Silicon Tracking Detectors

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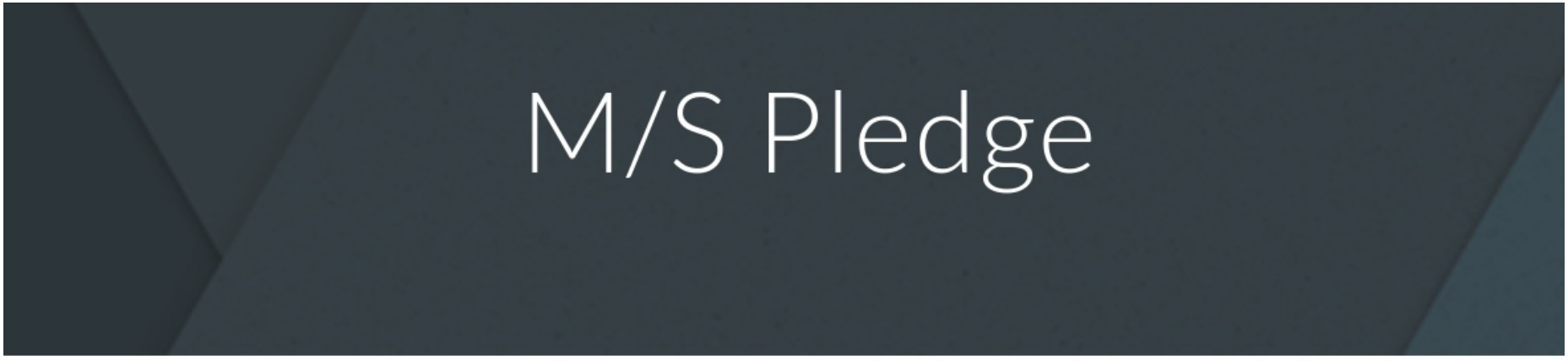
Lawrence Berkeley National Lab

2023 HEPIC Summer Week – SLAC

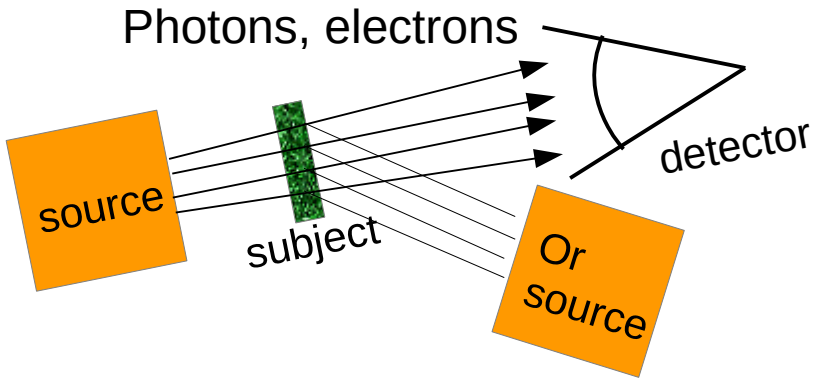
Close-up of ATLAS pixel detector, installed in 2007

