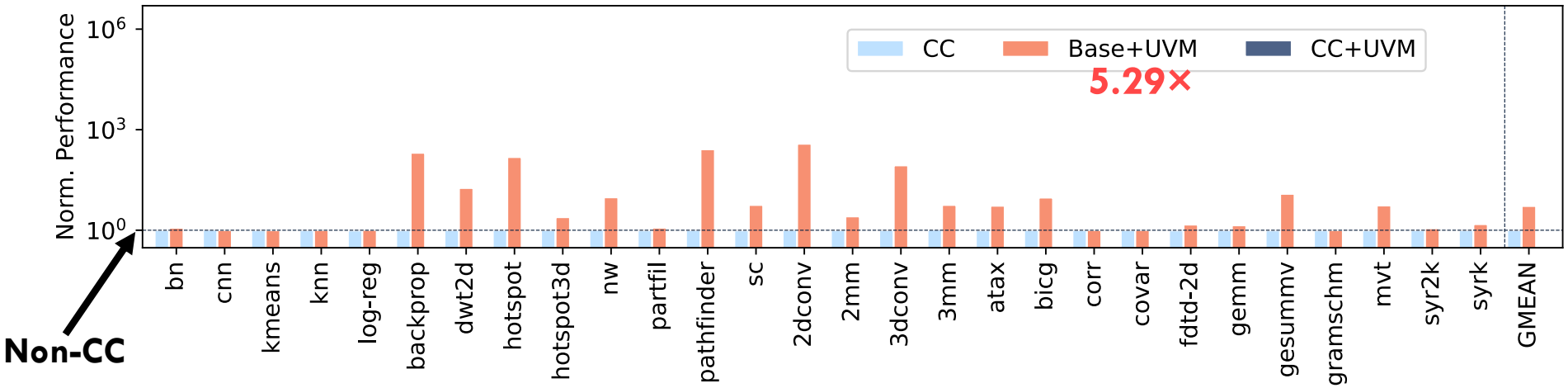
Single Address Space



Source: NVIDIA

Frequent CPU-GPU interaction!

Kernel Execution Time



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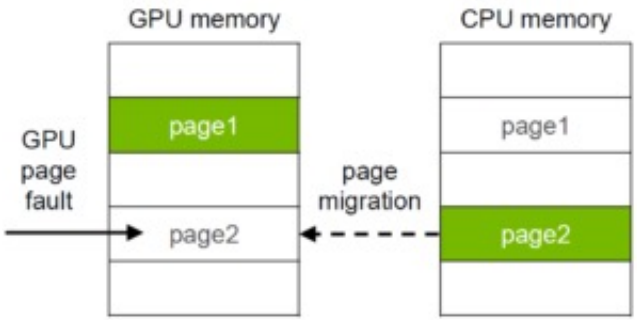

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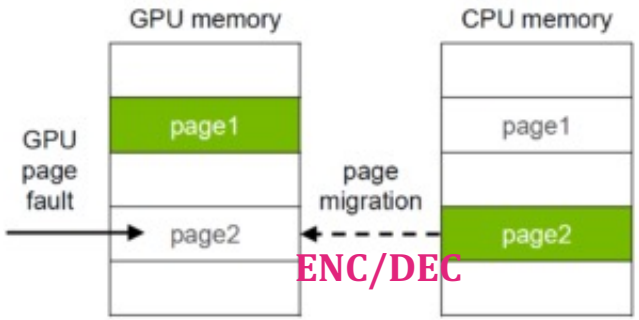
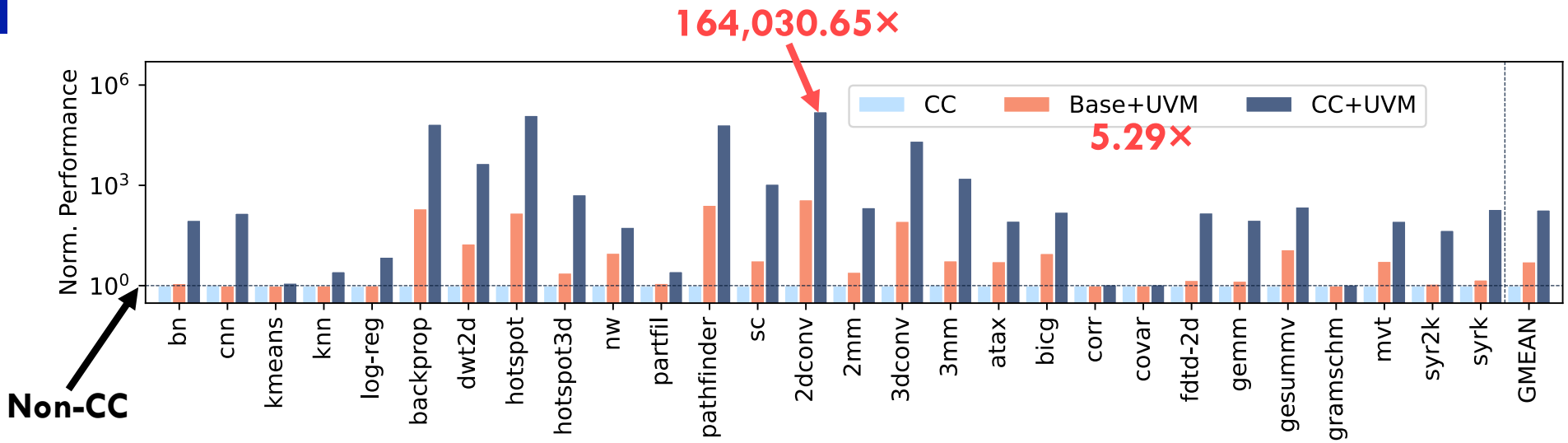


