Year 1858: When the vast ocean symbolically shrunk into a “channel”

H.M.S. Agamemnon Laying the Atlantic Telegraph Cable in 1858 while a whale crosses the line.

Early Silicon of Raptor

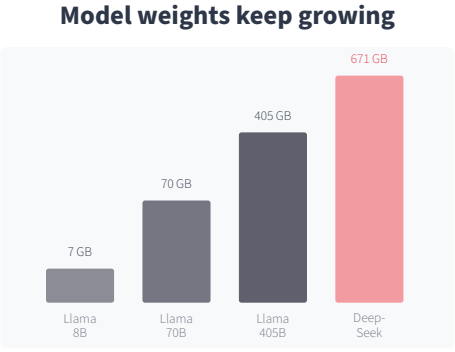
The First 3D-DRAM Accelerator for Generative Inference †

Prashant J. Nair * – d-Matrix Inc. and UBC
Ramyad Hadidi, Subramani Ganesh, Sangamesh Kodge, Shubhankit Rathore, Neil Thanawala, Nikitha Reddy, Gyanesh Saharia, Vinayak Patankar, Arun Tiruvur, Nithesh Kurella, and Sudeep Bhoja – d-Matrix Inc.

* Also affiliated as an Associate Professor at the University of British Columbia (UBC).
† Work done during sabbatical/leave from UBC.

1st July 2026

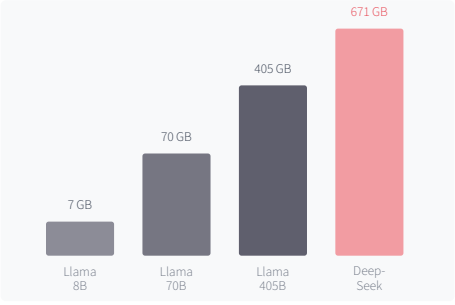
The Growing Data Problem



INT8 weights. Larger models need more cards.

The Growing Data Problem

Model weights keep growing



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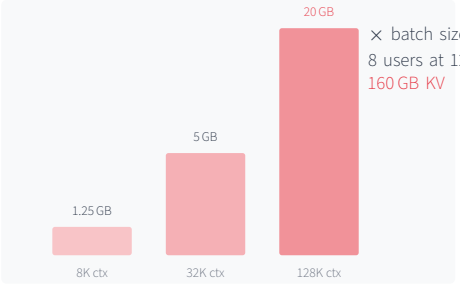
KV cache grows with context

(Llama-3.1 70B, INT8, per user)



Longer context × more users ⇒ KV cache dominates.

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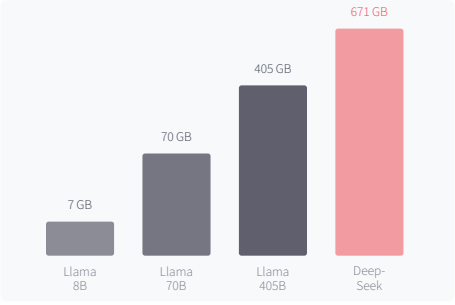

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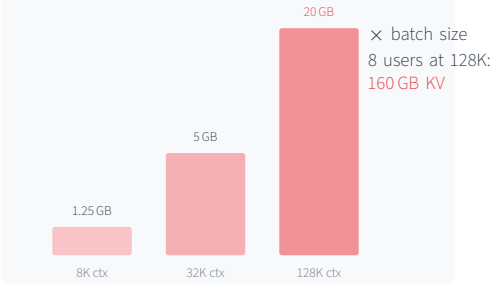

Longer context × more users ⇒ KV cache dominates.

Weights and KV cache present a **capacity and bandwidth problem**. Both of these are growing.

The decode bottleneck is fundamental. Batching cannot solve it. Parallelism taxes it further.

The question becomes:

What kind of memory do we actually need?

Fast enough to feed the compute. Large enough to hold the model.