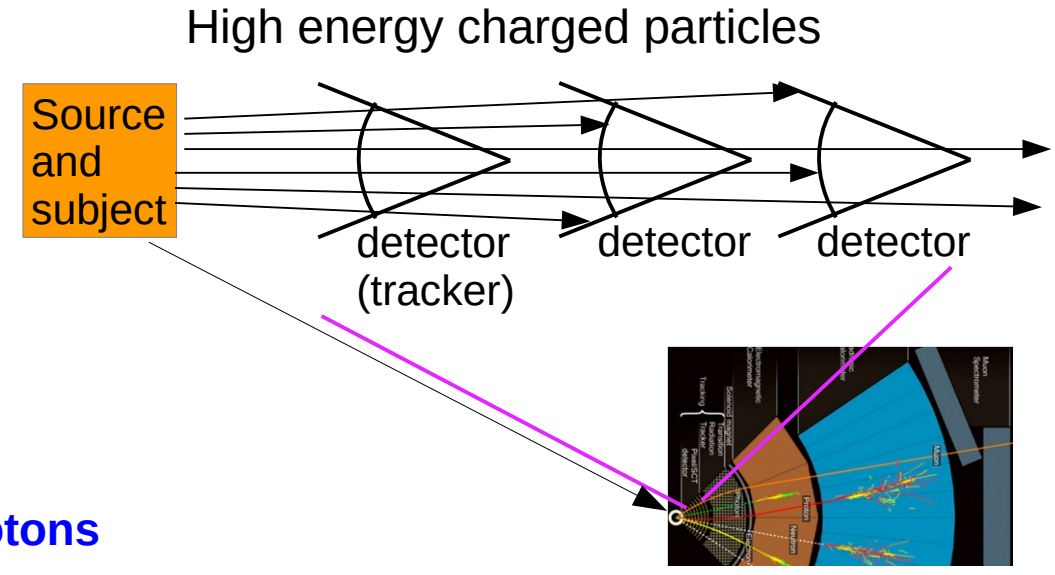
June 19



https://sites.google.com/view/mspledge/

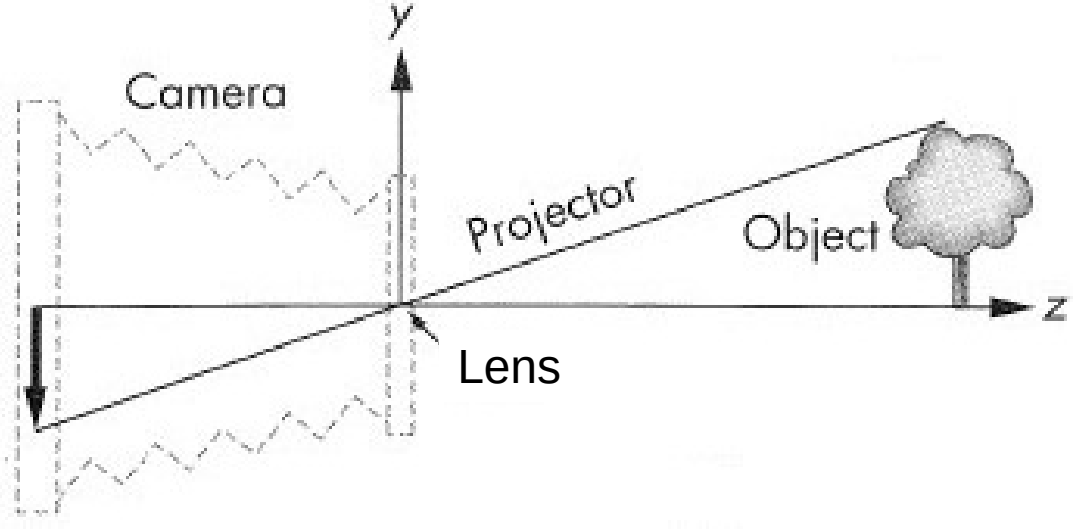
Imaging Particles



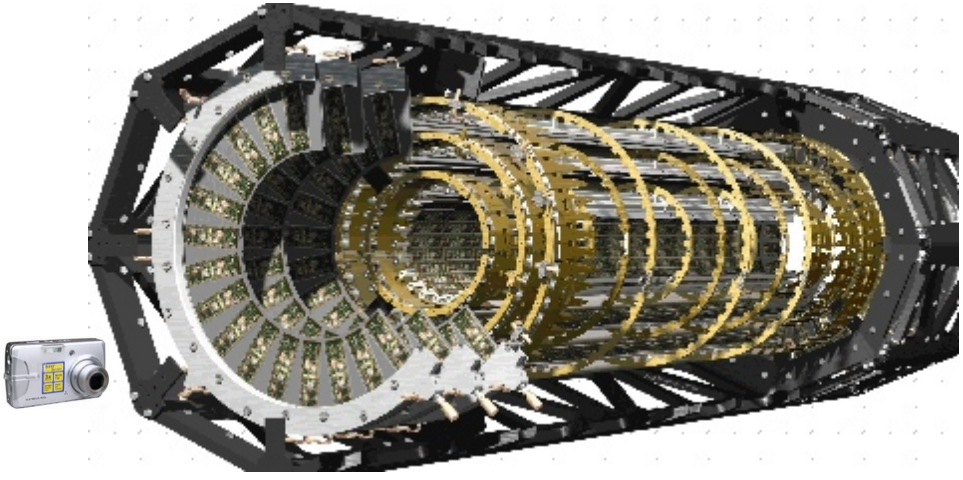


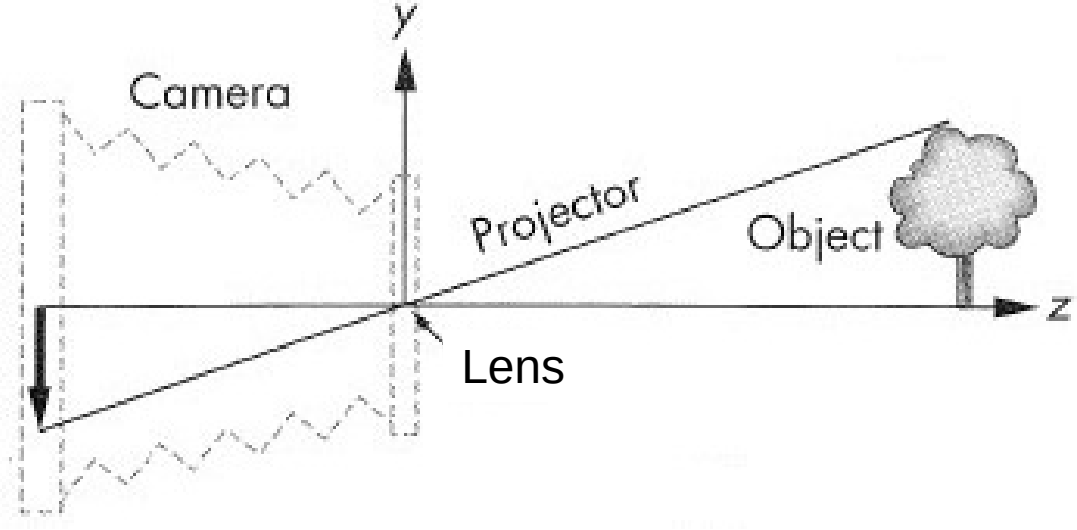
- **What you're used to:**
  - **Detector to completely stops photons**
  - **Lots of photons- every pixel gets some- source intensity limited on purpose**
  - **Integrate or count many photons per channel**
- **Crucial differences for Imaging high energy charged particles**
  - **Want particles to pass thorough imaging detector (aka tracker) as if it was not there. There are other detectors behind it**
  - **There is no sample. We are looking at the quantum vacuum. Want intensity as high as possible.**
  - **Measure every particle individually**