With CC ON

Kernel Execution Time



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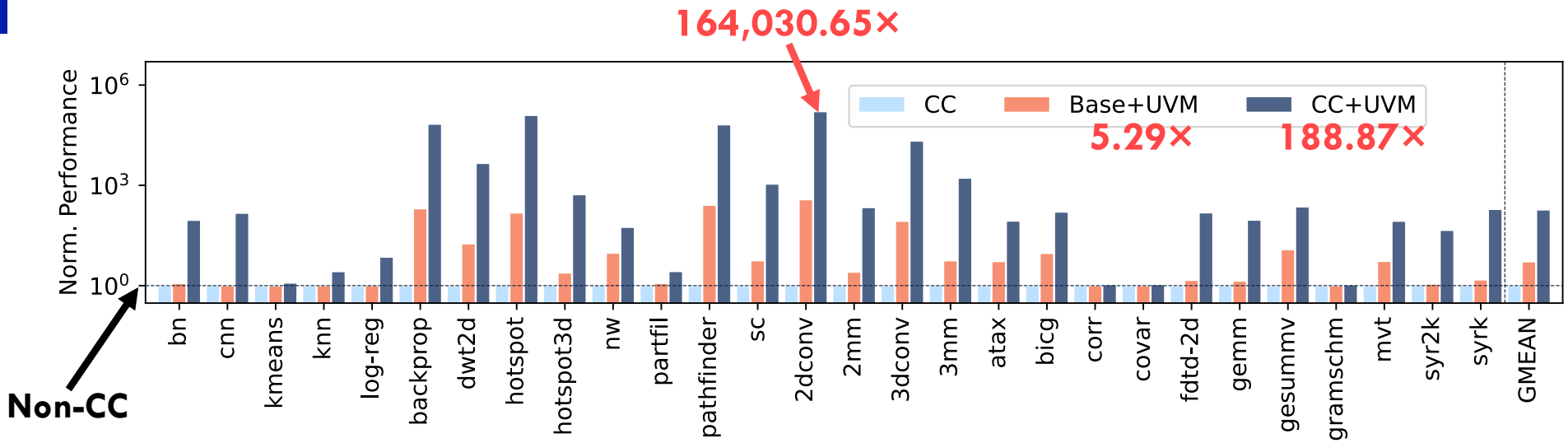

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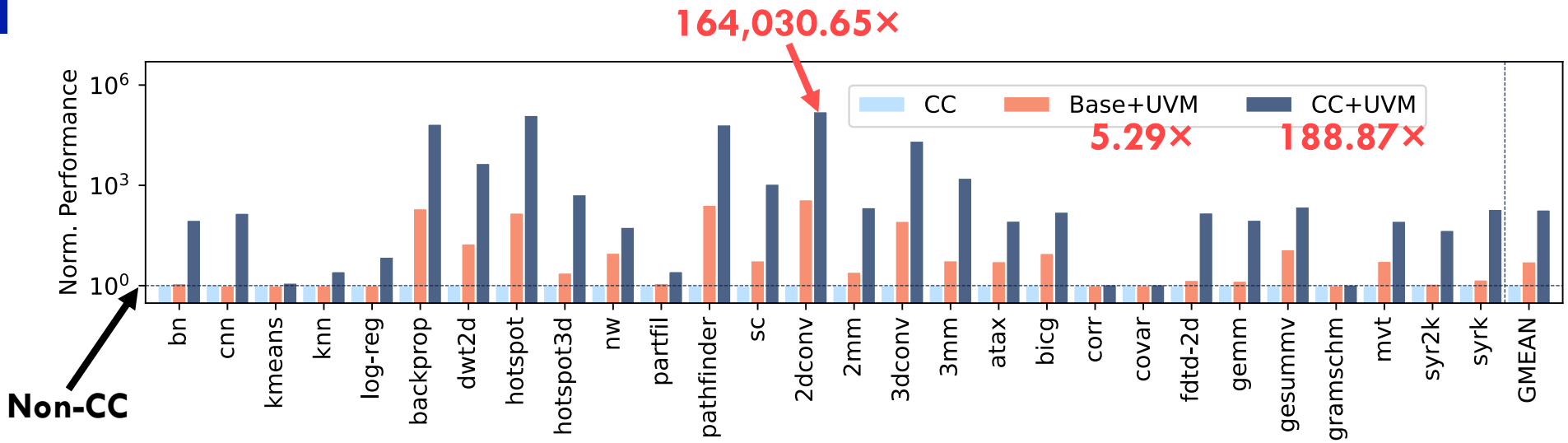