Today’s Memory Technologies

SRAM: Bandwidth Advantage

Why SRAM is fast:

- 6T cell with direct bit-line access
- On-die: no interposer, no package crossing
- Sub-nanosecond access latency

Specs (on-die, per card):

Bandwidth	**150 TB/s**
Capacity	**4 GB**
Latency	∼1 ns
I/O energy	∼0.5 pJ/bit

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- Sub-nanosecond access latency

Why SRAM cannot scale:

- 6T cell is **100–150× larger** than DRAM 1T1C
- Leakage: ∼1 nW/bit (significant at GB scale)
- Practical limit: ∼**4 GB** per card
- Cost: ∼$1000/GB vs. ∼$10/GB for DRAM

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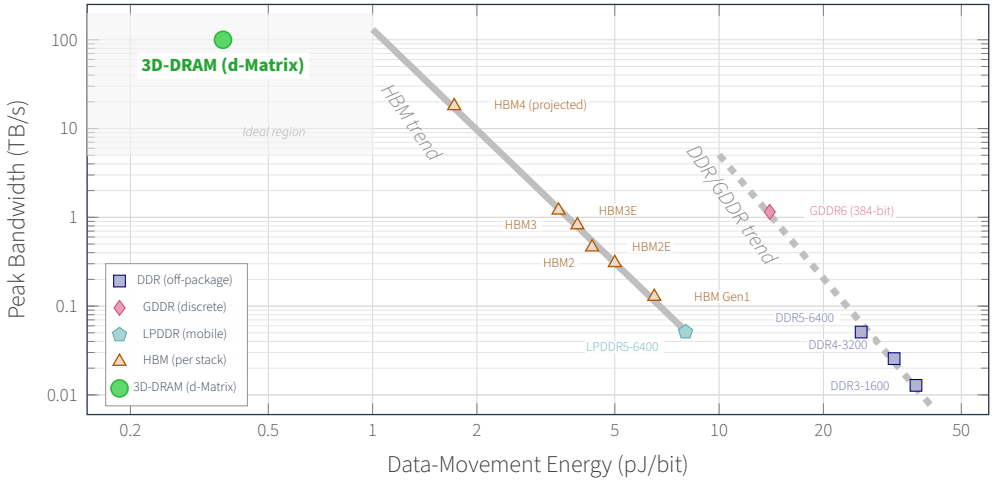
Very fast memory ⇒ but **4 GB** cannot hold a 70B model.

DRAM Landscape: The Power-Normalized Bandwidth (PN) Inversion Law



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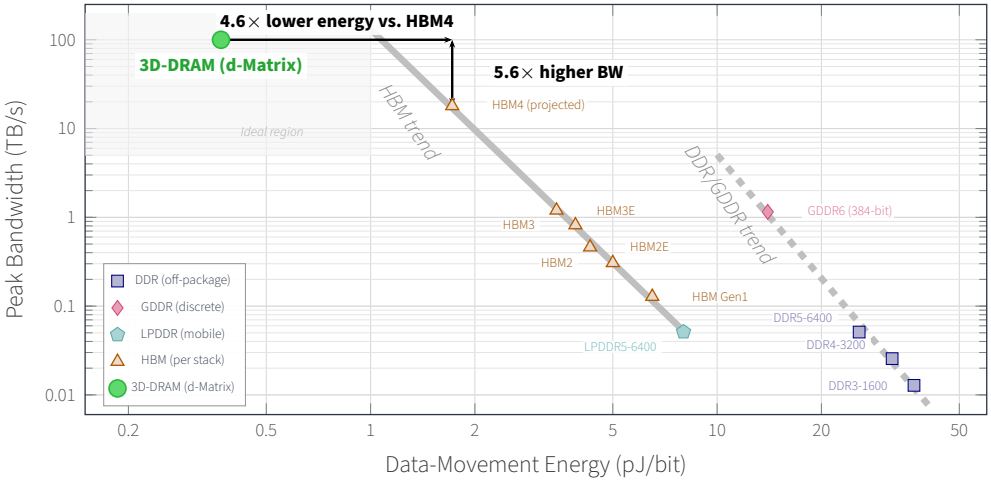
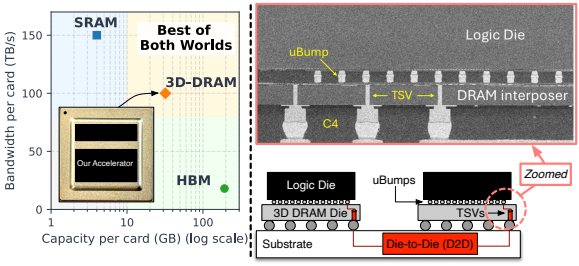


3D-DRAM: The Opportunity

Commercial 3D-DRAM-Based Accelerator for Gen-AI



Logic die bonded face-to-face to 3D-DRAM die.
Vertical interconnects replace mm-scale HBM traces.