Inverse problem to usual imaging

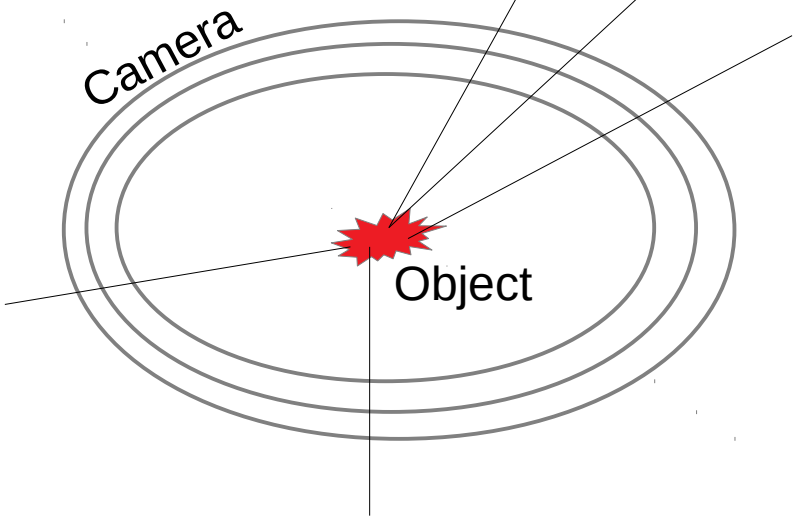


Inverse problem to usual imaging





Particle trajectories are the projectors

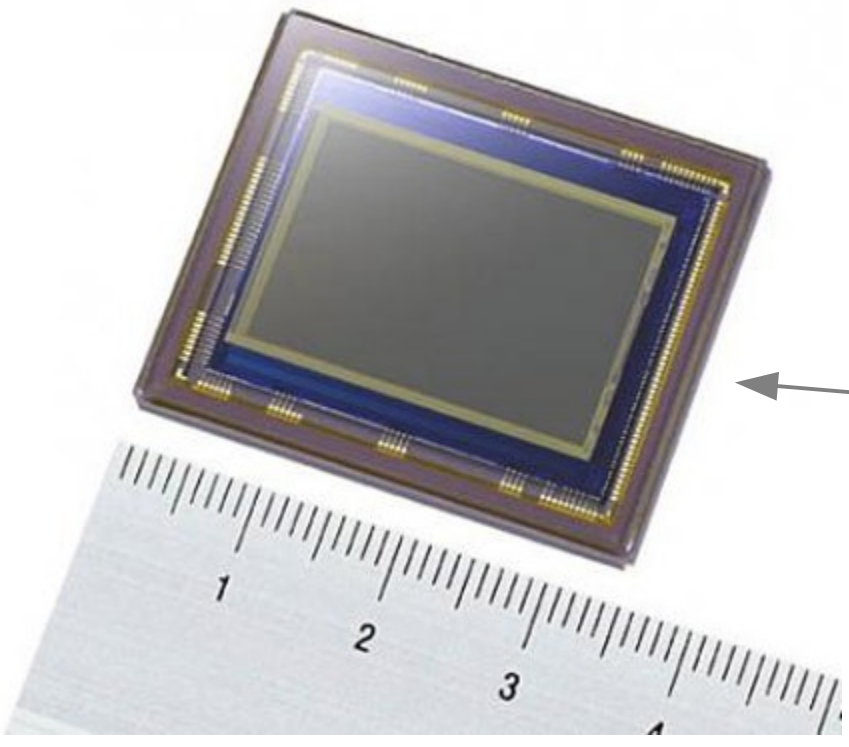


Clear?

Let’s do it

Let’s build ourselves a silicon pixel tracking detector

Let's do it

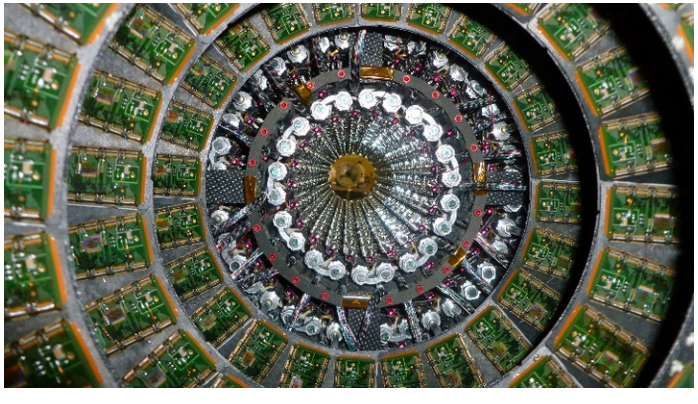


~2 cm^2

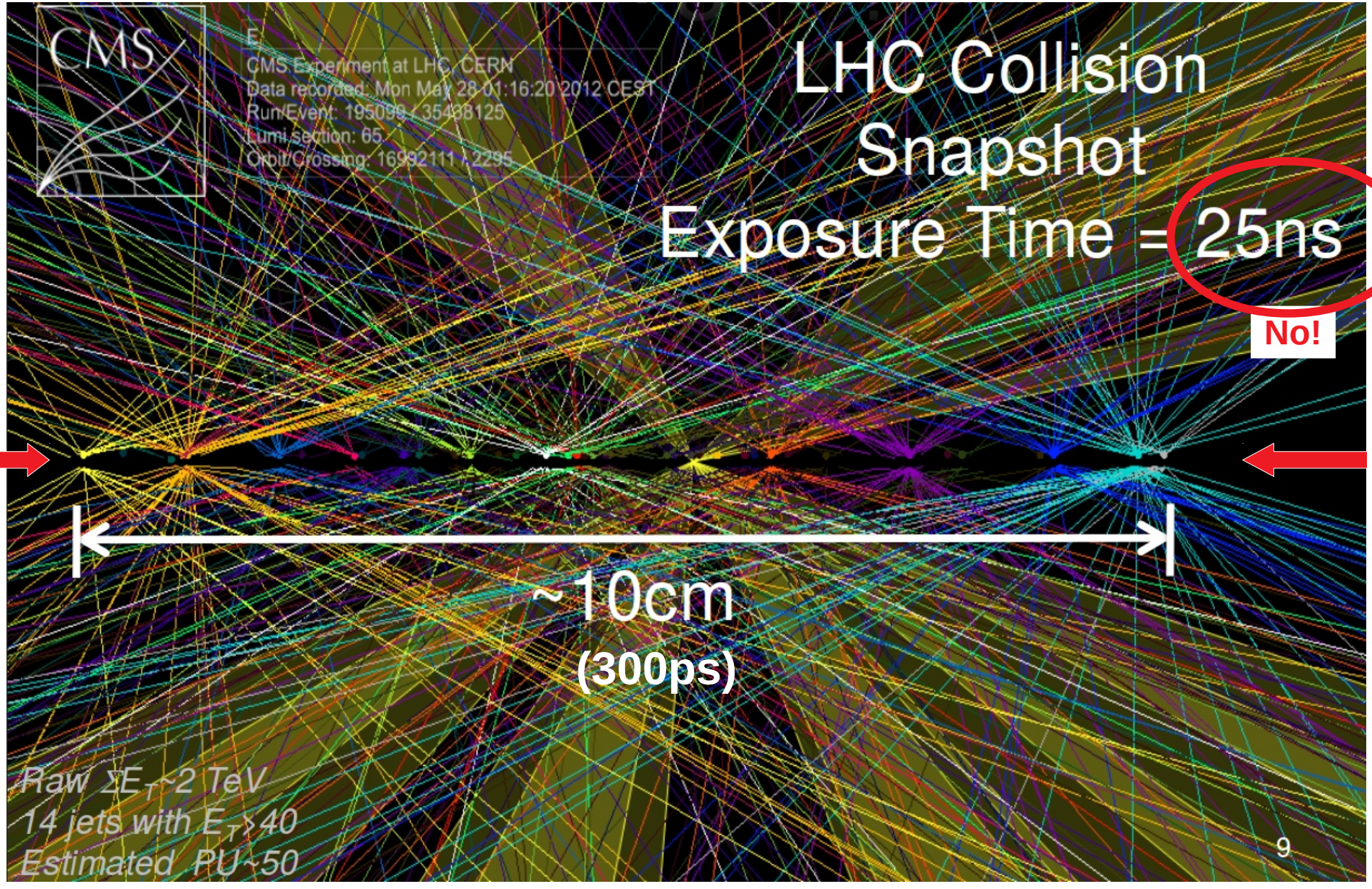
Surround interaction point with few layers of sensors

~100 000 cm^2

($500K plus tax)

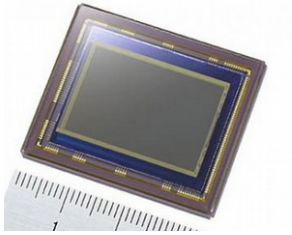


Will it work?