Fig.3 Normalized kernel execution time.

Observation 3.

- CC has **minimal** impact on **non-UVM** kernels (**0.48% increase**).
- **UVM** in CC mode incurs an average slowdown of **188.87×**.

Memory Transfer Time

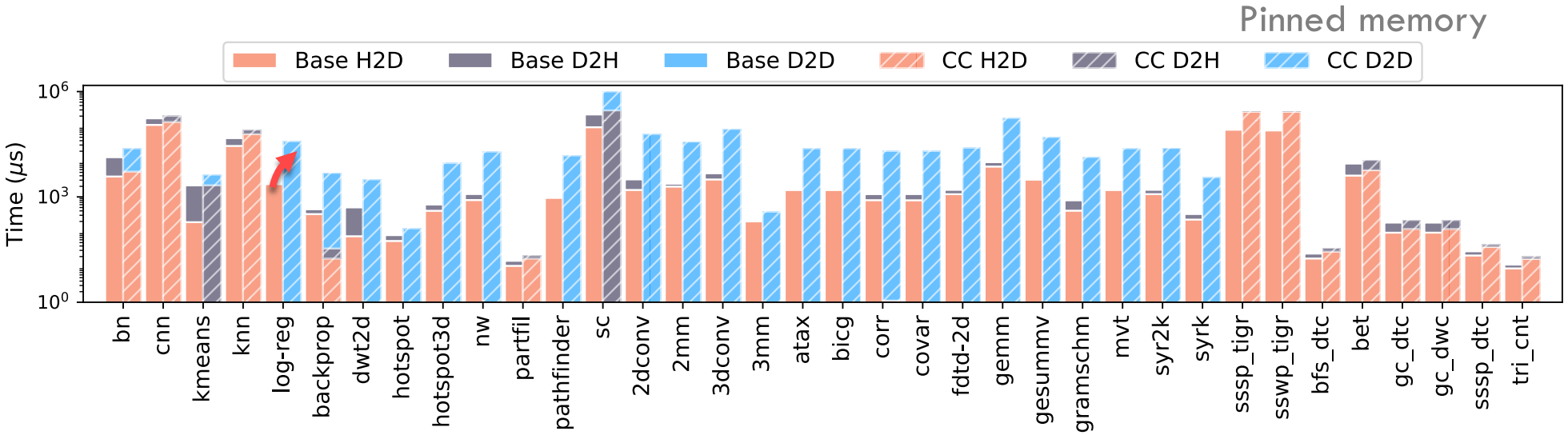


Fig.4 Time (μs) spent on memory copy.

Observation 4.

- ✓ On average, copy operations in CC mode take **5.80×** longer compared to non-CC mode, with a maximum slowdown of **19.69×**.
- ✓ Pinned memory is converted to UVM encrypted paging in CC mode which incurs high overhead.

Launch and Queuing

Results are normalized to non-CC time.