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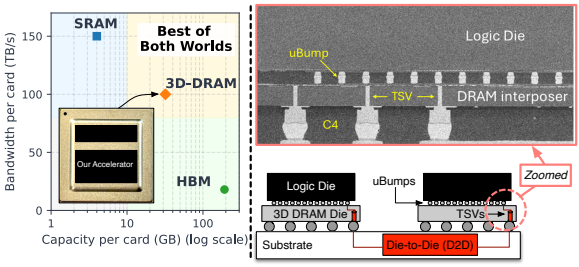

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	HBM	3D-DRAM
Topology	2.5D (beside)	F2F (below)
I/O energy	2–3 pJ/bit	0.37 pJ/bit
BW / card	18 TB/s	100+ TB/s
Capacity	192 GB	32 GB

5.6× higher BW

5× lower energy/bit

7× denser I/O

Integration

The 3D-DRAM Integration Landscape

Hardware	Architecture	Co-Design
TSV density vs. routing congestion trade-offs	Bank-to-channel mapping: 840 banks $\neq 256 \times 4$	Thermal: T_j=105°C $\Rightarrow 8\times$ faster refresh
Power delivery through 3D stack (IR drop, decap)	Weight & KV-cache tiling across banked memory	ECC, DBI metadata, & scrub share bank rows
Signal integrity: crosstalk & SSN on wide parallel bus	Redundancy without breaking channel symmetry	Refresh scheduling vs. compute pipeline bubbles
I/O power: no burst structure $\Rightarrow$ no PHY DBI	LPDDR5X as secondary tier: data placement policy	Known-good-die testing $\rightarrow$ post-package repair flow
μBump yield & alignment at 36 μm pitch	Compiler support for stream-aware access patterns	Multi-high stacking: routing, power, thermals
Clock distribution & skew across die stack	Runtime KV-cache alloc & eviction across banks	Hybrid bonding roadmap: <2 μm pitch, 8-high

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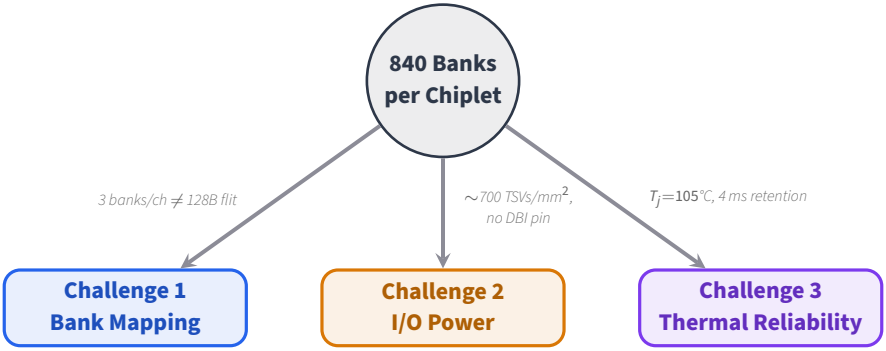
★ The **challenges** we discuss in this talk

These Challenges Are Entangled



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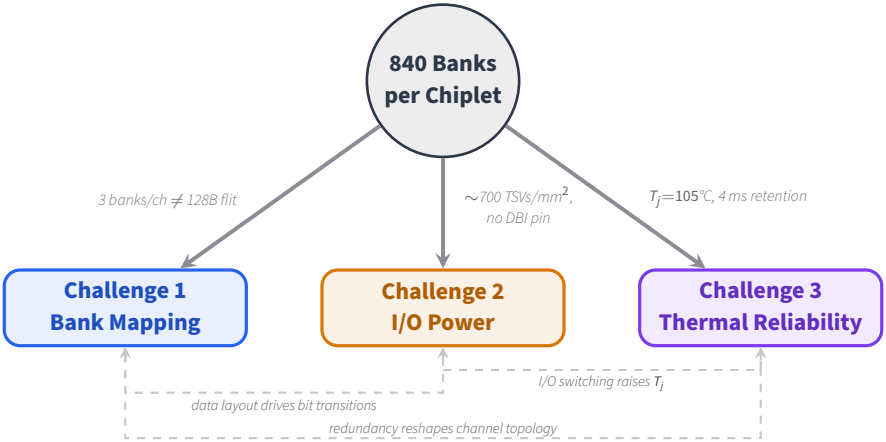

A solution to any one challenge **constrains the design space of the other two.**