CMS
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295
LHC Collision
Snapshot
Exposure Time = 25ns
No!
p
p
~10cm
(300ps)
Raw ΣE_T~2 TeV
14 jets with E_T>40
Estimated PU~50
9

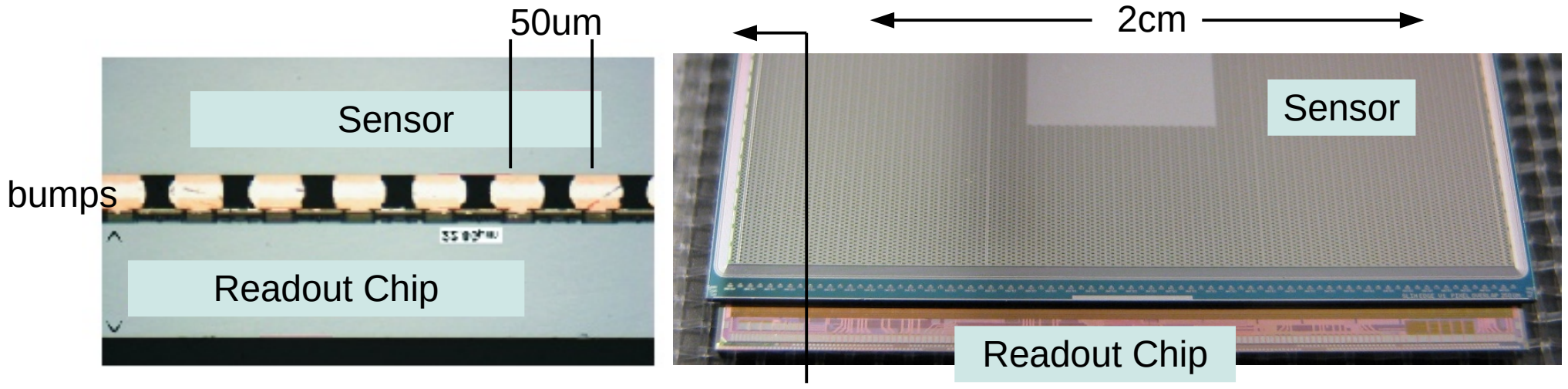
Back to the drawing board

- OK, so this thing can do 30 fps right?

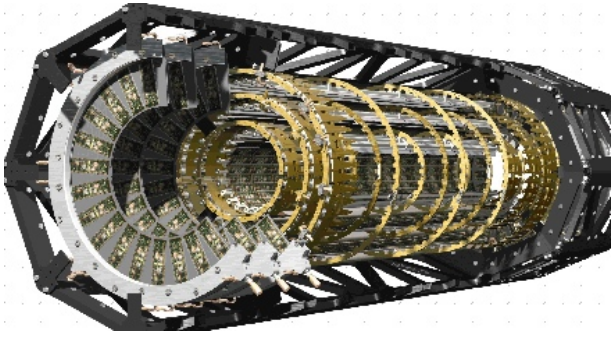


- Then instead of 50,000 sensors we need (40,000,000 / 30) * 50,000 = 65B sensors, which will only cost us $650B. Maybe we can get a volume discount?
-
-
-
- And that’s why we need custom ASICs to make tracking detectors
- Review how they’re actually made next (or just remember the tour)