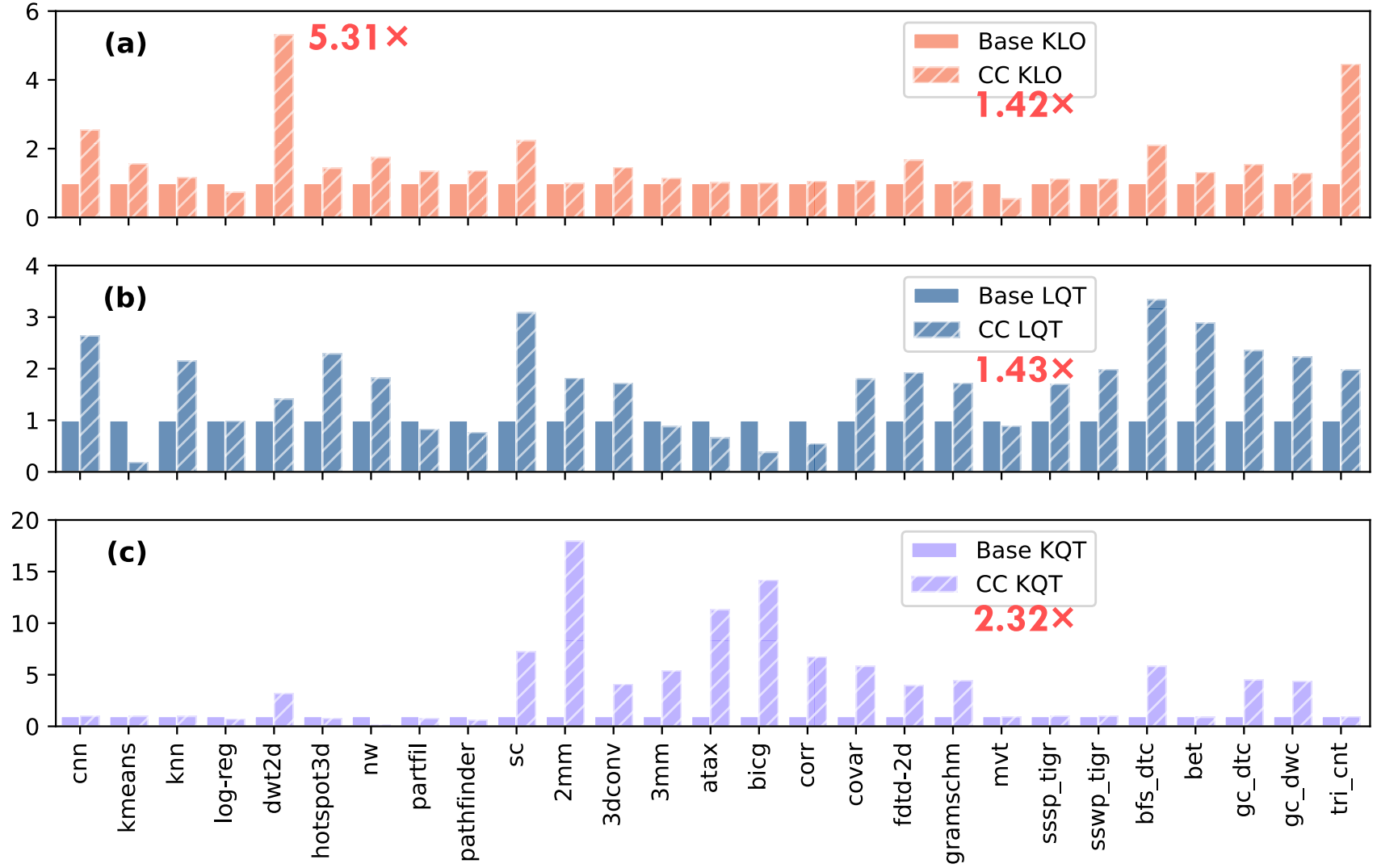


Fig.5 Effect of CC on KLO, LQT, and KQT.

Closer Look

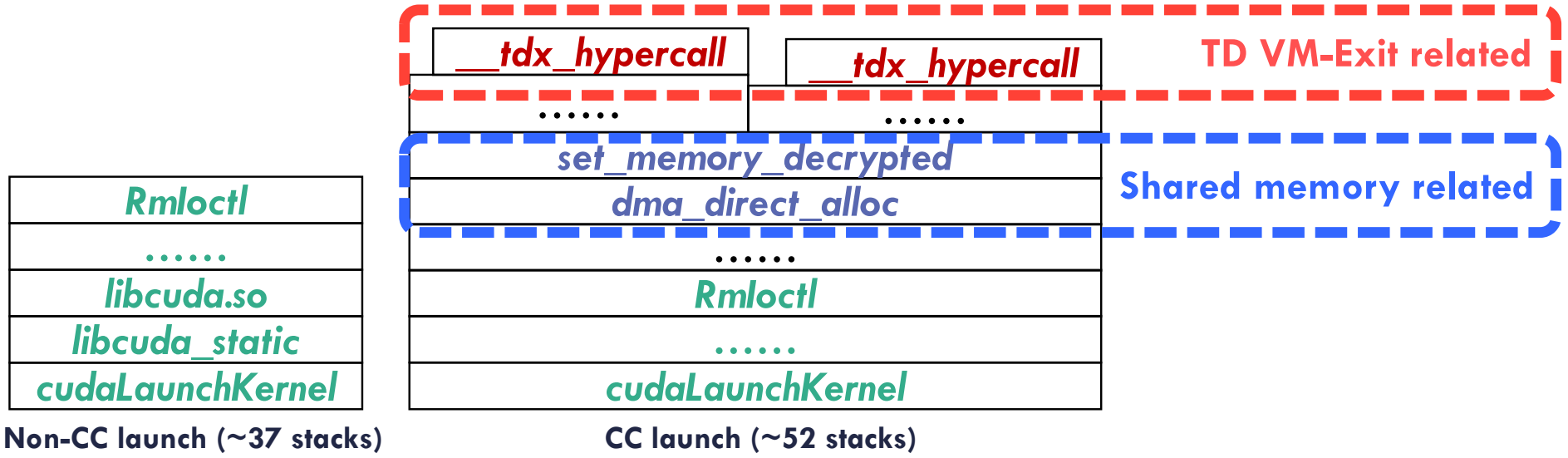


Fig.6 Simplified call stack of a cudaLaunchKernel call, obtained via perf.