Challenge 1: Bank Mapping

Challenge 1: The Bank-to-Channel Mapping Problem

The setup

- Each TE needs a **128 B flit** per access
- 16 ch × 16 TE-Groups = **256 ch/chiplet**
- Each bank delivers **32 B** per column access

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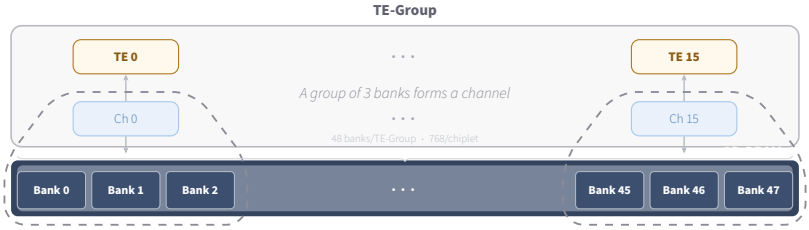
The arithmetic

- 128 B ÷ 32 B = **4** banks/ch *needed*
- DRAM die: **840 banks** (768 after 72 spares)
- 768 ÷ 256 = **3** banks/ch *available*

Need 4 banks/channel ⇒ have only 3 ⇒ **the 128 B flit does not divide evenly**

Challenge 1: The Overfetch Dilemma



With 3 banks per channel:

- One channel access returns **96 B** (3×32 B)
- 128 B flit $\Rightarrow$ two accesses $\Rightarrow$ 192 B fetched
- **33% overfetch $\approx$ 33 TB/s wasted**

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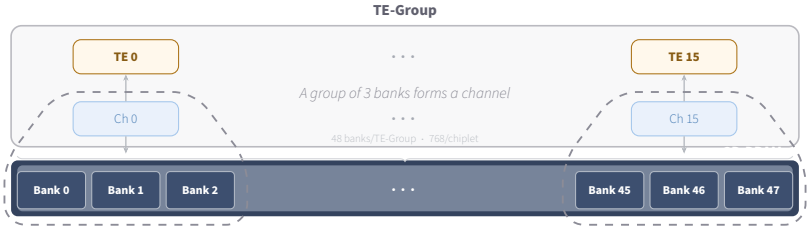

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- **33% overfetch ≈ 33 TB/s wasted**

Naïve fix — column staggering:

- Stagger column indices to pack one flit per pair
- Requires a **192 B shifting buffer**
- Complicates timing closure and verification

How to deliver 128 B from 3 × 32 B banks **without wasting bandwidth or adding complex datapaths?**

Challenge 1 ✓ Solution: Stream Blocking

Challenge. A 128 B flit = **4×32 B**, but each channel has only **3 banks** — a naïve fetch reads 192 B per 128 B flit (⇒ **33% overfetch**).

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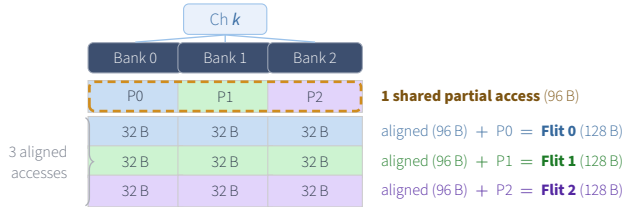

Puts the 4th 32 B (the *partial*) into one access *shared* by 3 flits — $4 \times 96 = 384$ B in $= 3 \times 128 = 384$ B out ⇒ **0% overfetch**.

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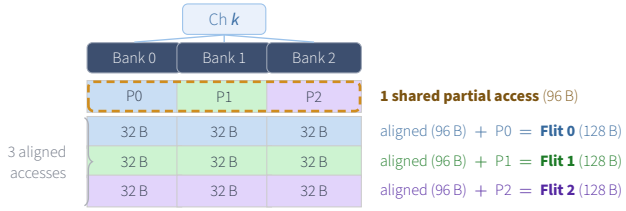

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Every column access is fully utilised — the **33 TB/s** lost to overfetch is reclaimed, with **no shifting network**.

Challenge 2: I/O Power at Scale

Challenge 2: The I/O Power Wall

The power cost of 100 TB/s:

Measured I/O Power

$P_{I/O} = 100\ \text{TB/s} \times 0.37\ \text{pJ/bit} = \mathbf{296}\ \text{W}$

Why conventional DBI cannot help:

- HBM uses multi-cycle bursts (BL 4–16)
- PHY sees full burst ⇒ decides on inversion
- DBI pin per byte lane signals choice

Our 3D-DRAM has **none of these**: single-cycle transfer, no burst, no sideband pin.

