VLBI: The Next 20 Years

Colin Lonsdale
MIT Haystack Observatory

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Talk Overview

- A historical perspective - drivers for progress in VLBI over the last 20 years
- The nature of transformational change in technology, with examples
  - Latency in technology adoption and use
- Future VLBI-relevant technologies
- Future VLBI stations and arrays

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- Future VLBI stations and arrays
    - The technically feasible

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- Future VLBI-relevant technologies
- Future VLBI stations and arrays
  - The technically feasible 😯
  - The economically plausible 😃

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- The nature of transformational change in technology, with examples
  - Latency in technology adoption and use
- Future VLBI-relevant technologies
- Future VLBI stations and arrays
  - The technically feasible 😯
  - The economically plausible 😃
  - The likely reality 😕

20 Years Ago …

- **VLBA recently commissioned**
  - Sustained 128 Mbit/sec record rate on tape
  - Analog filtering and baseband conversion
  - Multiple frequency bands with fast switching
  - Imaging u-v coverage by design, not by chance
  - Major leap in capability
- **'Ad-hoc' VLBI**
  - EVN and other arrays, several large apertures
  - MkIII recording systems, comparable to VLBA
  - Good sensitivity, low duty cycle, difficult imaging
- **Mostly 1.6 GHz to 22 GHz, some 43 GHz**

10 Years Ago ...

- **VLBA 10 years older**
  - Sustained 128 Mbit/sec record rate on tape
  - Analog filtering and baseband conversion
  - Multiple frequency bands with fast switching
  - Imaging u-v coverage by design, not by chance
  - Static capability, except for software improvements
- **'Ad-hoc' VLBI**
  - EVN and other arrays, several large apertures
  - Transition from tape to Mk5A disk units in progress
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  - Stat

Modest change …

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Today

- **VLBA 20 years older**
  - Sustained 2 Gbit/sec record rate on disks
  - Full digital signal path from IF (RDBE)
  - Multiple frequency bands with fast switching
  - Imaging u-v coverage by design, not by chance
  - Major leap in capability
- **‘Ad-hoc’ VLBI**
  - EVN and other arrays, EHT, several large apertures
  - Mk5, Mk6 recording systems, up to 16 Gbit/sec
  - Data transfer over internet at 1Gbps+
- **Mostly 1.6 to 86 GHz, some 230 GHz**

Today

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Transformational change!

(what happened?)

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Basic Elements of VLBI

- Antennas
- Receivers
- Analog and digital stages
- Recorders and data transport
- Correlation
- Postprocessing, imaging, geodesy

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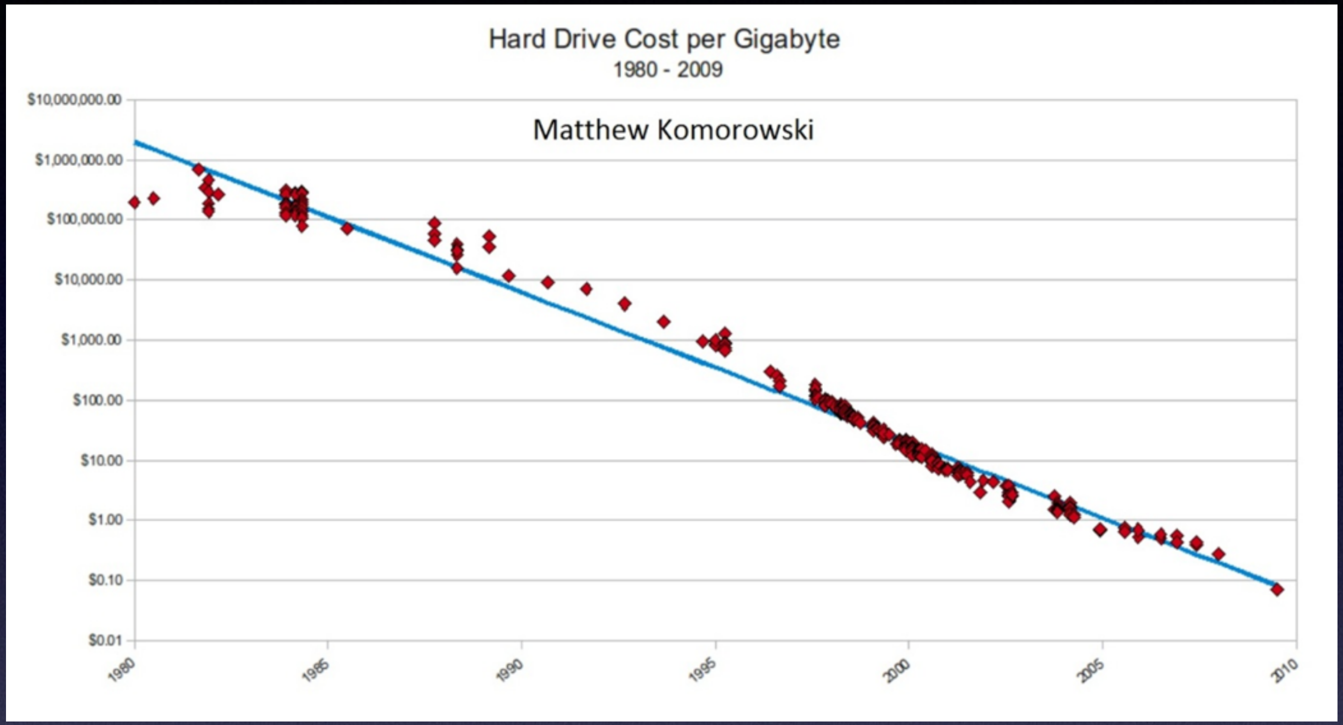
Two Technologies

- Hard disk drives got big, cheap and fast

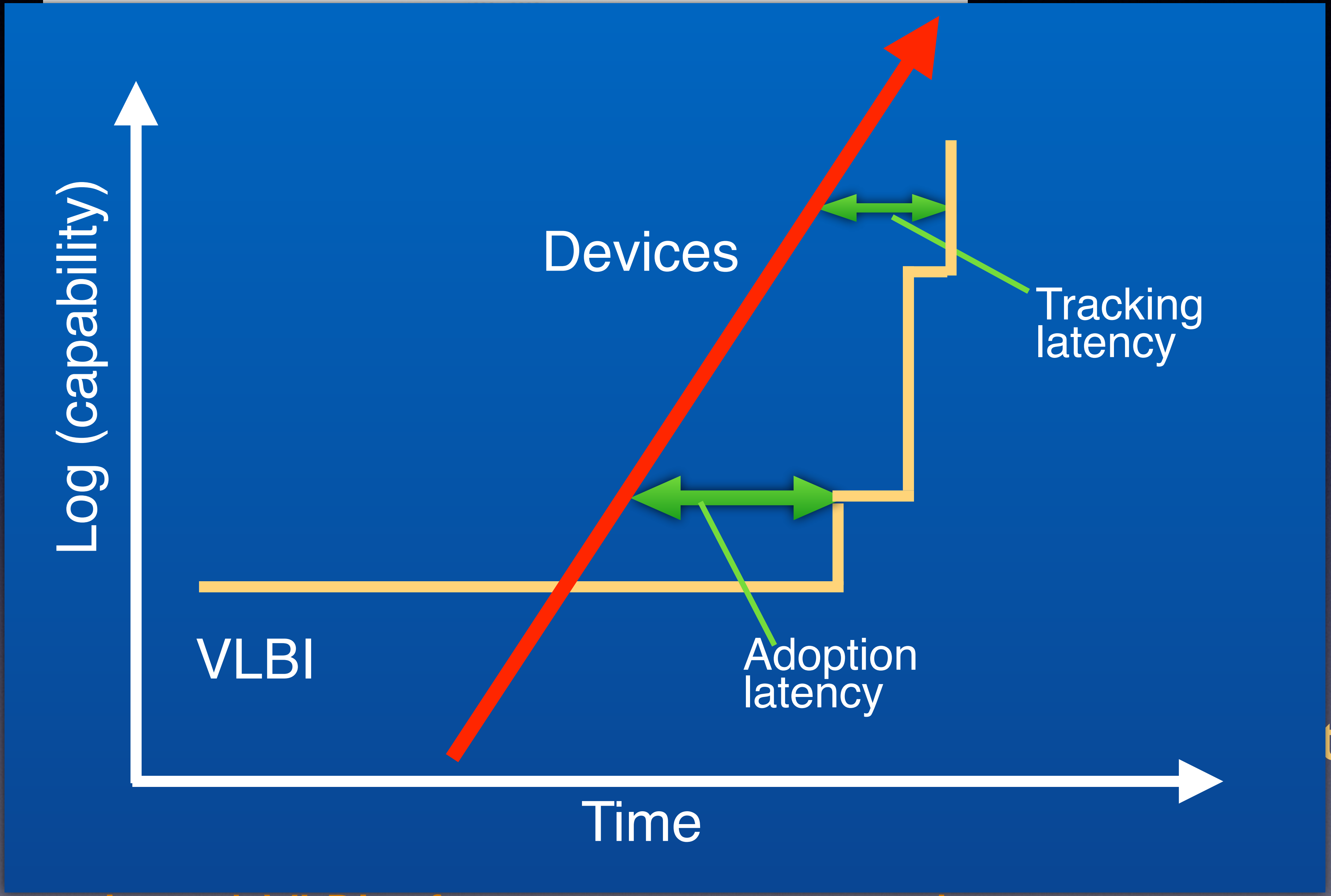


- Samplers and FPGAs got cheap and fast
  - Similar performance gains
- Multi-Gbit/sec recording went from impossible to easy in just a few years …
  - It took VLBI a few more years to implement

Two Technologies

- Hard disk drives got big, cheap and fast

Hard Drive Cost per Gigabyte



-
- ... to
    - It took VLBI a few more years to implement

From Impossible to Trivial

- Ubiquitous feature of modern technology
  - Vinyl records ➔ CDs ➔ internet streaming
  - Video rental stores ➔ internet streaming
  - Land lines ➔ cell phones
  - Slide rule ➔ electronic calculator
  - Typewriter ➔ word processor
  - Film ➔ digital imaging
  - PC and console gaming ➔ VR (growth 100%/yr)
  - … and many more
- Each transition has been abrupt - just a few years
  - It's the exponential nature of IT progress on a broad front
  - IT progress catalyzes rapid gains in many other areas too

Key future technologies for VLBI

- RF over fiber
  - Very wide IFs, simplification at feed
- Digital receiver components
  - ADC, FPGA/CPU, I/O capacity
- Inexpensive clocks
- Non-volatile solid-state memory
  - 3D NAND, RRAM (Racetrack, PCM, …)
- Fiber transceivers, internet backbone capacities
- Massively parallel computing
  - multicore, hybrids, integrated NVRAM, …
- Lower cost, more flexible apertures
- Advanced computing techniques and software

Digital Receivers

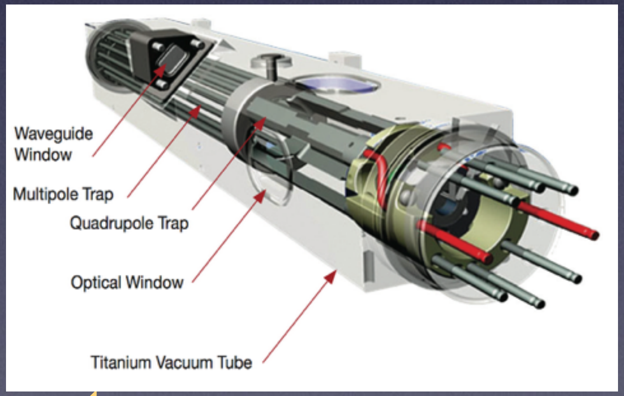
- ADCs are getting faster, cheaper, lower power
  - September 2014, Semtech announced 64 Gsps part, dual-channel, 4mm^2 chip area, 2.1 watts
  - Faster, lower power units in early 2016
- FPGAs are keeping pace
  - Latest high-end chips can accommodate tens of 10Gbps data streams on a single device
- Multicore and hybrid processor designs are in the pipeline that can handle high I/O rates
  - Takes development into the software domain, not FPGA bitcode
- Inexpensive digital receivers capable of handling tens of GHz of RF are around the corner

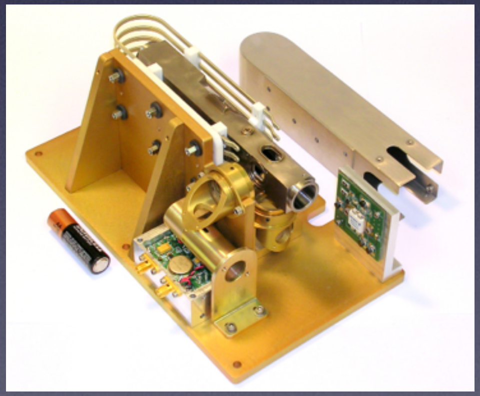
VLBI frequency standards

- Gold standard has been H-maser
  - ~10^{-15} in 1000 sec
  - Cost $250k, sensitive to temperature, vibration

- Strong market drivers for size/cost
  - Chip-scale atomic clock (CSAC)
    - Limited to 10^{-11} level

  - Deep Space atomic clock (DSAC)
    - Mercury ion, 1 litre, 3kg
    - Reaches 10^{-14}, but still costly