Observation 5.

- ✓ On average, CC increases KLO by **1.42×** mostly due to TDX ***hypercalls***. It increases LQT by **1.43×** and KQT by **2.32×**.
- ✓ For applications with a low number of kernel launches, KQT can be significantly amplified.

Case Study

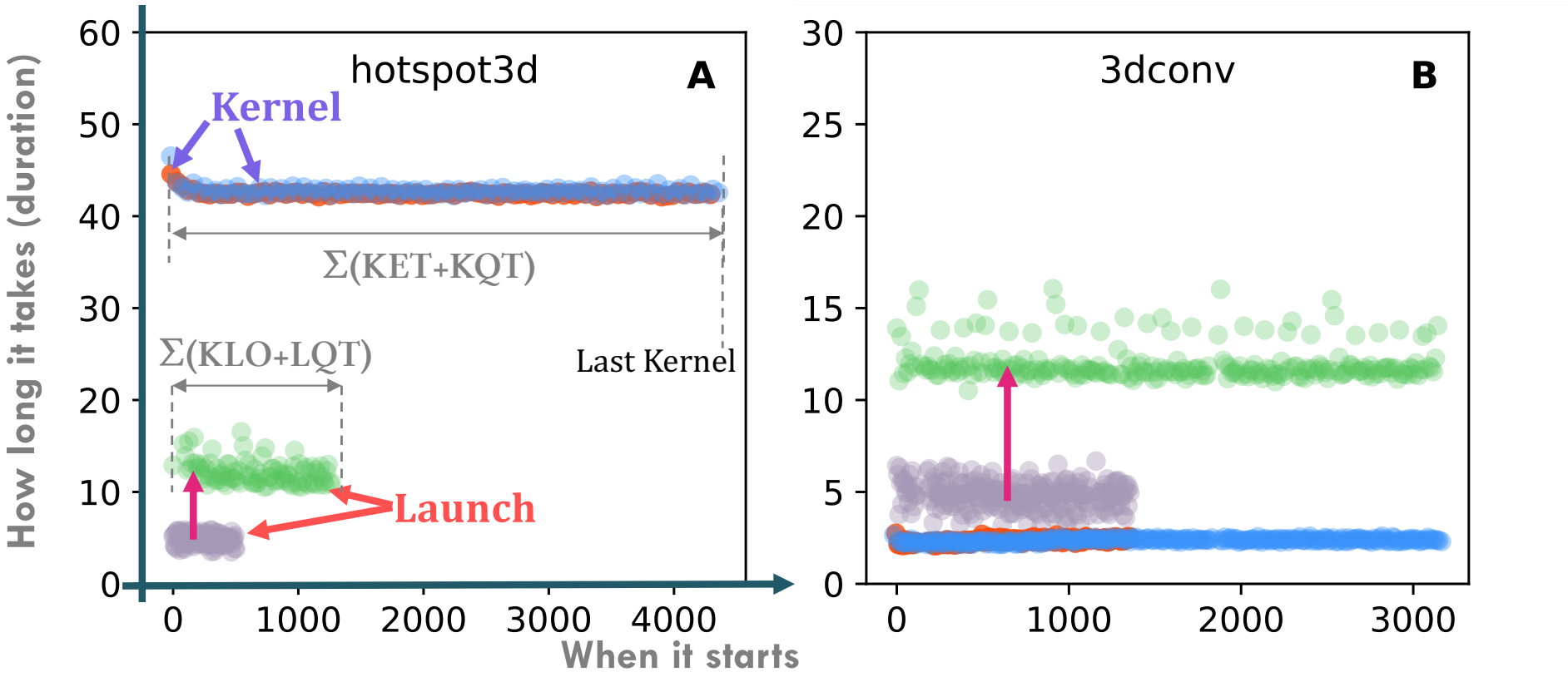
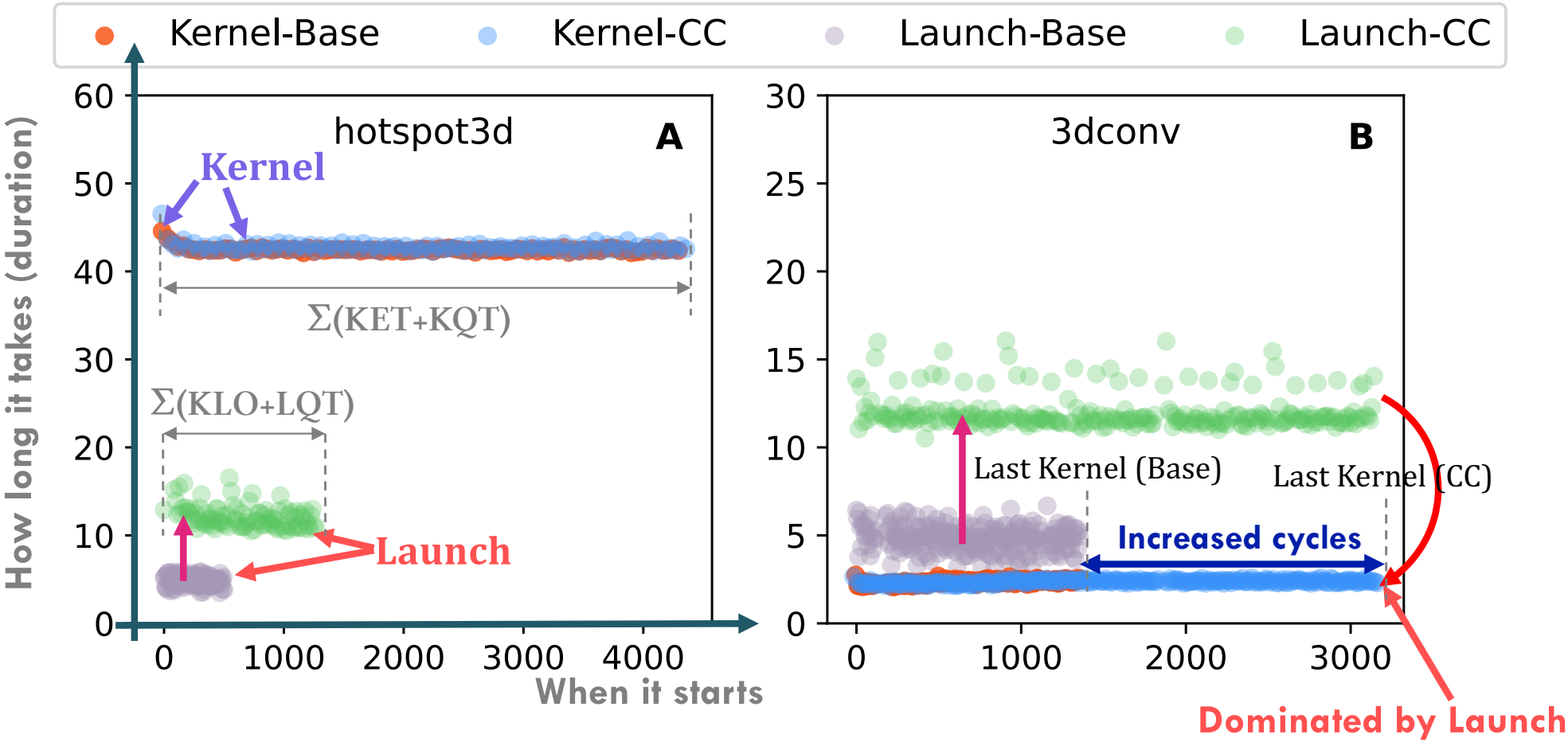