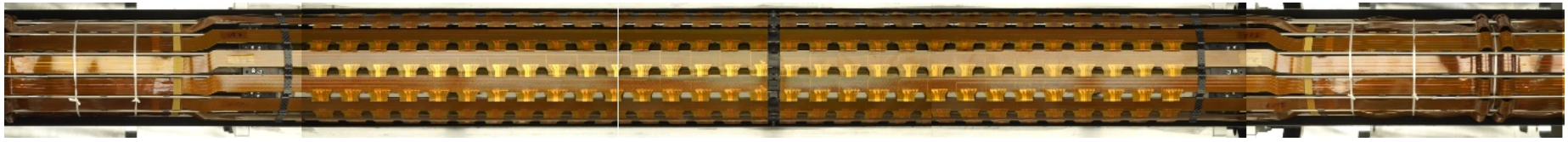
Hybrid Pixel Detector Technology



ATLAS PIXEL 2007 80M pixels

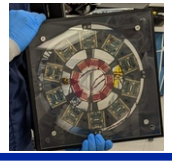


ATLAS IBL 2014 12M pixels

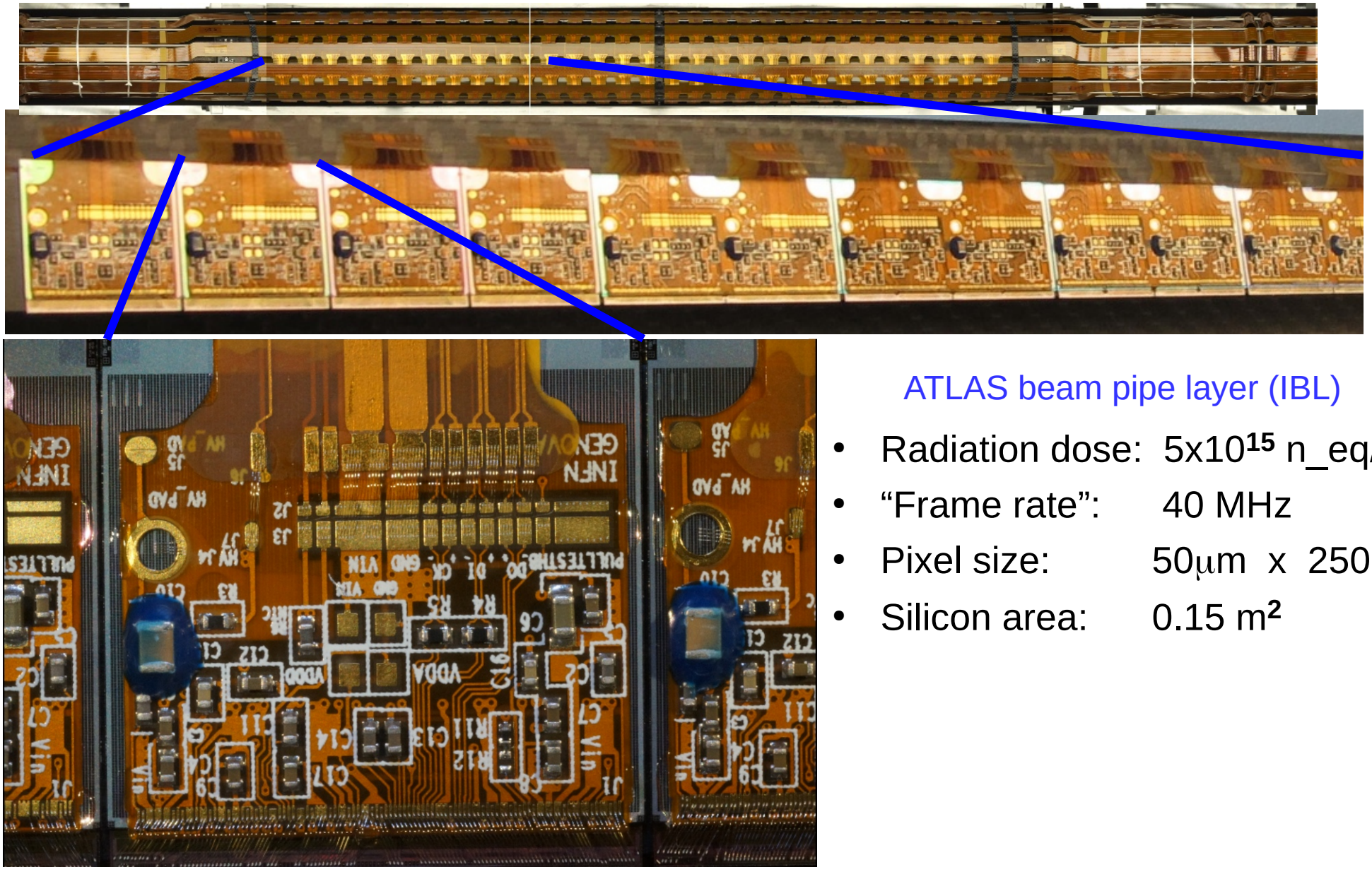


ATLAS ITK 2026, 5G pixels

Remember the tour...



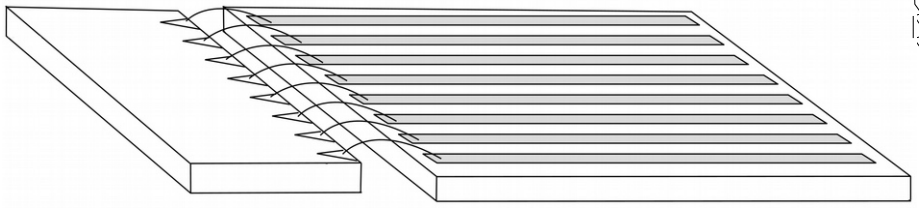
Hybrid Pixel Technology (IBL)



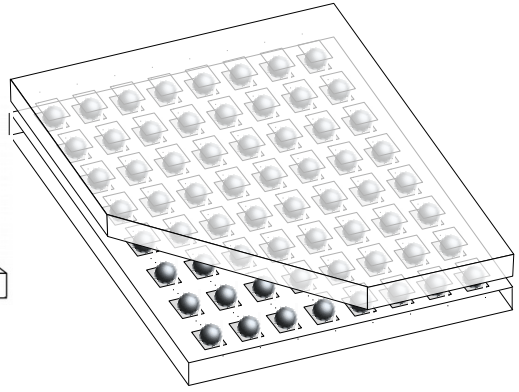
ATLAS beam pipe layer (IBL)

- Radiation dose: 5×10^{15} n_eq/cm^2
- "Frame rate": 40 MHz
- Pixel size: 50μm x 250μm
- Silicon area: 0.15 m^2