- Many options under development
- Requirements will decline

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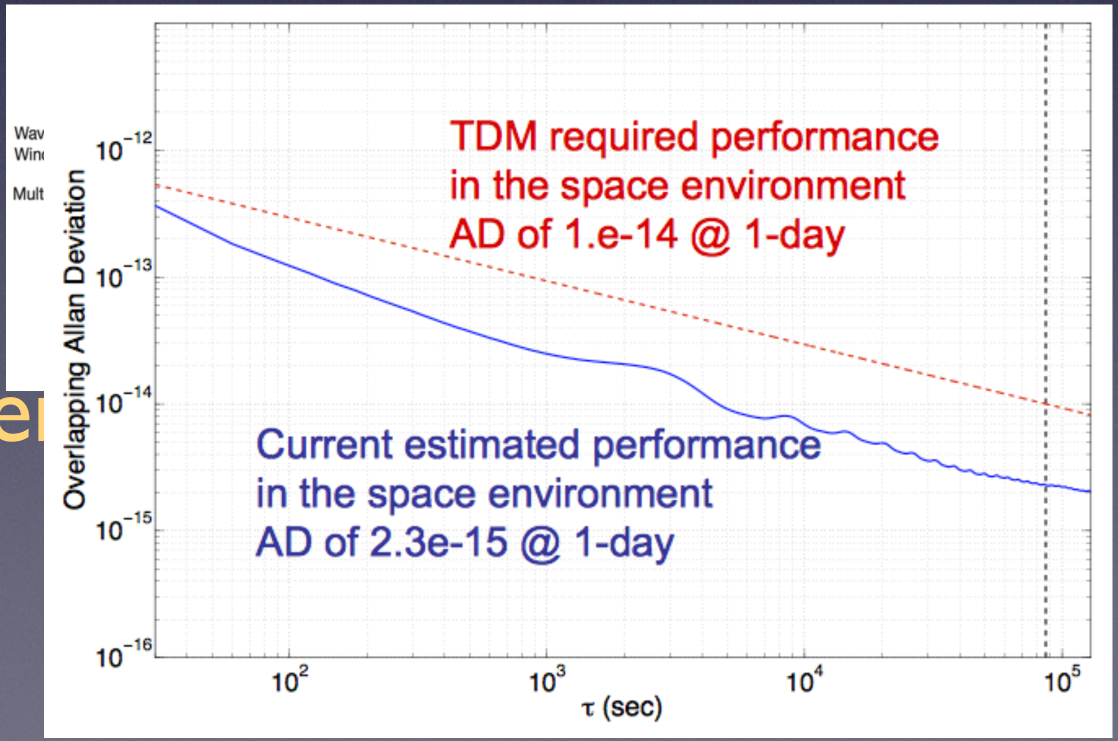

NV Solid State Memory

- Current state of the art - 3D NAND
  - e.g. Samsung USB SSD
  - $600, 1 TB, 26 grams, 1Gbit/sec

- Many contenders for replacement …

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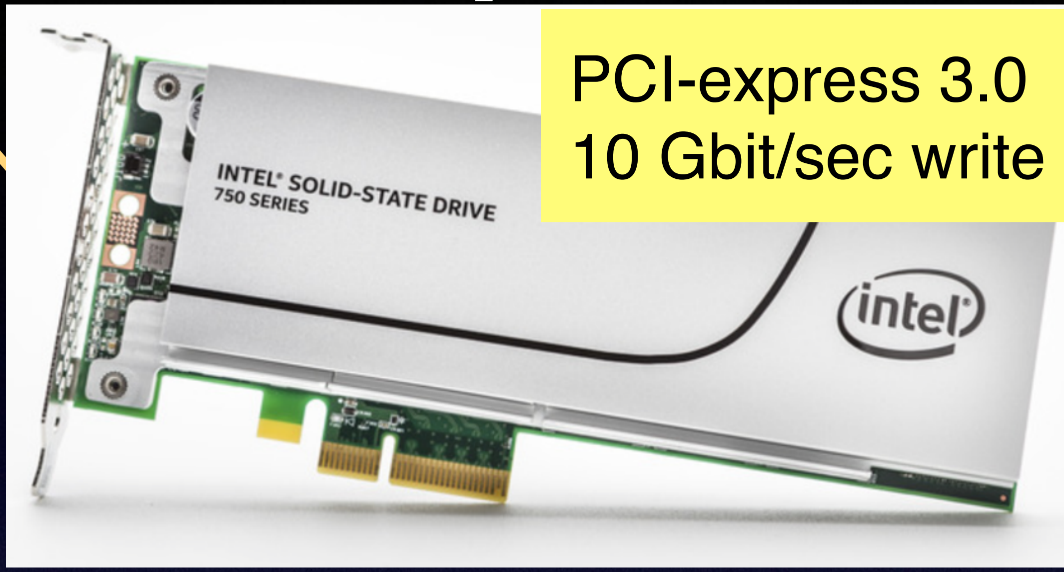

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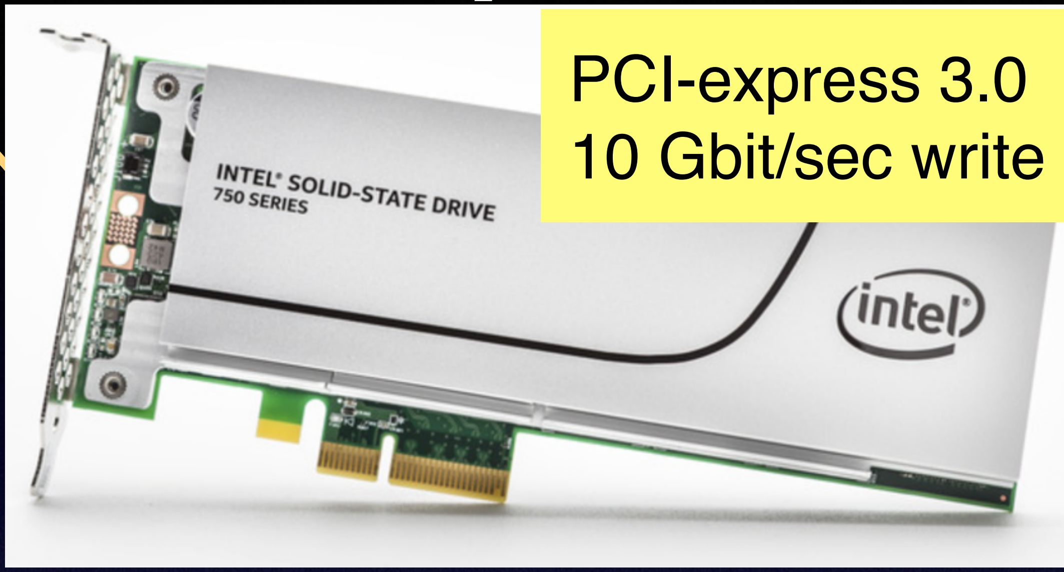

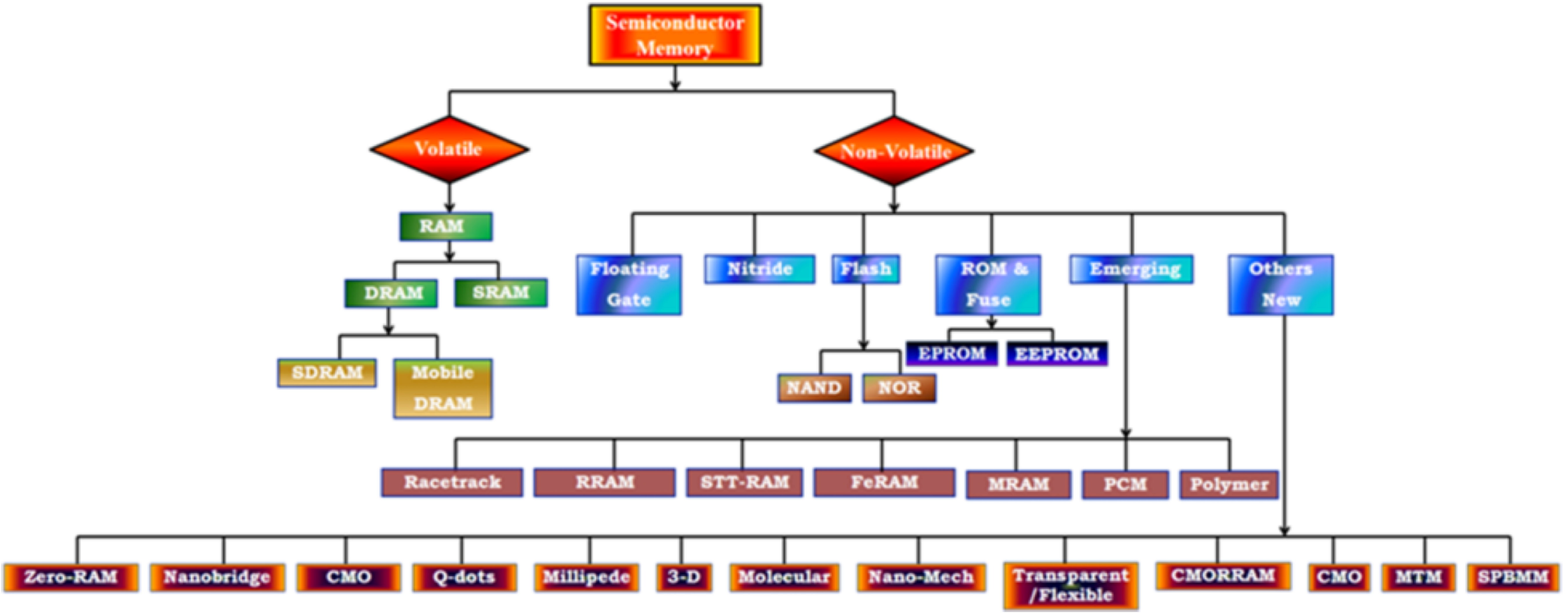

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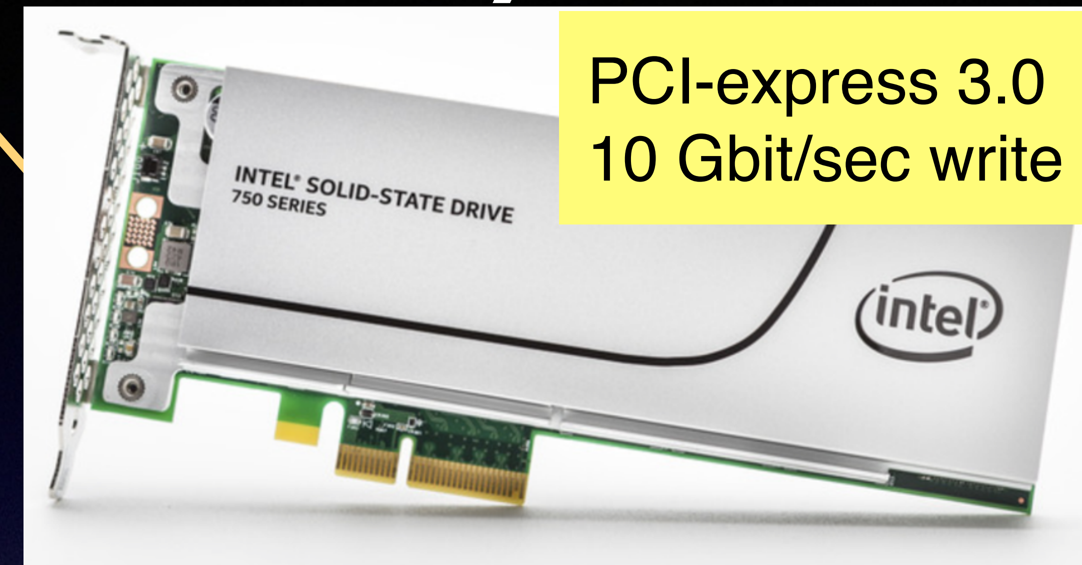