Fig.7 Distribution of events and their durations for representative applications, in μs.

Case Study



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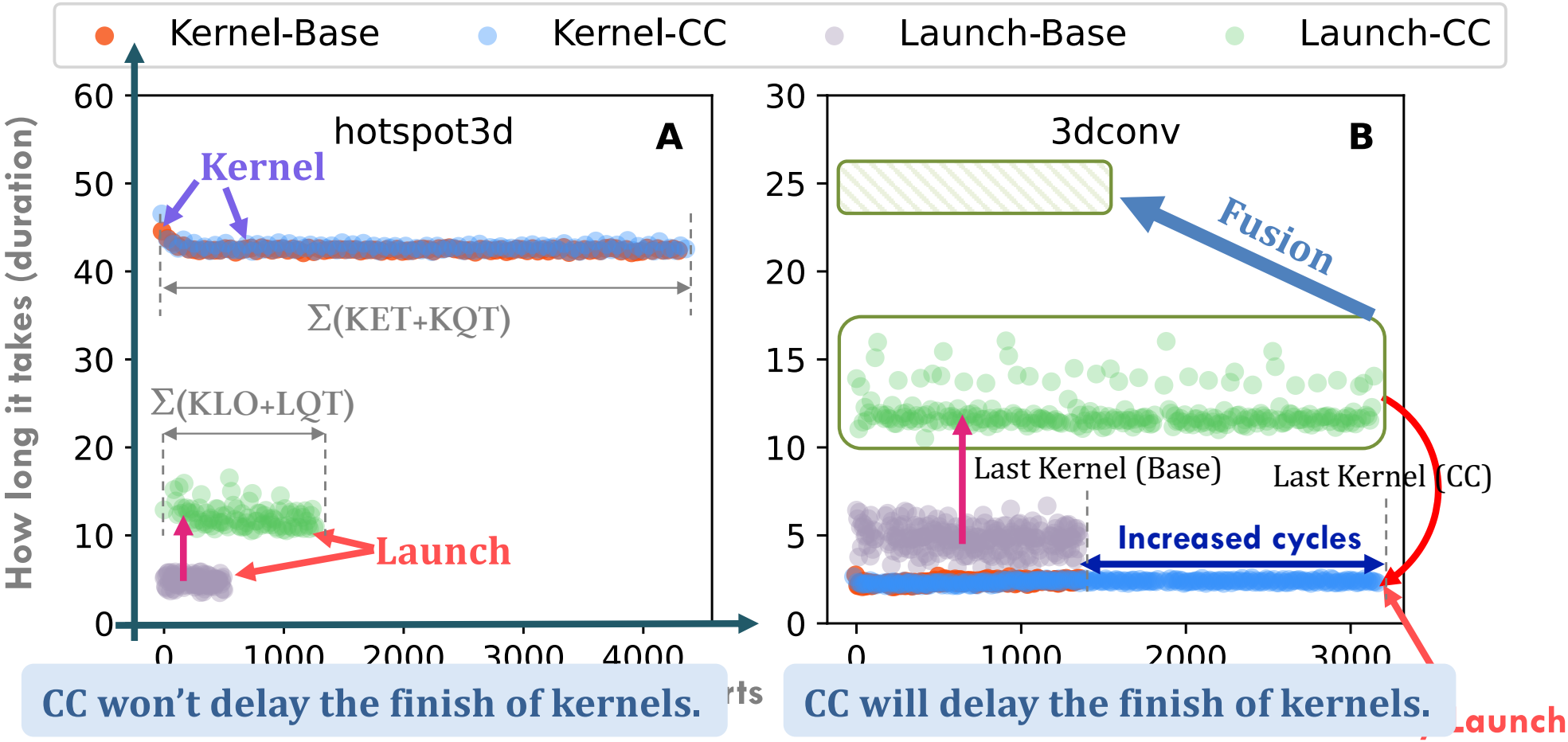
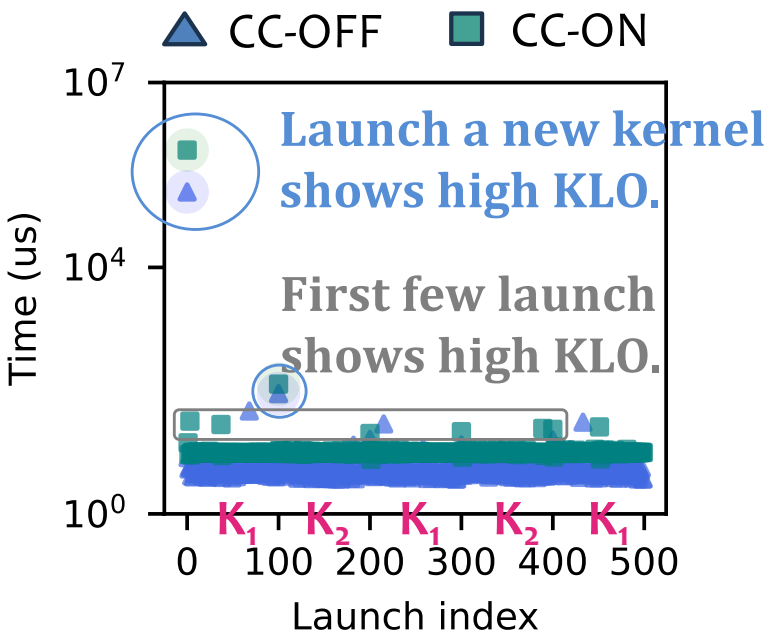
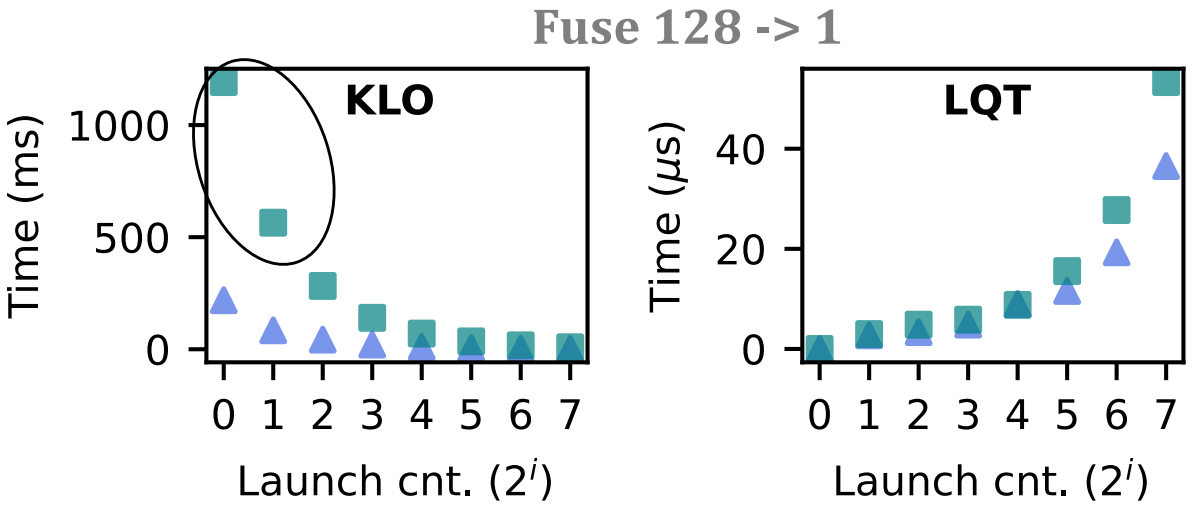