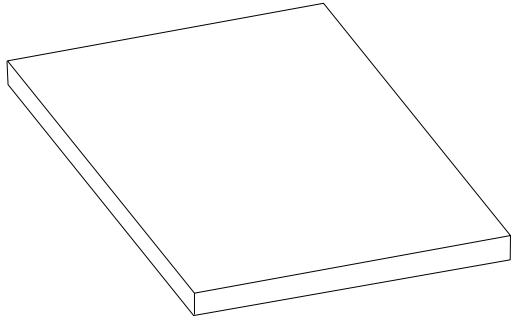
Silicon Tracker Types



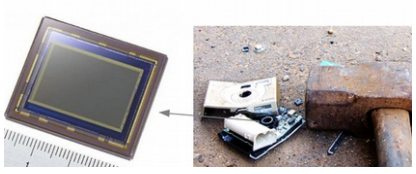
Hybrid Strips



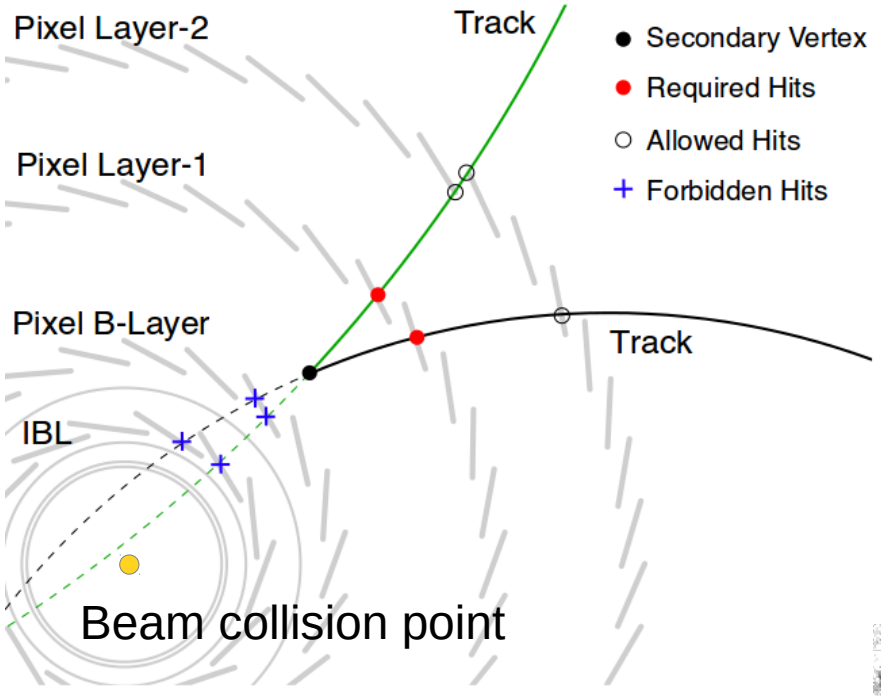
Hybrid Pixels

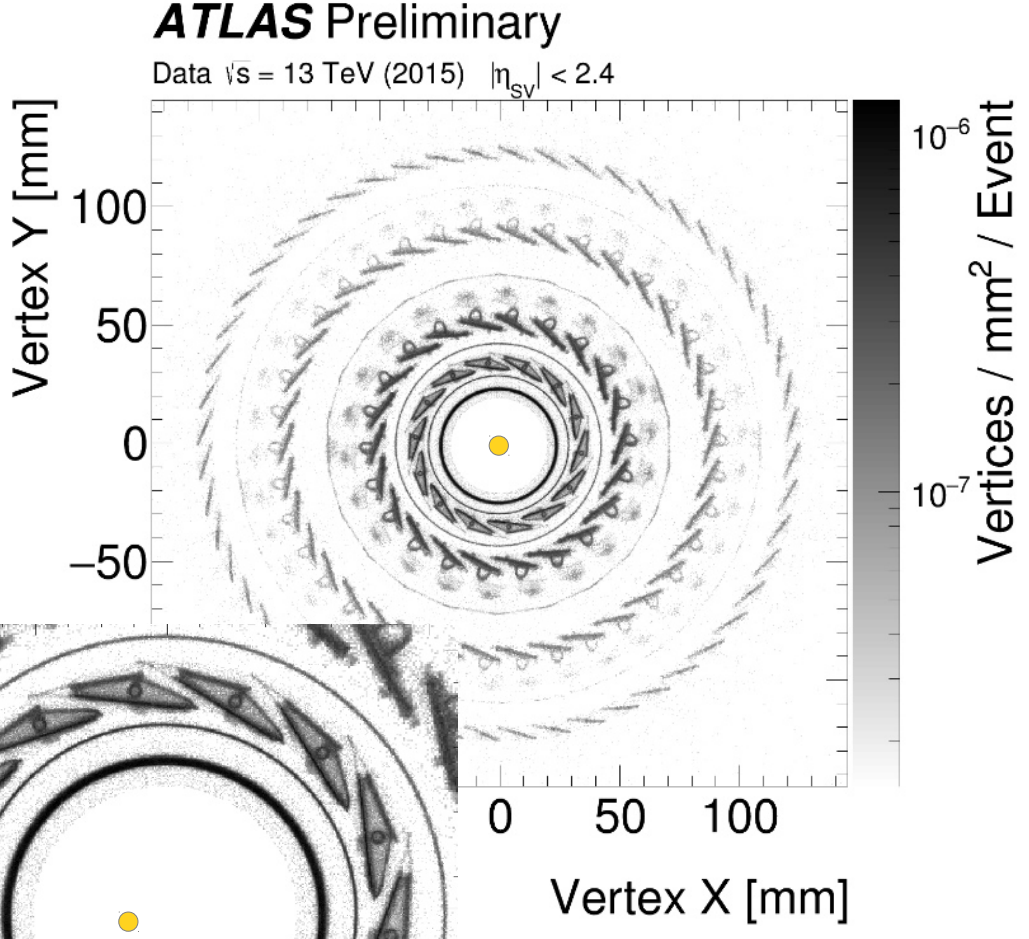


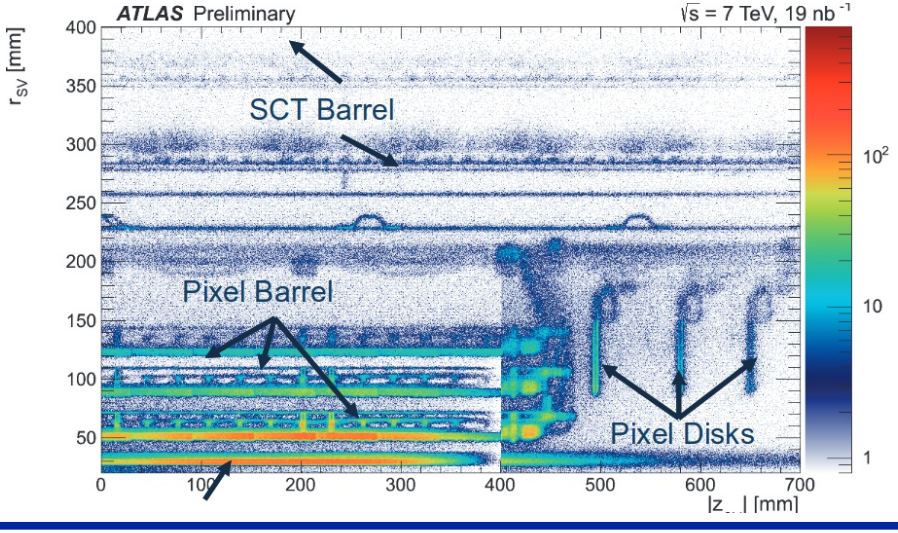
Monolithic

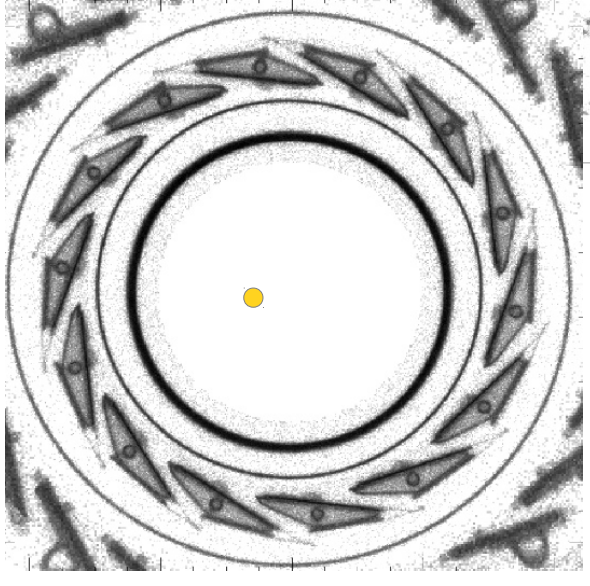


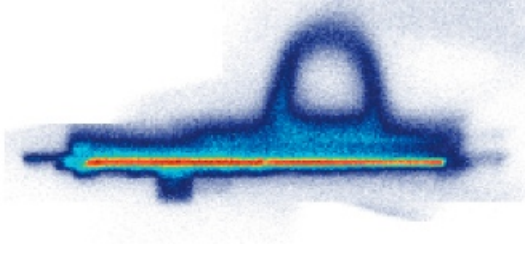
Detector can image itself in 3D



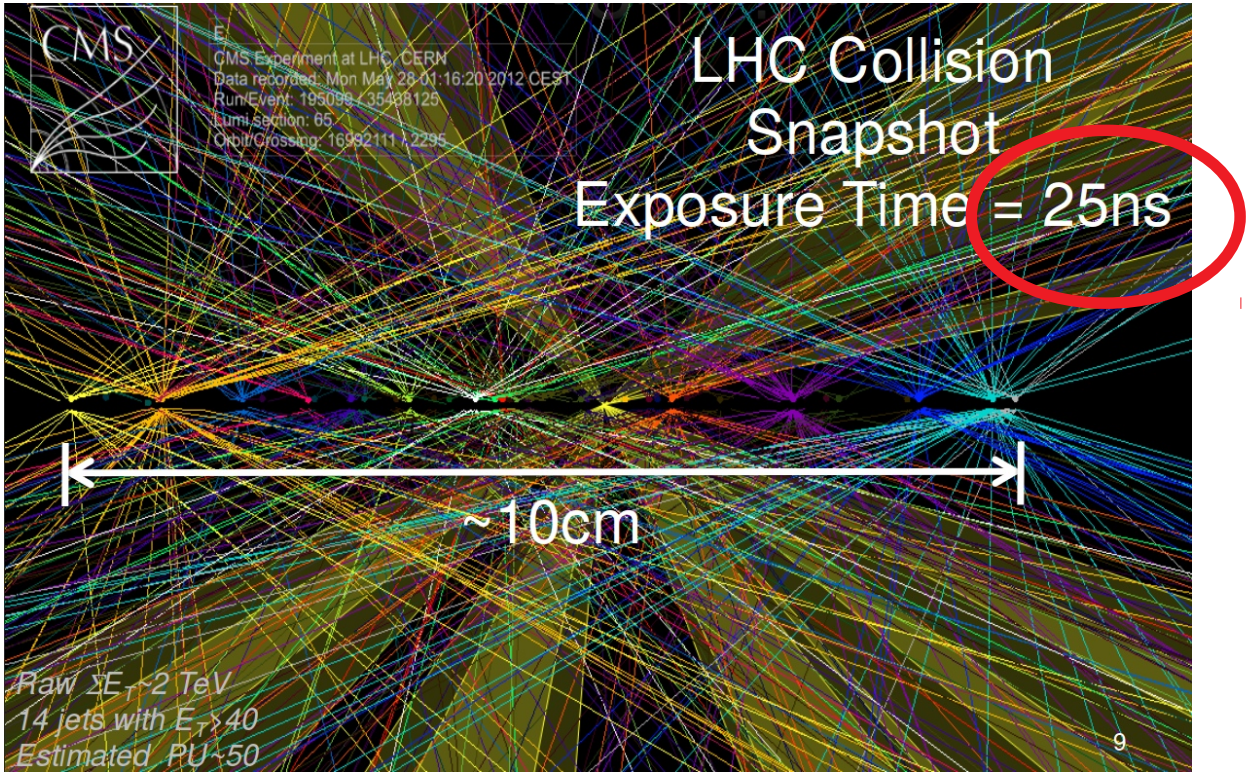