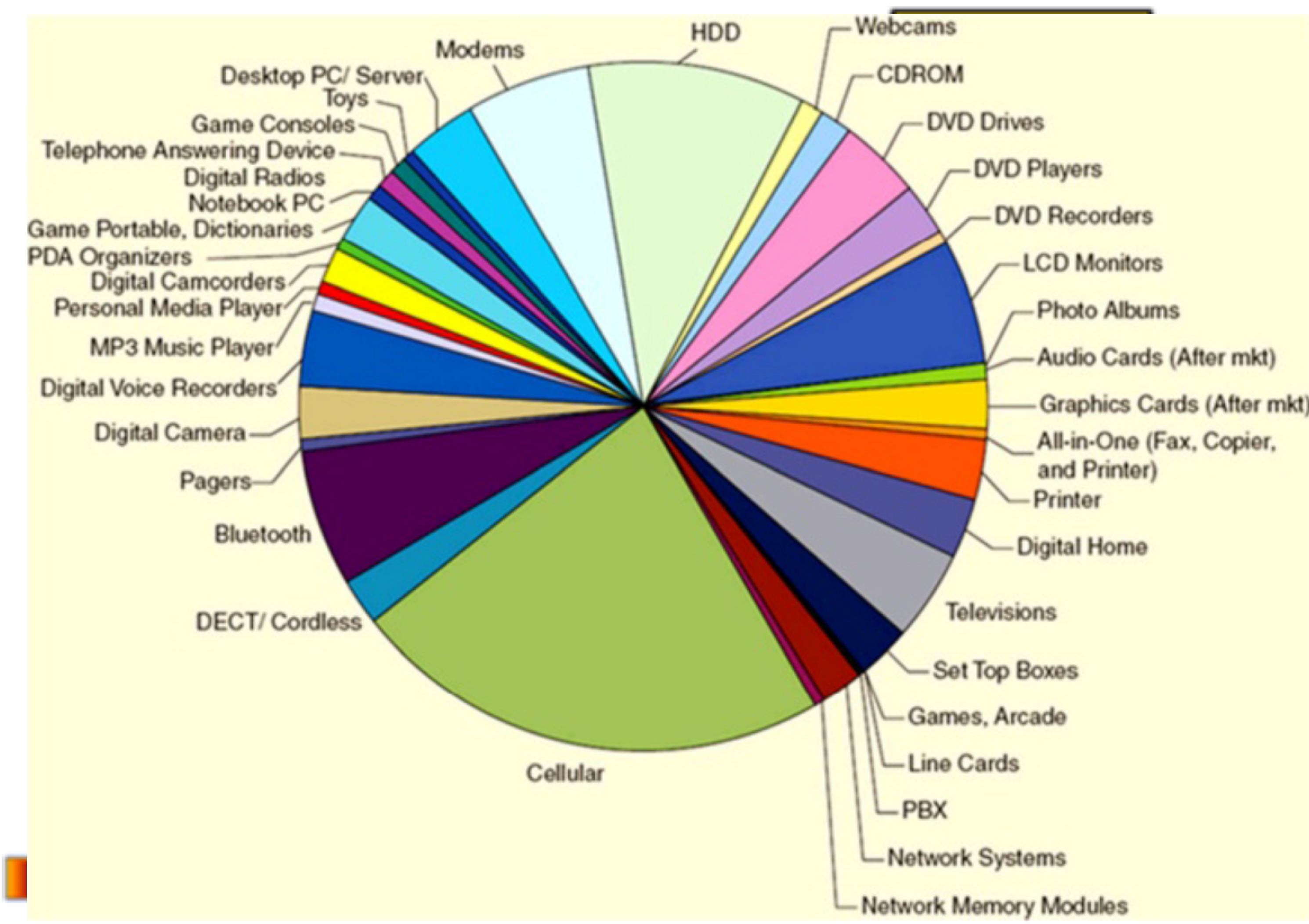

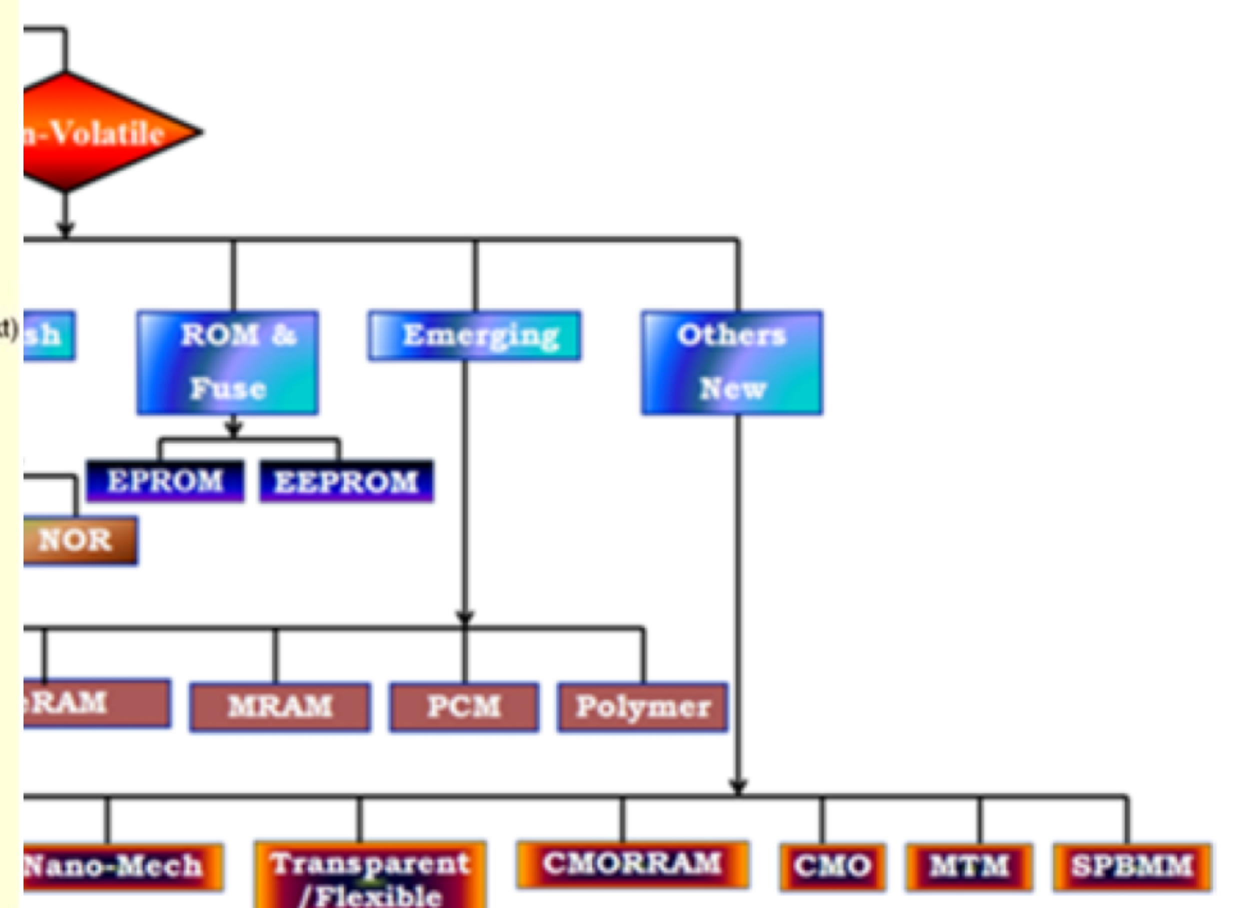

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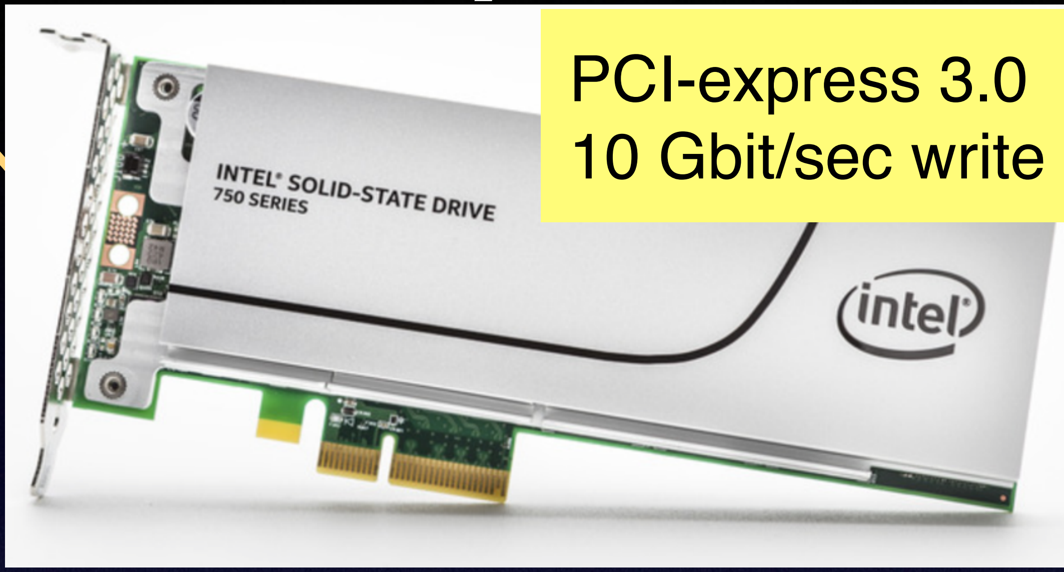
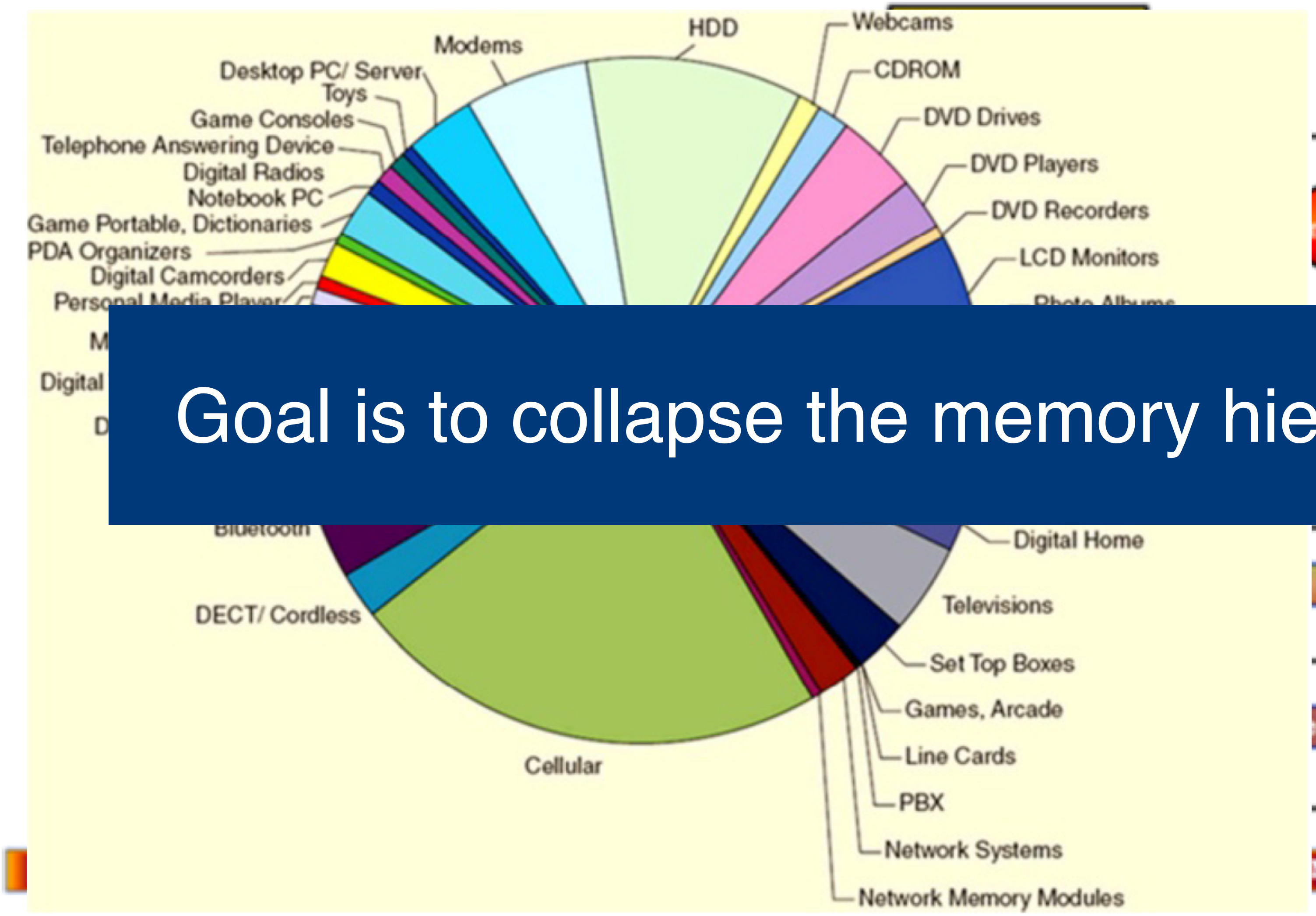
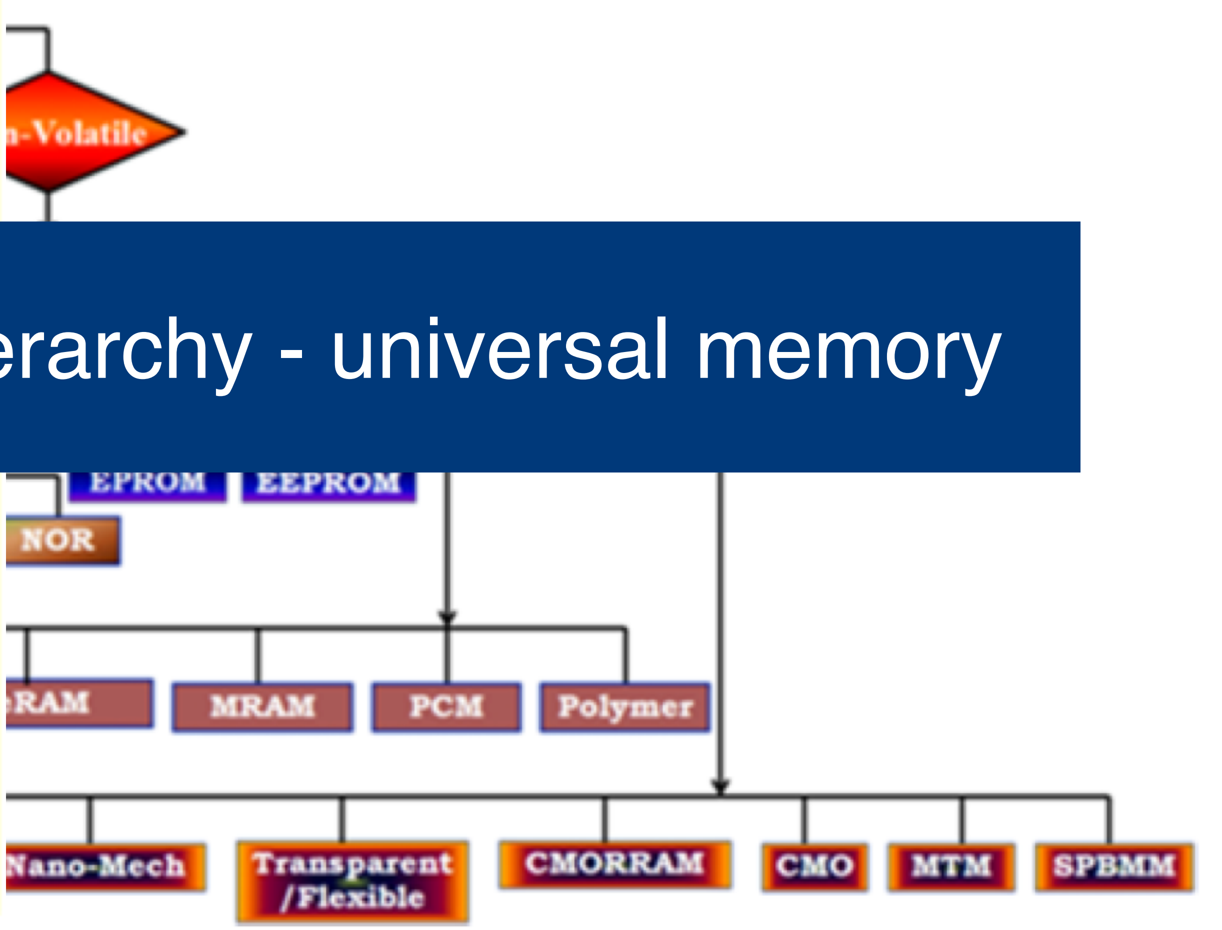