Fig.7 Distribution of events and their durations for representative applications, in μs.

How to optimize? **Insights: Fusion and overlapping!**

Insight: Fusion





Aggressive fusion is not working, a right fusion parameter helps.

More Details

- Memory Management
- Kernel-to-Launch Ratio
- Overlapping
- CNNs
- LLMs
- Quantization
- …

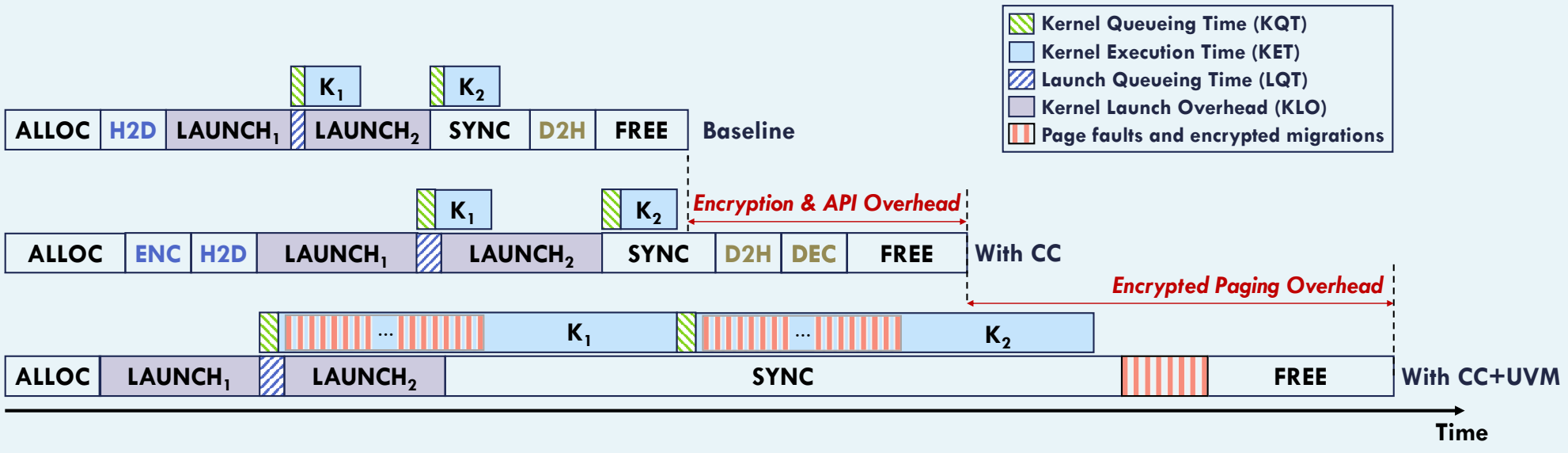
More details in the paper!

Conclusion

We present a **comprehensive performance evaluation** of GPU-based CC guided by a simple performance model, and considered several **optimizations** towards addressing the overheads of CC.

Our results on real hardware show that GPU-based CC comes with:

- Data movement: **5.80× (avg)** **19.69× (max)** **3.03 GB/s**
- Encryption: **3.36 GB/s (AES-GCM)**
- Kernel Execution: **0.48% (CC)** **188.87× (avg, CC+UVM)**
- Kernel Launch: **1.42× (avg)** **5.31× (max)**
- Queuing: **1.43× (avg, LQT)** **2.23× (avg, KQT)**



Thank You!

Questions?

Dissecting Performance Overheads of Confidential Computing in GPU-based Systems

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