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Interface comparison:

	DDR / HBM
Transfer	Multi-cycle burst
Lookahead	Full burst visible
DBI	Dedicated pin/lane

	Our 3D-DRAM
Transfer	Single-cycle 256-bit
Lookahead	**None**
DBI	**No pin. No sideband.**

DBI would save 20%

Need to rethink interface.

How to achieve DBI **architecturally?**

Challenge 2 ✓ Solution: Stream Flipping (Pinless DBI)

Challenge. I/O dominates: **100** TB/s × **0.37** pJ/bit = **296 W**, and conventional DBI needs a **sideband pin** the single-cycle 3D-DRAM link doesn't have.

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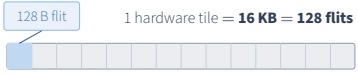

⇒ **long** per-channel flit streams; each flit compared to the *previous* one.

(a) Without DBI

flit $i-1$: 0 0 · · · 0
flit i: 1 1 · · · 1
flit $i+1$: 0 0 · · · 0

→ every bit toggles twice

(b) Stream flipping: invert flit i

0 0 · · · 0	**0**
0 0 · · · 0 (was 1 · · · 1)	**1**
0 0 · · · 0	**0**

meta

→ ≈0 toggles + 1 metadata bit / flit

Architectural DBI, no pin:

- **Write:** compare each flit to the previous → invert.
- **Read:** fetch the 1-bit tag; invert if set
- Tag co-located with ECC ⇒ **0.8%** overhead, **no PHY change → 20% savings.**

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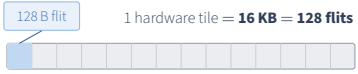

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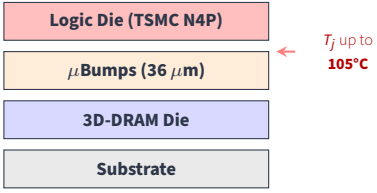
The full **20%** I/O saving with **no pin and no PHY change**.

Challenge 3: Reliability Under Thermal Stress

Challenge 3: DRAM Reliability at 105°C



Retention consequence

Standard: 32 ms at 85°C

At 105°C: drops to **4 ms**

⇒ **8**× more frequent refresh

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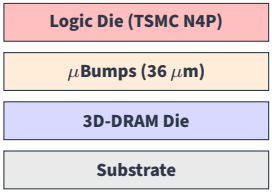

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Three compounding problems:

1. Yield — 840 banks/die. Even a 1% fault rate risks losing entire channels. Discarding bonded dies is uneconomical.

2. Symmetry — Disabling a faulty bank narrows its channel. Tensor engines expect *uniform* channel widths—one weak channel throttles the entire slice.

3. Error accumulation — Higher T_j drives more soft errors. ECC, scrub, and refresh must all coexist without stalling throughput.

How to maintain full-bandwidth, symmetric channels when banks fail and refresh is **8**× nominal?

Challenge 3 ✓ Solution: Thermal-Aware Refresh & ECC

Challenge. At **105°C**, retention falls 32 ms $\rightarrow$ 4 ms (**8**$\times$ more refresh), and bits still need correcting — all *without losing significant bandwidth*.

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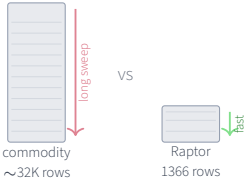
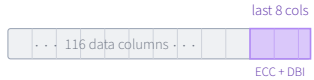
Deep banking makes refresh cheap



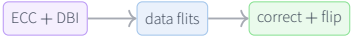
16–32× fewer rows ⇒ 4 ms refresh (8× more frequent) costs only **1.37%** → **∼103 TB/s**.

Interleaved ECC, co-located with DBI



Last **8 of 124** columns: paired **[132,128]** Reed–Solomon + DBI bits, interleaved with the subarray.

Read order:



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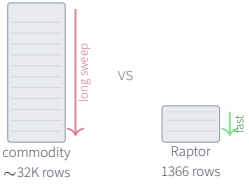

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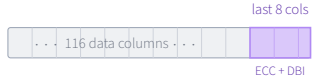

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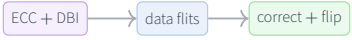

Deep banking turns an 8× refresh penalty into only a **<1.4% bandwidth loss**

Challenge 3 ✓ Solution: Bank Chaining

Challenge. The **72 spare banks** must cover faults *anywhere* on the die — without making channels asymmetric or adding long edge wires.