PCI-express 3.0
10 Gbit/sec write

- Many contenders for replacement …

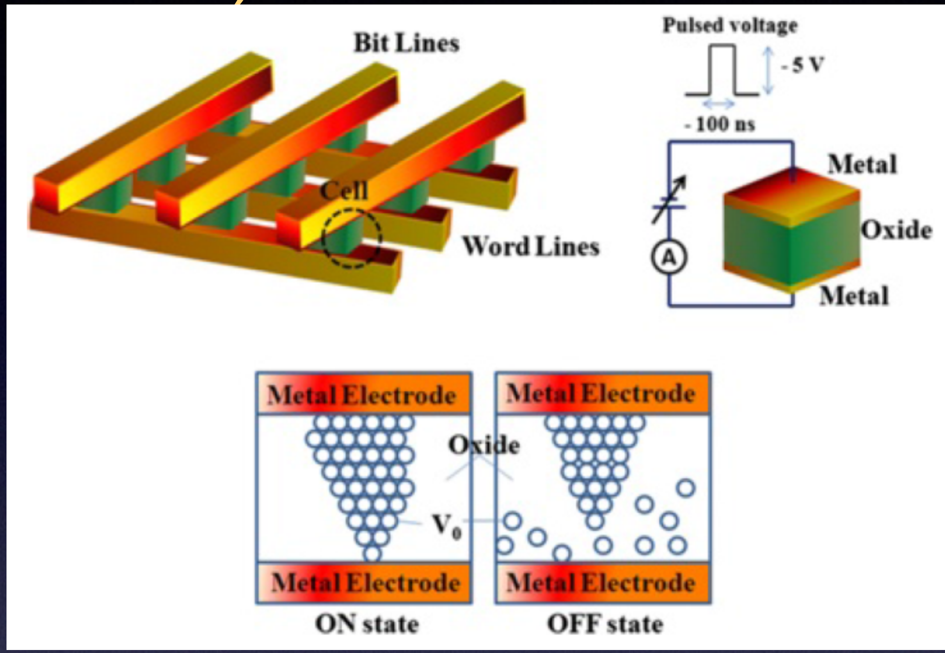




Goal is to collapse the memory hierarchy - universal memory

NV Solid State Memory

- A leading candidate - resistive RAM (RRAM)
  - Fast switching
  - Low power
  - High durability
  - Excellent volume density potential
  - Can use existing fab facilities



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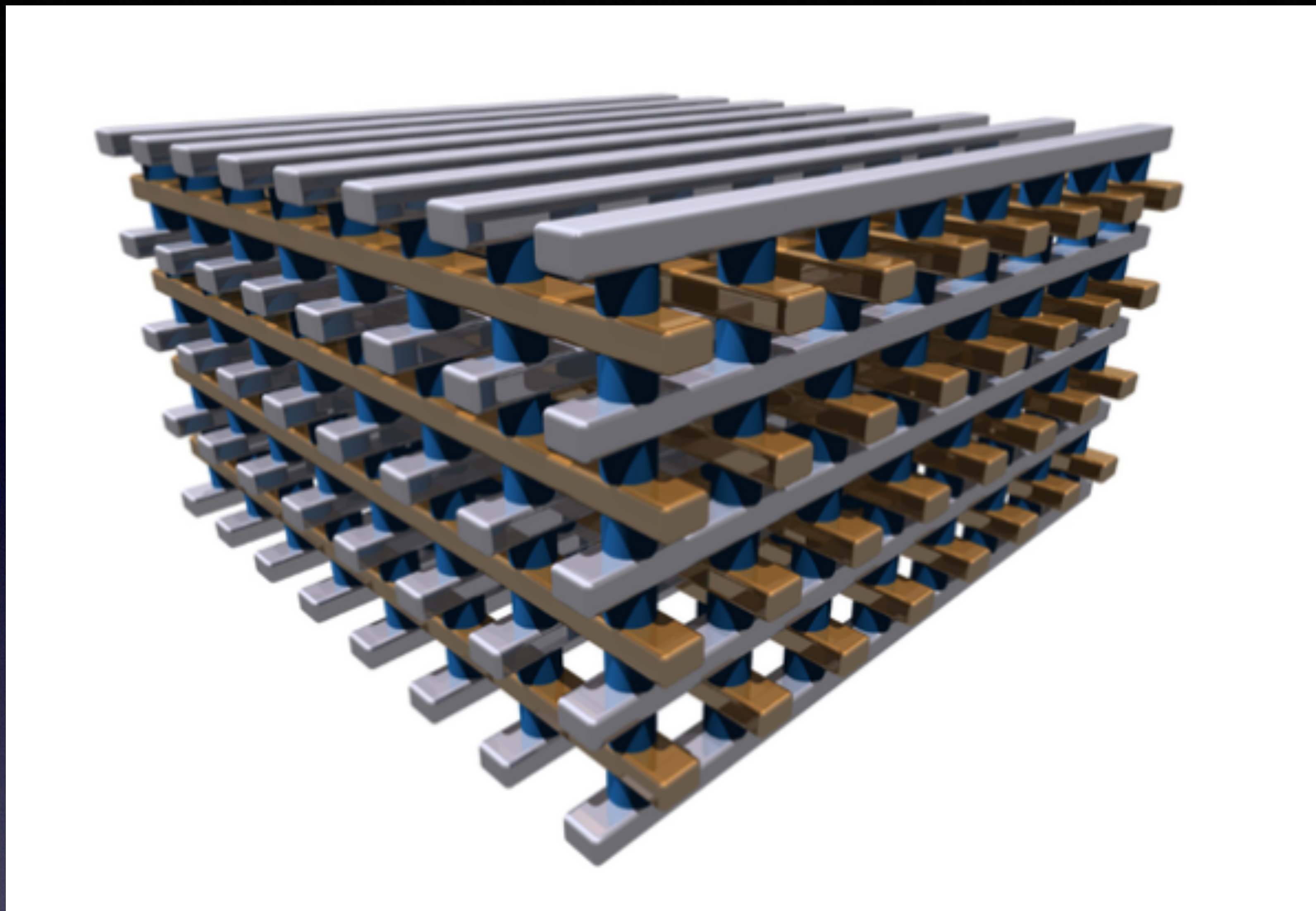
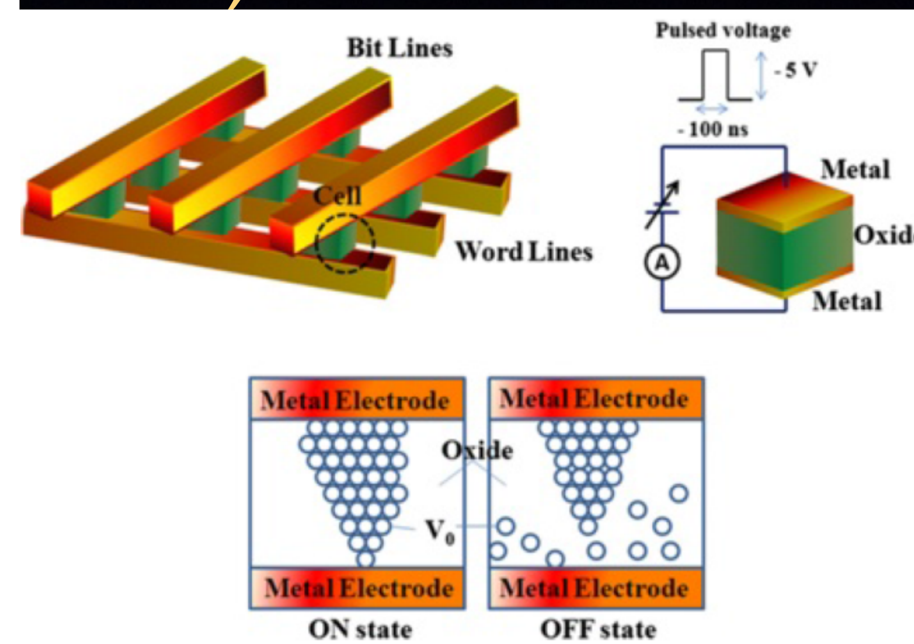


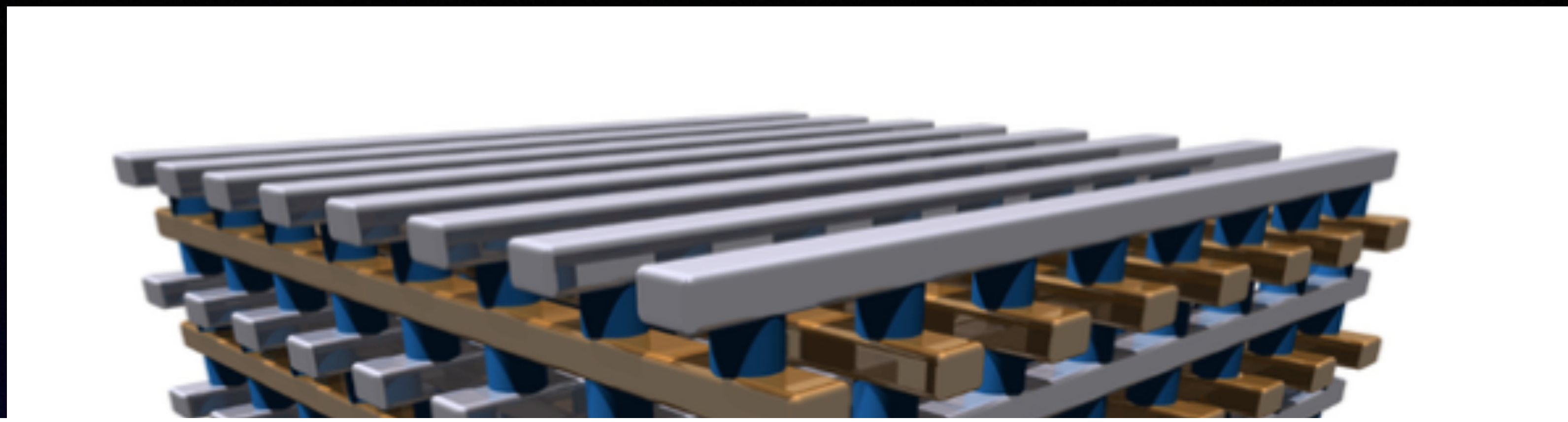
RAM)