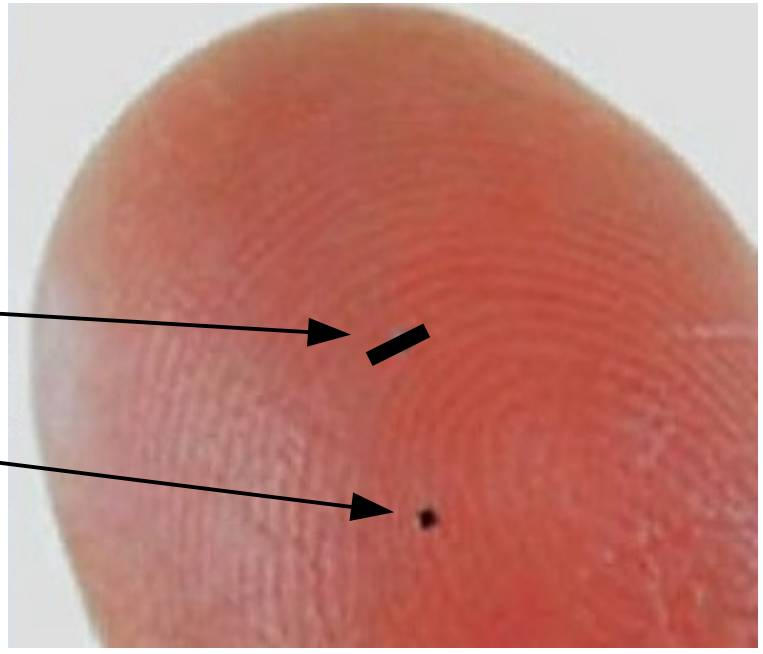
But how do we handle the rate?



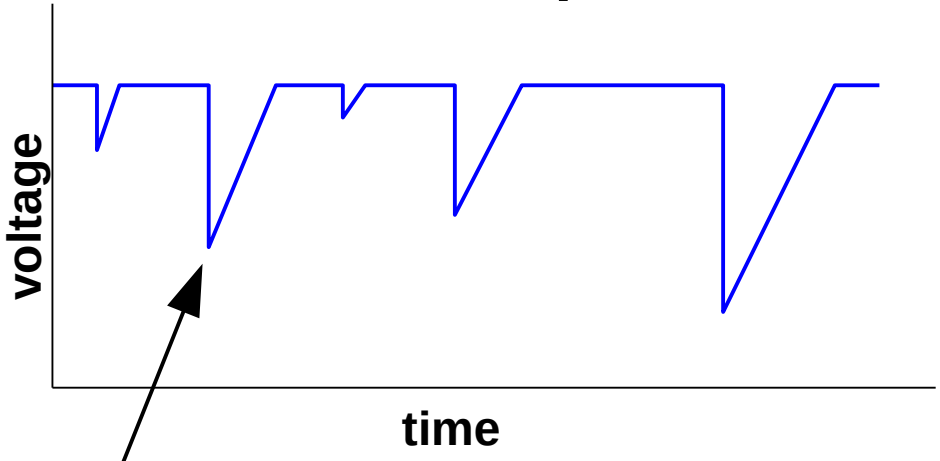
- Capturing 40M 5Gpixel images per second is not feasible.
- Triggering only saves a factor of 40 in readout
  - 1M 5Gpixel images per second is still far from feasible
- A: We do NOT do conventional image capture.
- We treat every pixel as an independent, free-running detector and store it's output (heavily redacted)