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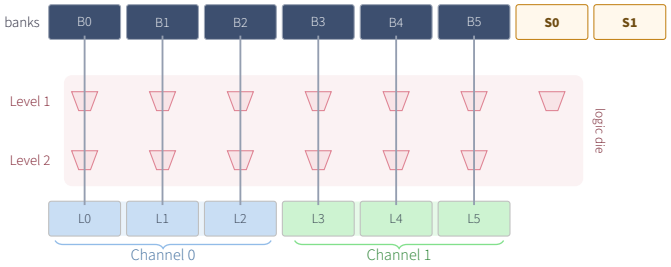

No faults — both mux levels pass each bank straight to its slot.

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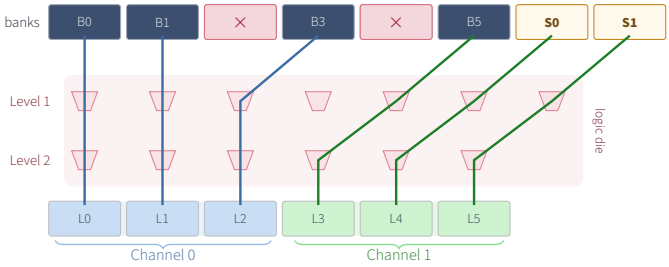
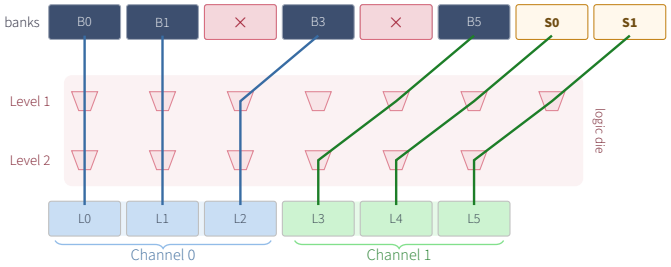


*Level 1 skips the first fault (B2); Level 2 skips the second (B4) — **M=2 physical mux levels tolerate 2 faults anywhere**, spares backfill, channels stay symmetric.*

Challenge 3 ✓ Solution: Bank Chaining

Challenge. The **72 spare banks** must cover faults *anywhere* on the die — without making channels asymmetric or adding long edge wires.



*Level 1 skips the first fault (B2); Level 2 skips the second (B4) — **M=2 physical mux levels tolerate 2 faults anywhere**, spares backfill, channels stay symmetric.*

The chiplet's **72 in-line redundant macros** absorb arbitrary faults — symmetric channels, negligible routing cost.

Performance Results

Experimental Setup

Hardware configurations:

	BW	Capacity
SRAM	150 TB/s	4 GB
HBM	18 TB/s	192 GB
3D-DRAM	100 TB/s	32 GB

All configurations: 10 PFLOP/s tensor compute

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Workloads and Deployment:

- **Dense LLMs:** Llama-3.1 70B
- **MoE:** DeepSeek-V3 (671B), GPT-OSS (20B, 120B), Kimi K2
- **Speech:** Whisper, Canary-1B
- **Context Lengths:** 4K and 64K

Headline Results

4.71×

higher TPS/card
vs HBM

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Averaged across all workloads
At 4K context, batch size 32, 0.5 μs network latency, 1 TB/s network bandwidth.

Conclusions

Our contribution

3D-DRAM puts bandwidth *and* capacity in one package → three co-designed solutions.

Raptor 3D-DRAM vs. HBM4 & Rubin R200 silicon-area basis

Metric	Raptor 3D-DRAM	HBM4 24 Gb	HBM4 32 Gb	Rubin R200
Capacity (MB/mm²)	**11.4**	21.9	26.3	21.9
Bandwidth (GB/s/mm²)	**32.6**	1.67	1.51	1.39
Power per GB/s (mW/GB/s)	**2.96**	40.0	40.0	40.0

Effective-BW basis (Raptor 83%, others 100% util.). Power per GB/s: lower is better. Rubin R200 = 8× HBM4 24 Gb SoC.

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≈20× the bandwidth per mm^2 and 13.5× better power per GB/s.

The memory wall is a technology problem. **3D-DRAM is the solution.**

Early Silicon of Raptor

The First 3D-DRAM Accelerator for Generative Inference

Thank You