NEWS

A terabyte on a postage stamp: RRAM heads into commercialization

NV Solid State Memory



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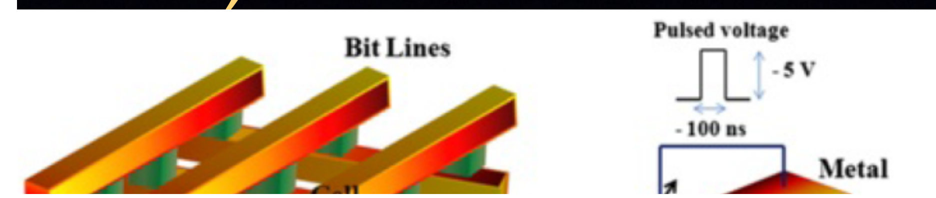
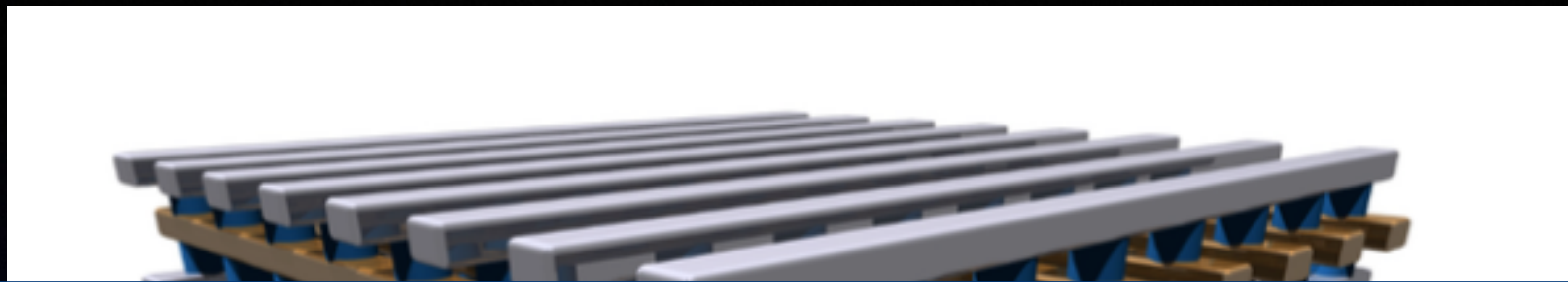
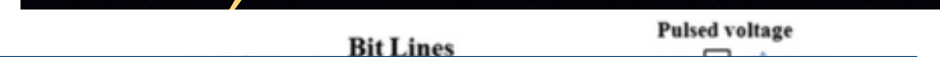


	Memristor	PCM	STT-RAM	DRAM	Flash	HD
Chip area per bit (F^2)	4	8–16	14–64	6–8	4–8	n/a
Energy per bit (pJ)[2]	0.1–3	2–100	0.1–1	2–4	10^1–10^4	10^6–10^7
Read time (ns)	<10	20–70	10–30	10–50	25,000	5–8x10^6
Write time (ns)	20–30	50–500	13–95	10–50	200,000	5–8x10^6
Retention	>10 years	<10 years	Weeks	<Second	~10 years	~10 years
Endurance (cycles)	~10^{12}	10^7–10^8	10^{15}	>10^{17}	10^3–10^6	10^{15} ?
3D capability	Yes	No	No	No	Yes	n/a

NV Solid State Memory

RAM)





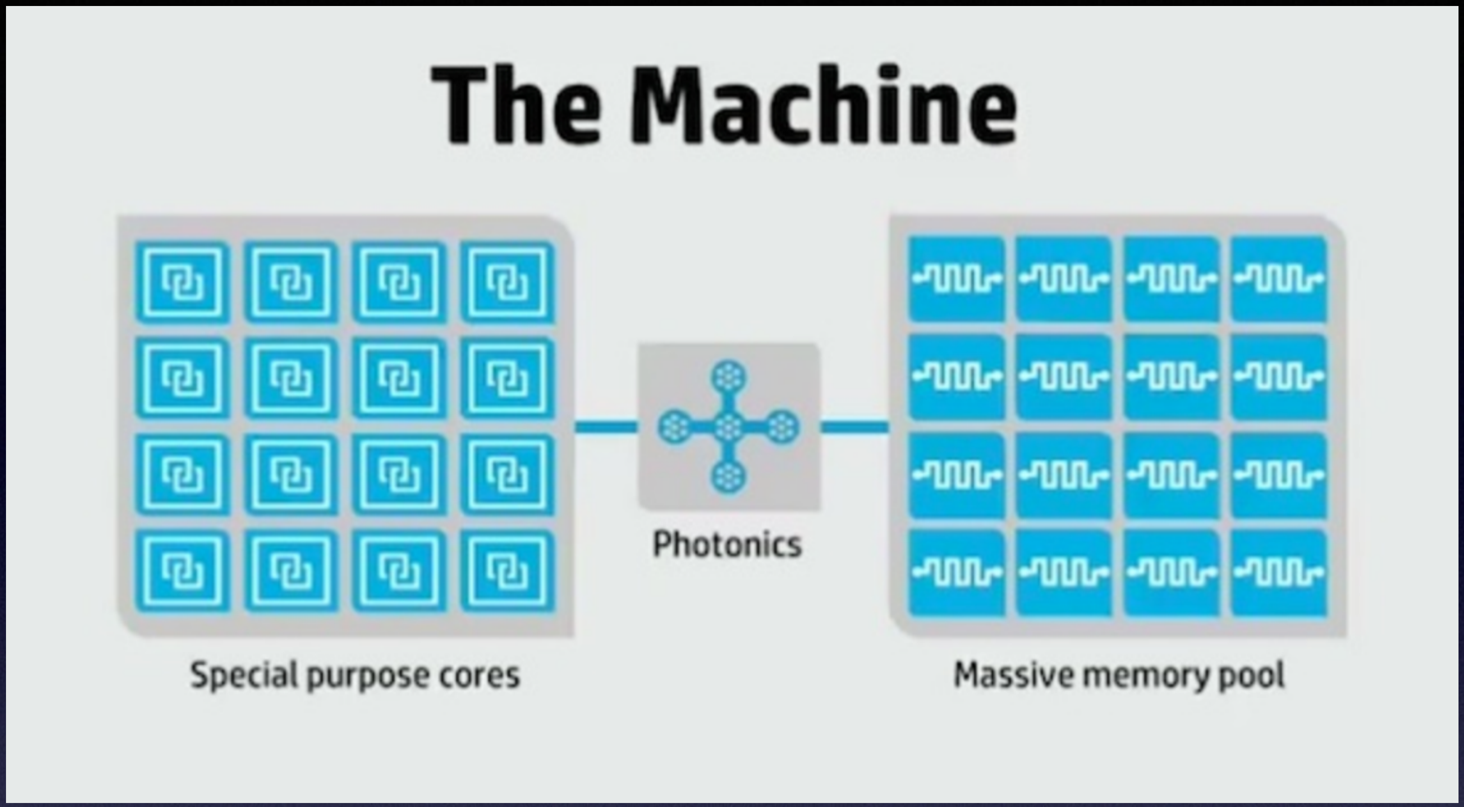
Because NVM technologies combine the fast access patterns of DRAM and the persistence and capacity of disks, they will cause a collapsing of the memory-storage hierarchy that will permeate all the way into the software we write across the board, from operating systems to middleware to applications. This will be a deep-reaching fundamental, powerful, and beneficial change.

3D capability	Yes	No	No	No	Yes	n/a

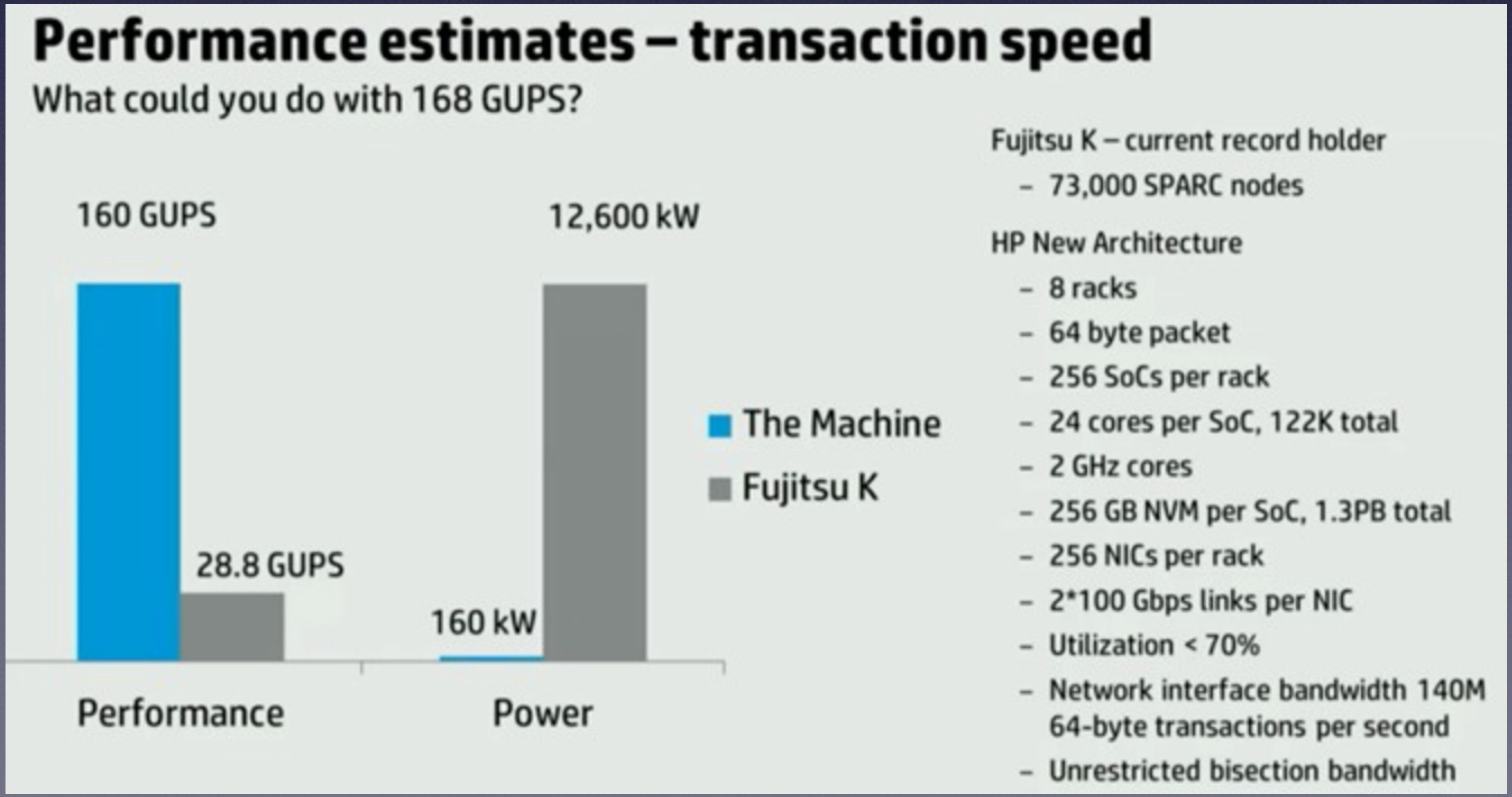
Fiber data transport

- Butter's Law
  - Fiber bandwidth doubles every 9 months
- Swift progression
  - 10 Mbit/sec, 100 Mbit/sec, 1 Gbit/sec, 10 Gbit/sec
  - Mass market soon - 40 Gbit/sec, 100 Gbit/sec, 400 Gbit/sec
  - Theoretical limit ~1 Pbit/sec per optical mode
- 400GbE link tested Tokyo-Osaka
- Intercontinental undersea capacities rapidly rising into tens of Tbit/sec regime
  - e.g. Southern Cross 14 Tbit/sec into Australasia using 100 Gbit/sec links

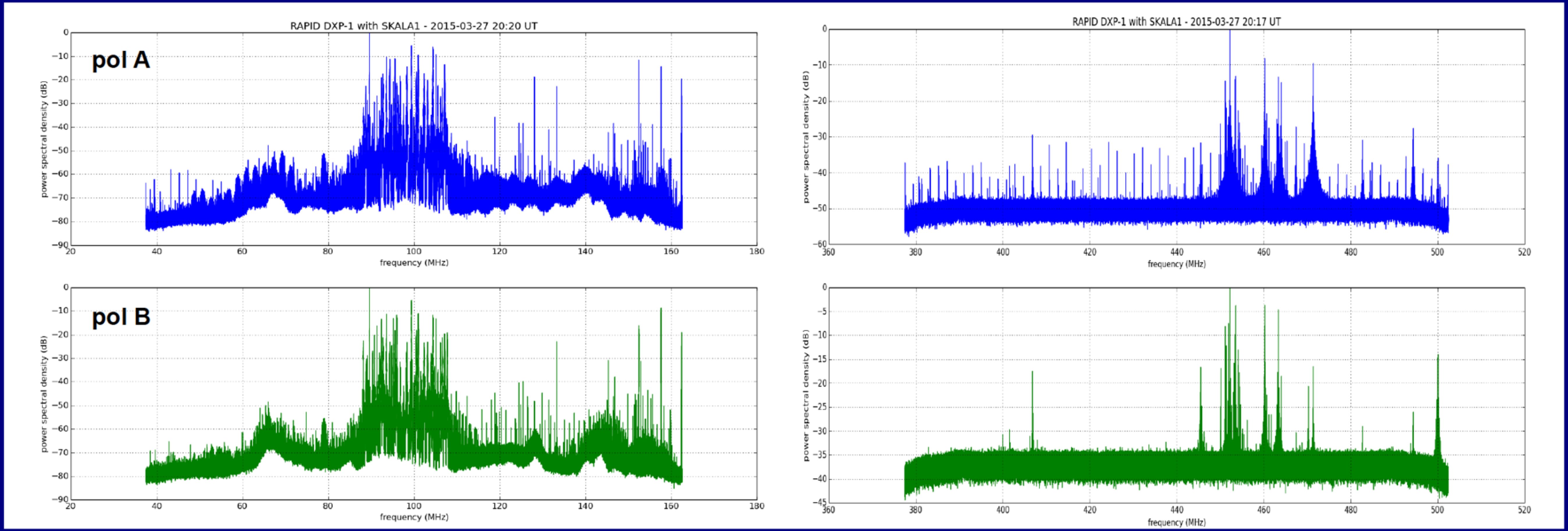
Massively Parallel Computing



"The Machine"
Hewlett Packard



RAPID DXP-1 RF Data

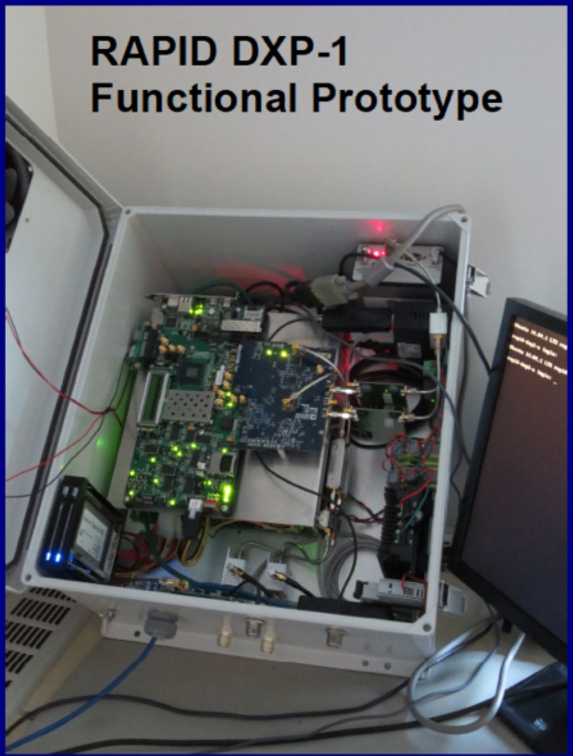


1 GSPS - Dual channel 16 bit IQ at 125 MHz final BW per channel

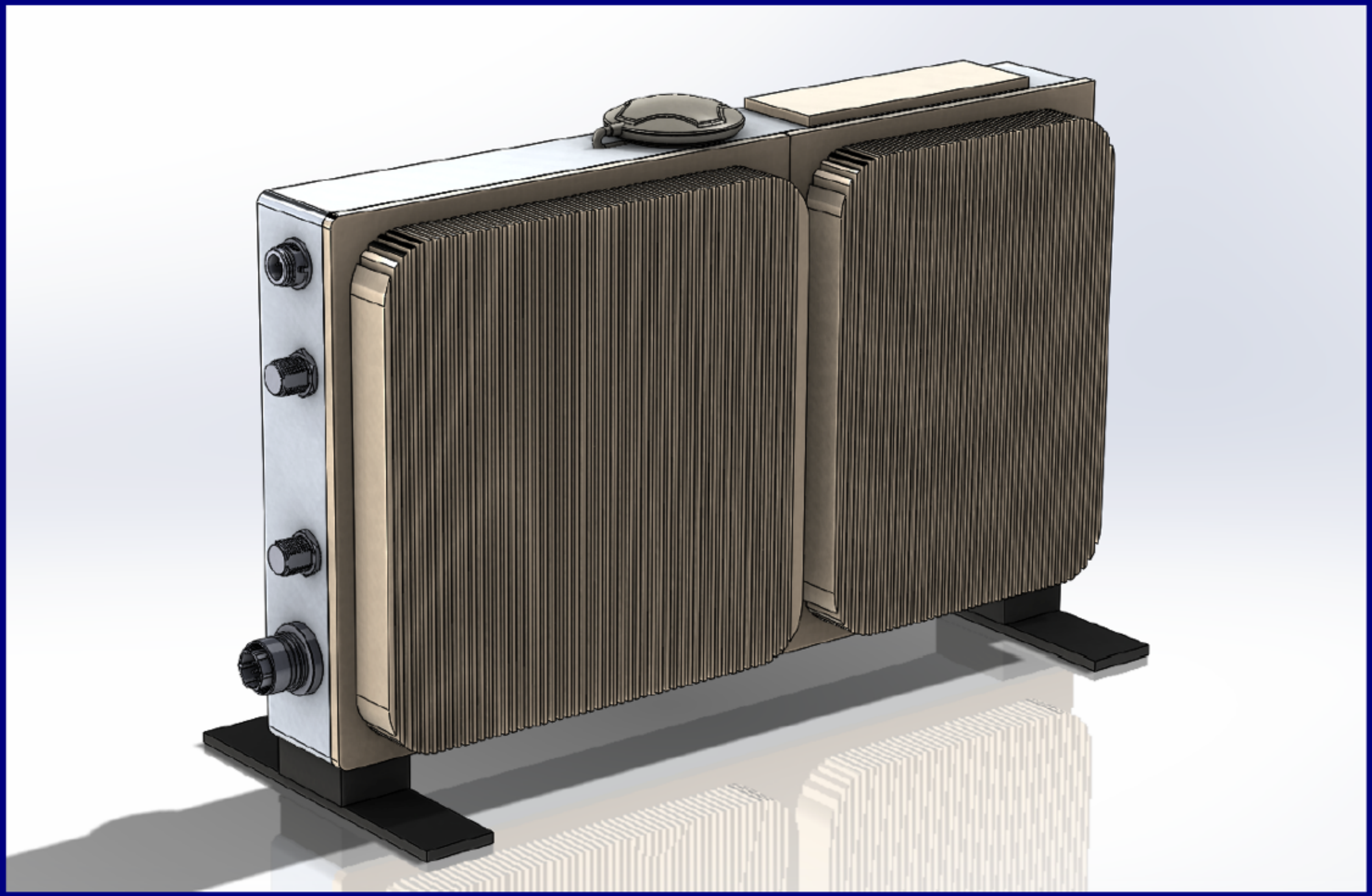
DXP-1 = DAQ eXperiment Platform 1

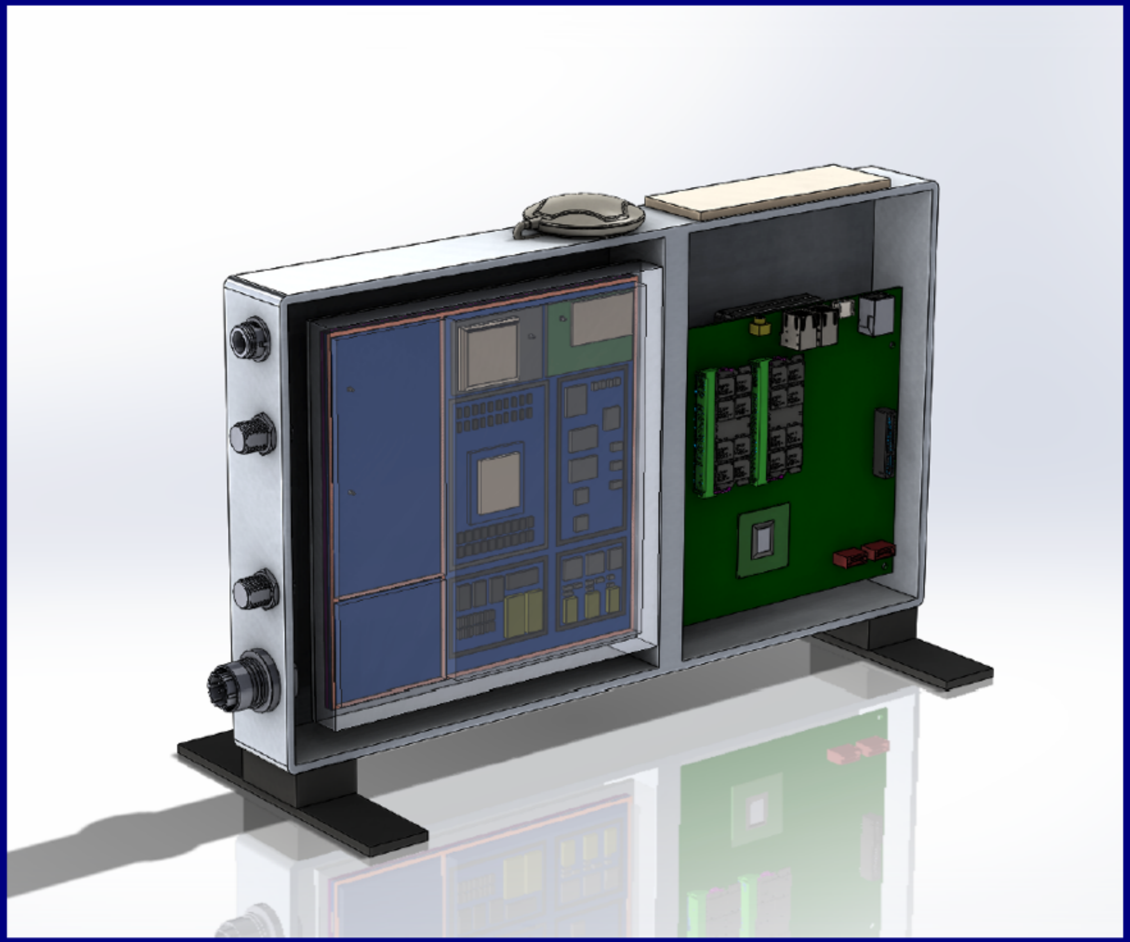
RF from DXP-1 and SKALA Generation 1 Antenna
2 Gbyte / second limit from FPGA to CPU
Digital downconverters and programmable FPGA filter bank
Currently 8 or 16 bit output for one or two RF inputs

Field testing with first SKALA Generation 2 antennas in ~ 1 month
Integrated unit prototypes soon to follow...
Production system will record 1 to 2 Gbytes / second (TBD)

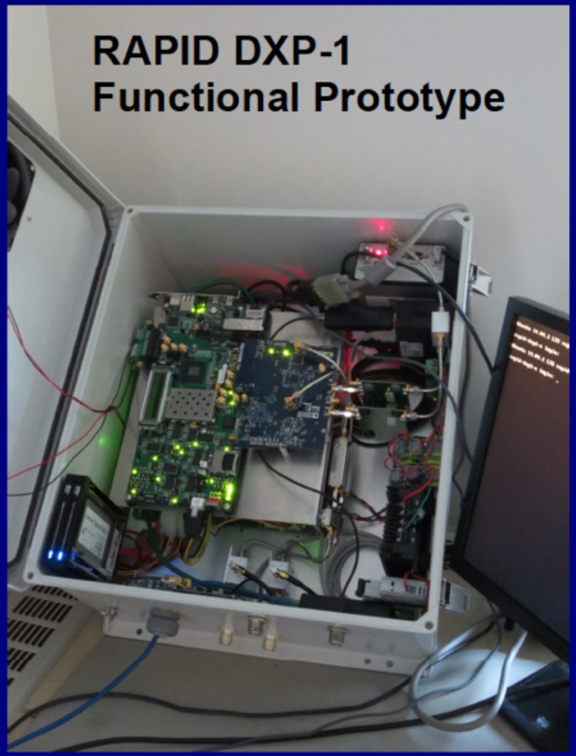


DAQ Unit

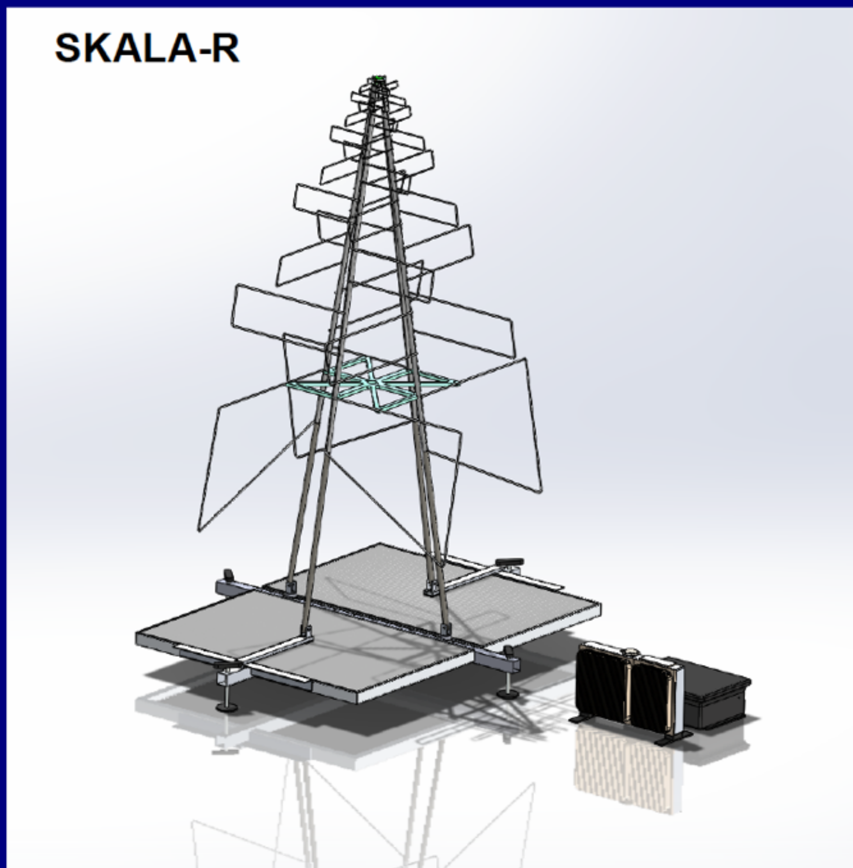


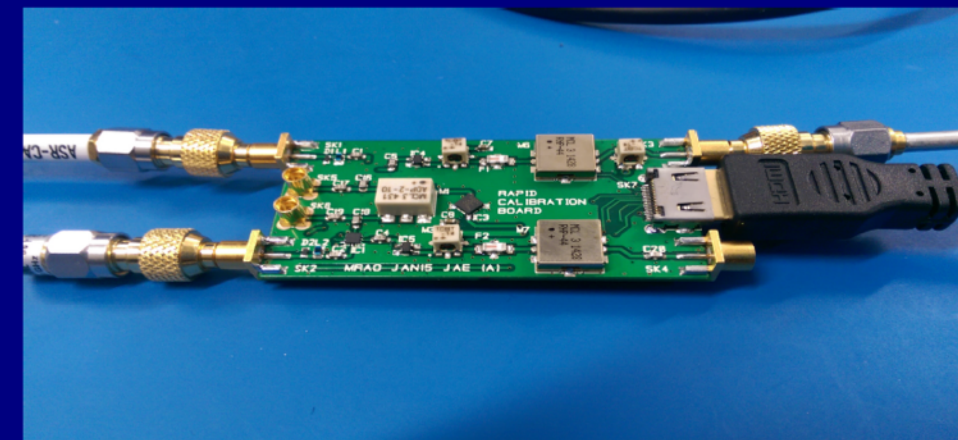


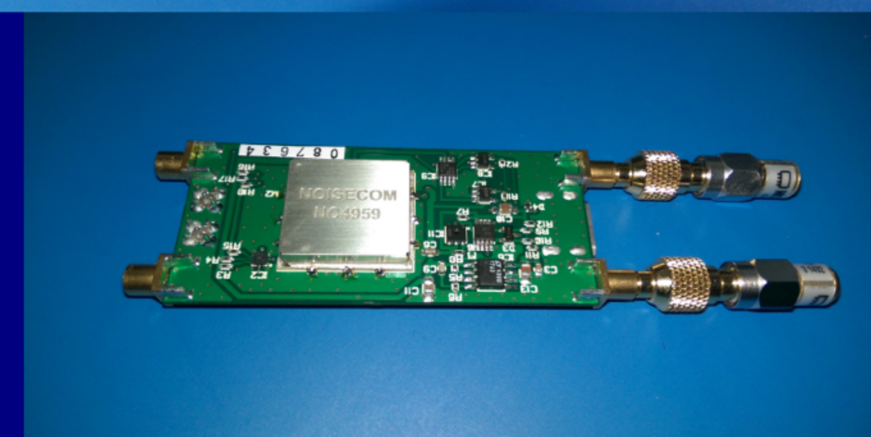
Highly Integrated Data Acquisition Unit (IP67 outdoor)
Equivalent Functional Prototype for Testing and Evaluation
Analog + ADC + FPGA (dual 14 bit ; > 1 GSPS)
Integrated Intel DAQ Computer (Intel quad core)
Dual RF inputs via N-connectors
WiFi and internal ports (e.g. USB 3.0) for connection
Hot swap SSD bay (2.5” drives)
Thermal interface via vapor chamber heatplate
Typical power draw during acquisition of ~ 30W peak

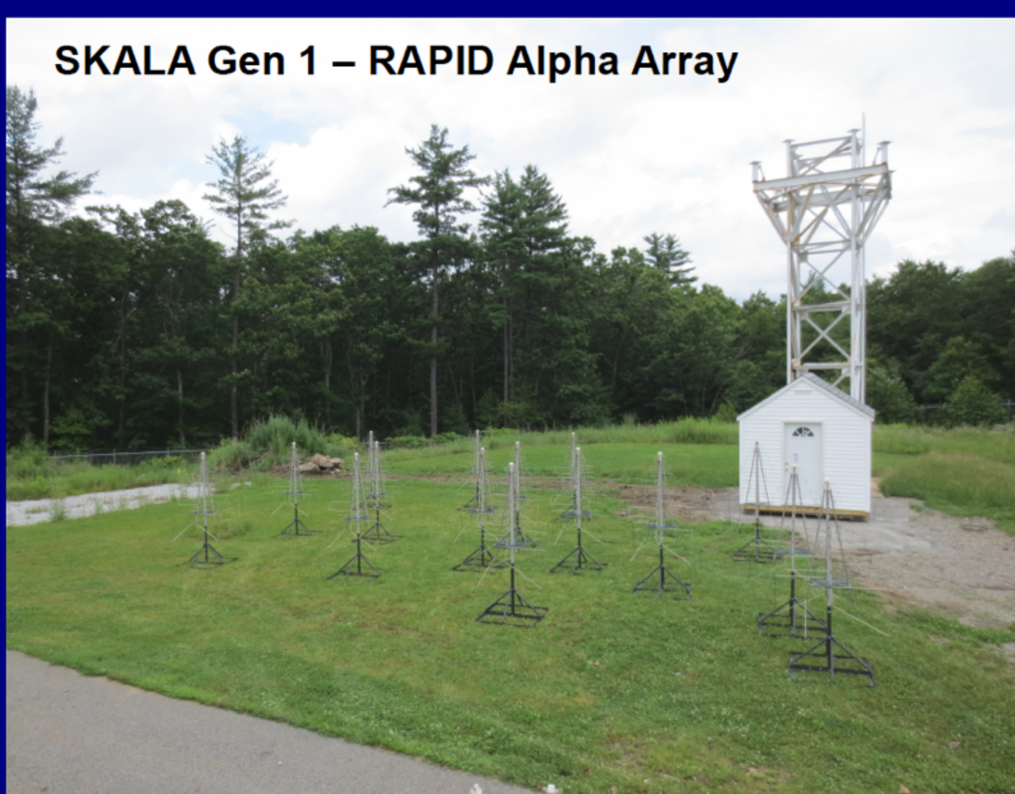


RAPID Antenna and LNA









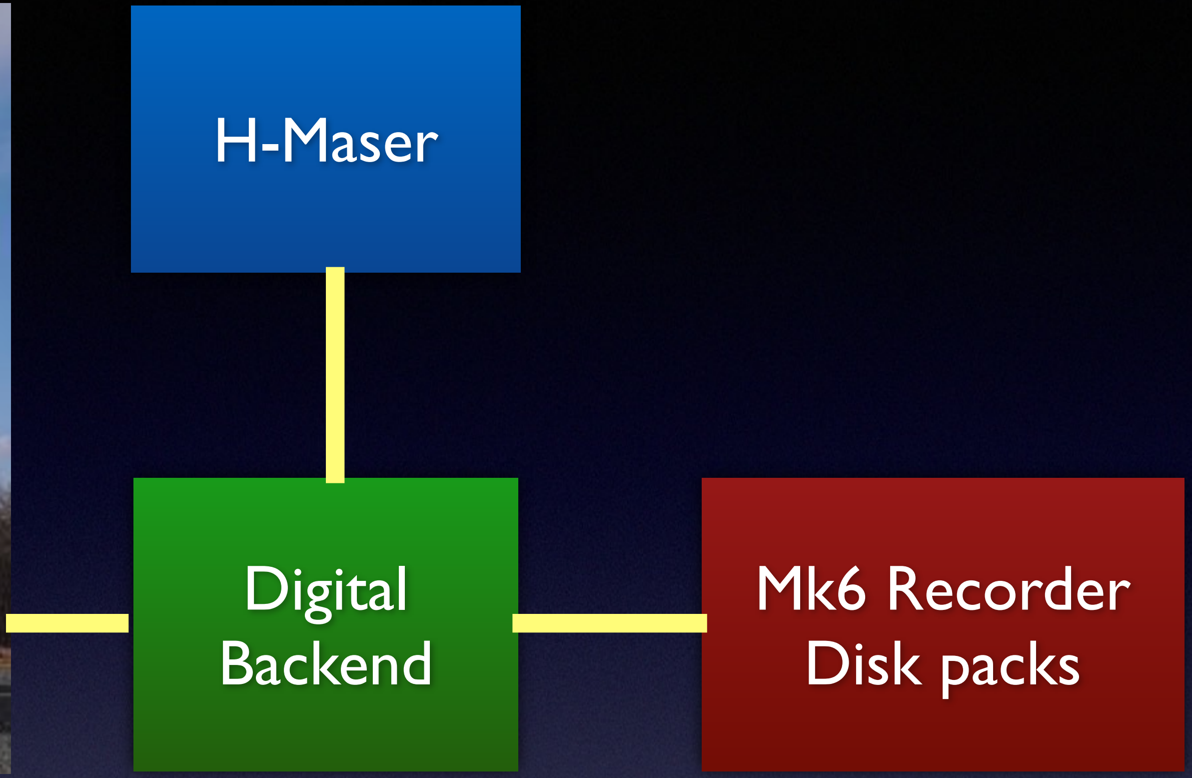
Derived from SKA Log Periodic Antenna

- Retains SKALA Design Electromagnetics
- Significant RAPID design contributions to SKA
- Alternate solar panel base structure
- Minor modifications for disassembly
- SKALA-R (RAPID variant)

LNA compatibility with SKALA

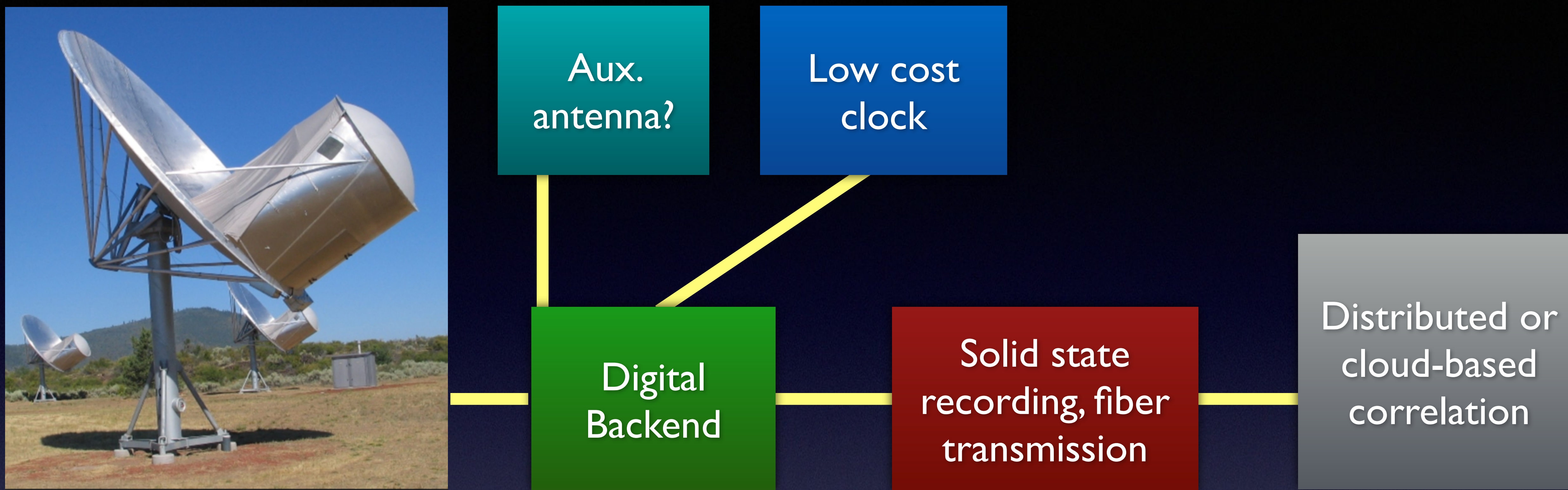
- Switched LNA / Calibrator design for RAPID
- Low power high stability calibrator
- Integrated laboratory test points

Current VLBI Station



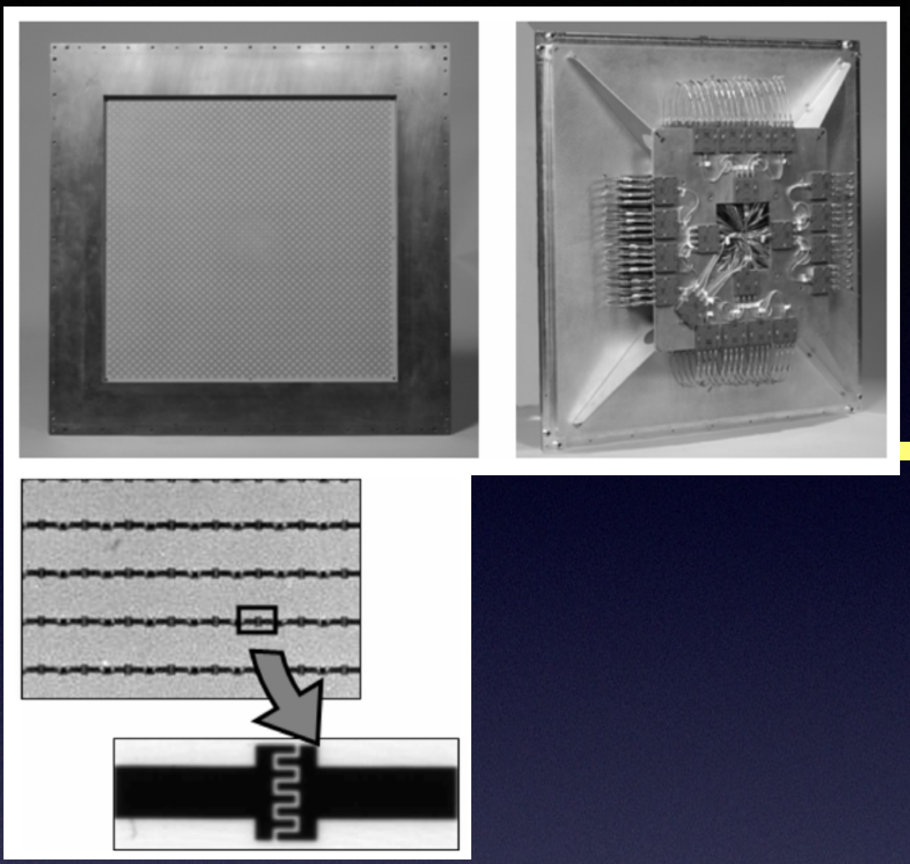
- VGOS system as a relevant example
- 12-meter antenna, ~2-14 GHz feed + receiver
- Multiple tunable bands within receiver range
- 1 GHz total bandwidth, dual-polarization, 8 Gbps
- Cost in $5M range

2025 VLBI Station



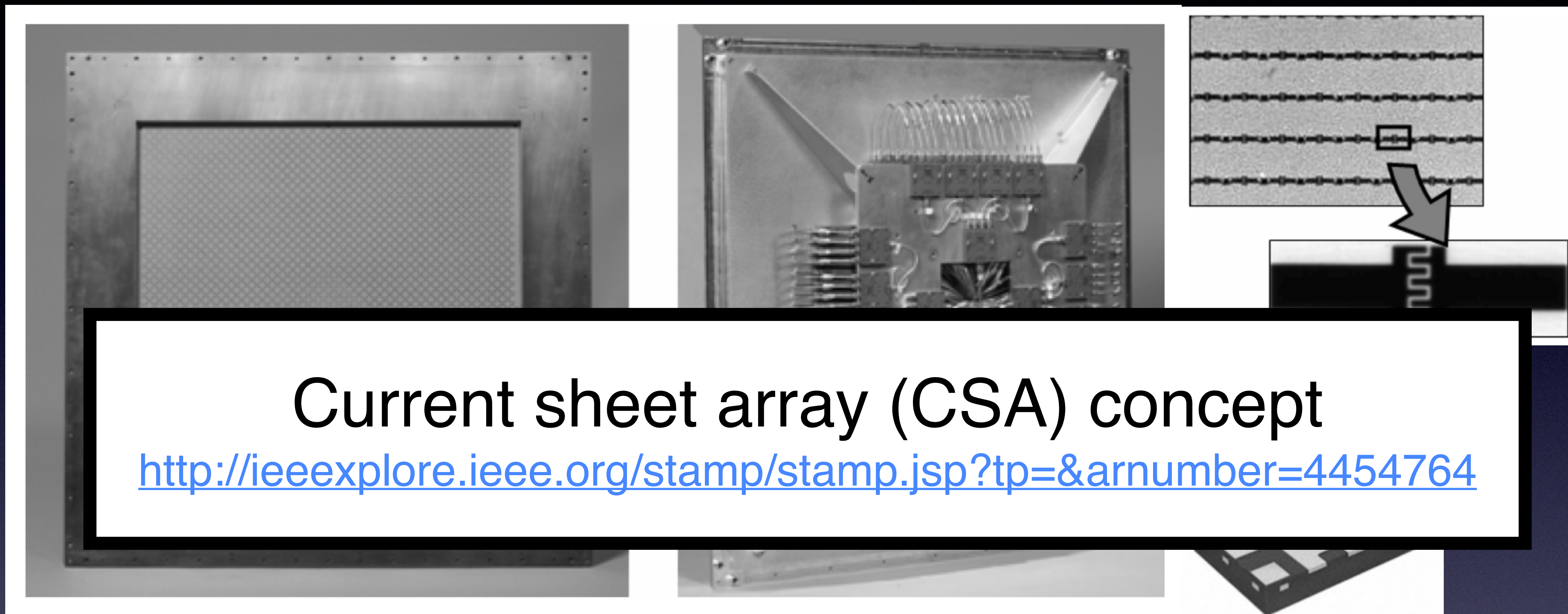
- Smaller antenna (e.g. ATA style, 6 meters)
- Auxiliary antenna on bright source for coherence
- One or more wideband feeds
- Digitize full receiver range, of order 20 GHz
- Store and/or forward at 100+ Gbps
- Cost in $1M range ??

2035 VLBI Station



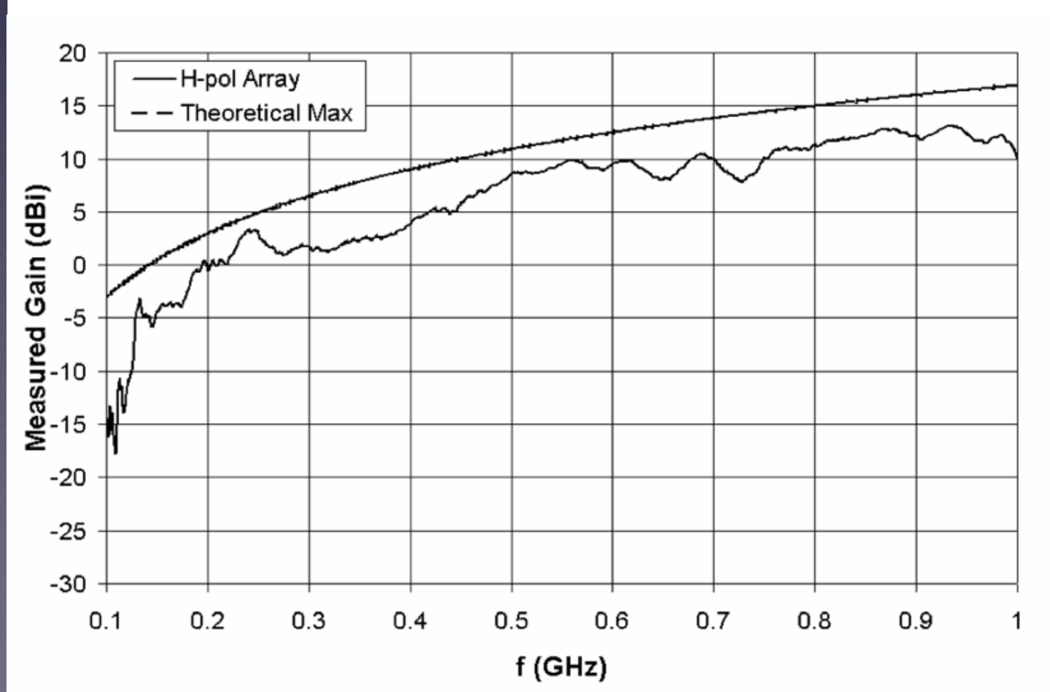
- Broadband phased array
- Many beams limited only by digital capacity
- Trade aperture size against aperture re-use
- Digitize entire RF band
- Deep local memory and full connectivity
- Cost - unclear …

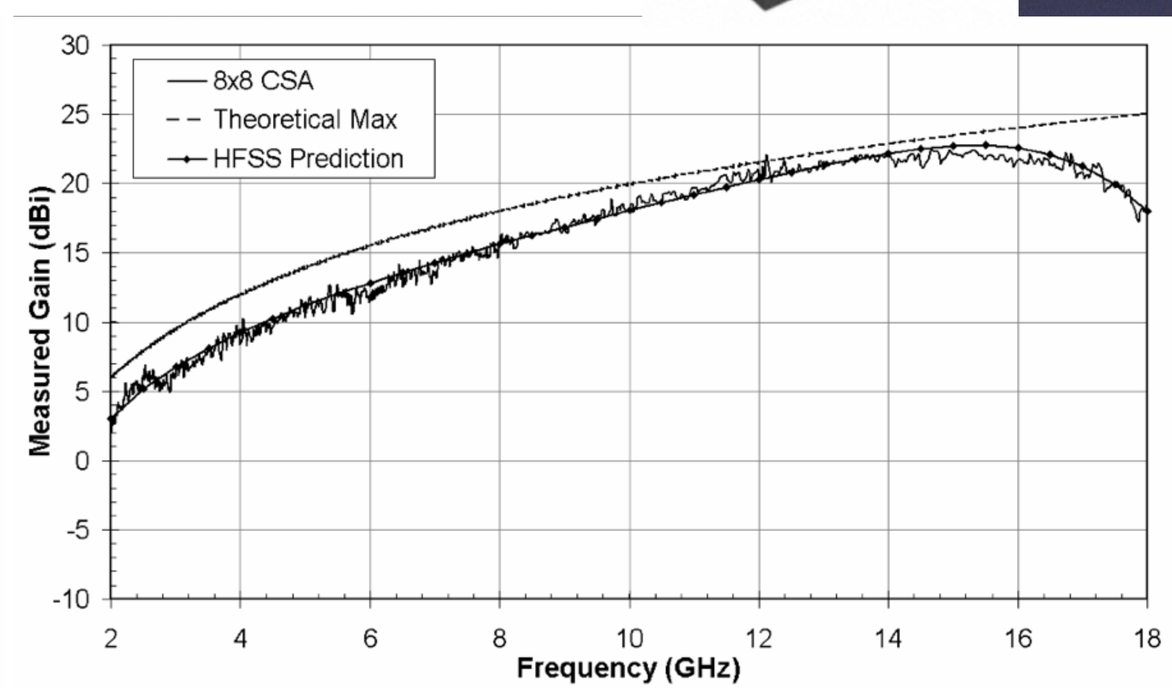
Broadband Phased Arrays



Current sheet array (CSA) concept

http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4454764





Technically possible …

- Large numbers of compact, inexpensive stations
- Full coherence, all frequencies, all the time
- Many independent beams all across the sky
- 10:1 frequency ratio or more, all frequencies all the time
- Continuous operation, extreme automation
- Full FoV correlation, archive, observing as a database query
- AI, machine learning, human-guided insight generation
- Science justification TBD (!)

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😯

Economically plausible …

- Digital upgrades of all existing stations
- Many new, inexpensive stations
- Full coherence through auxiliary small dishes
- Processed RF bandwidths 10 GHz +
- Increased duty cycle, much better performance
- Advanced software of various types
- Limited major investment, leveraging of Moore's law
- Science case per unit cost can/should be strong

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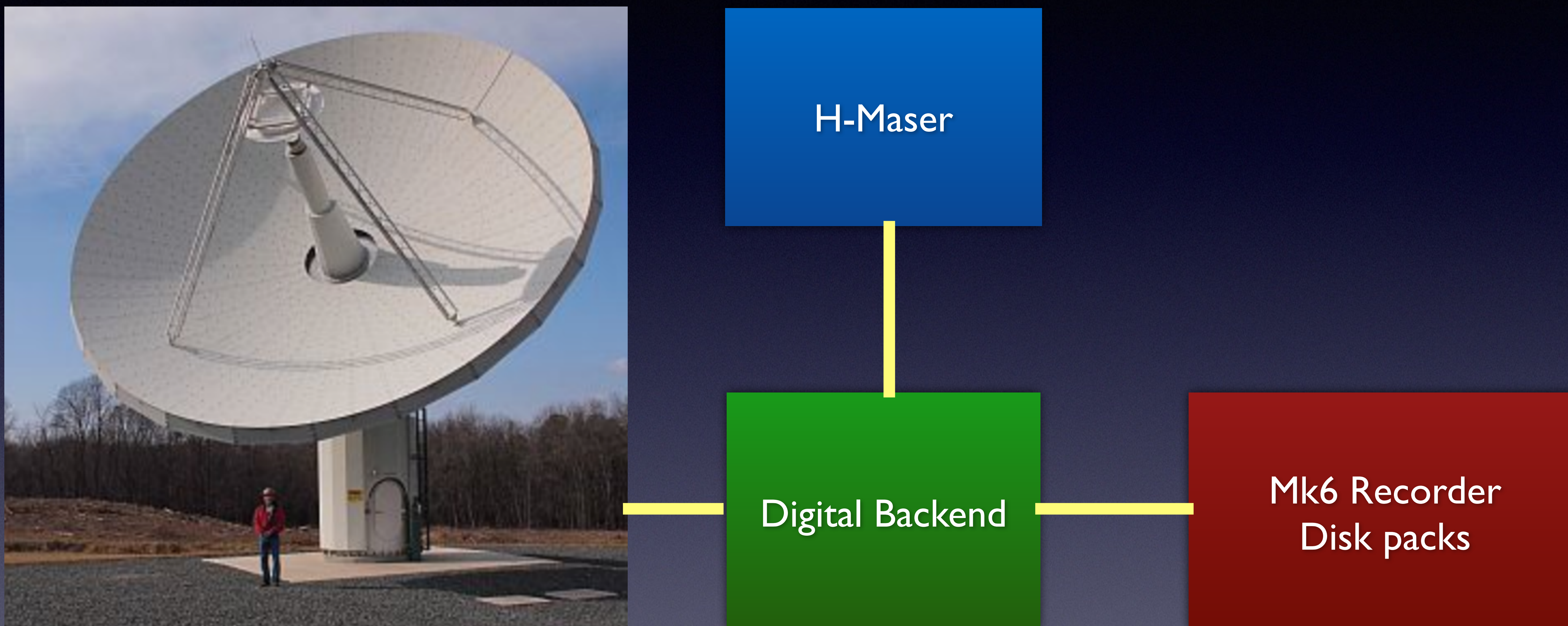
😃

Likely Reality



Likely Reality

H-Maser

Digital Backend

Mk6 Recorder
Disk packs

The Challenge

- Can we converge on a vision for the future?
- Mutual benefit
  - Common vision and goals
  - Coordinated development and implementation
  - Demonstrable cost sharing and efficiency
  - Strength in unity when seeking money
- Modularity and interfaces dictate tracking latency

Shift the needle from “likely” toward “economically plausible”