Single Pixel Perspective

Pixel size

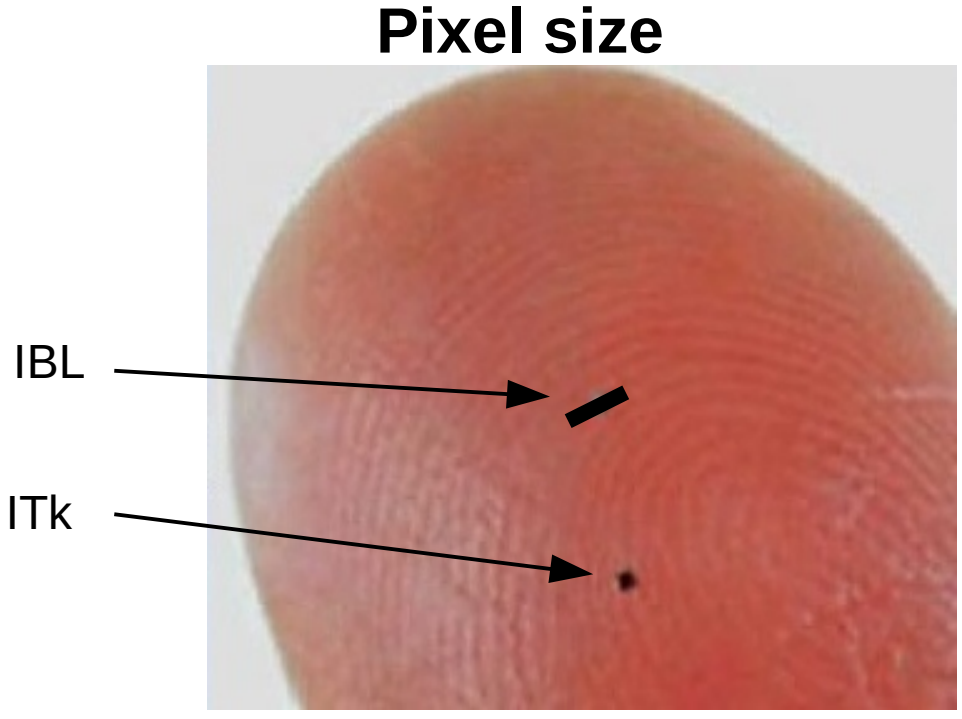


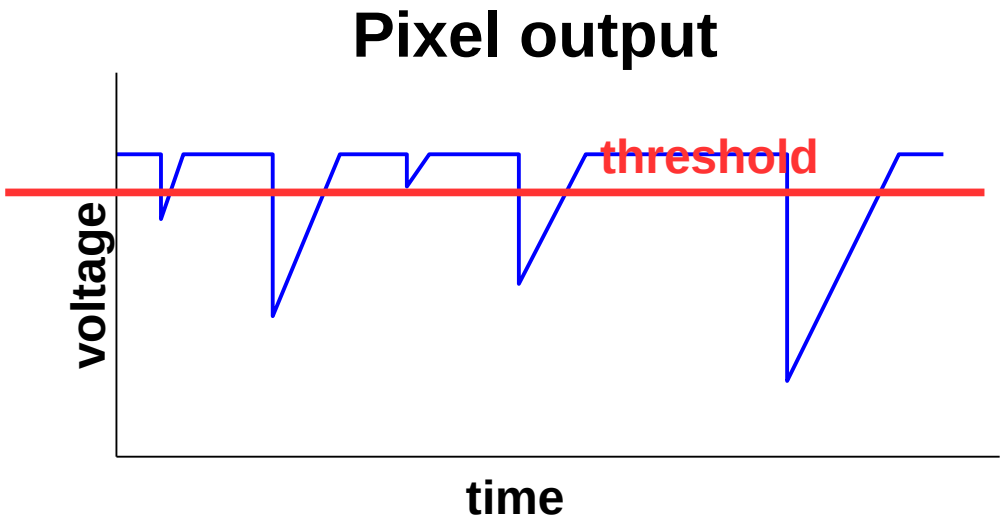
Pixel output



Hits
~50 kHz
(not too bad compared to 40 MHz)

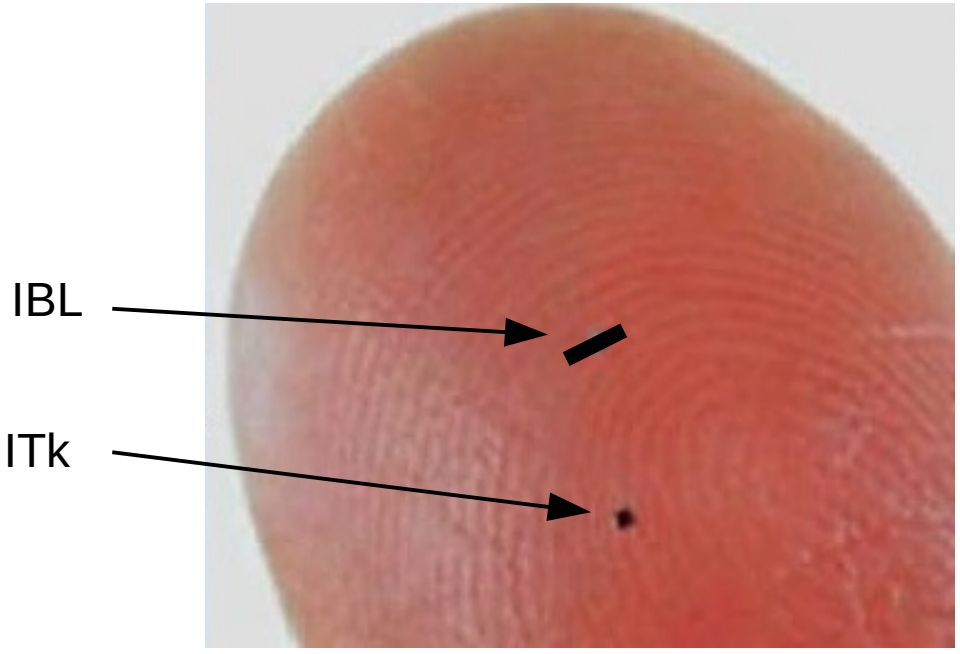
Single Pixel Perspective



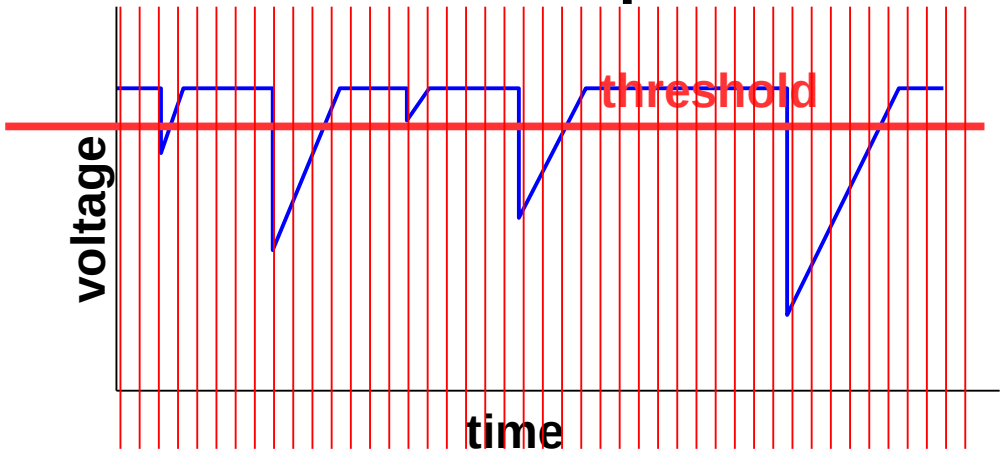


Single Pixel Perspective

Pixel size



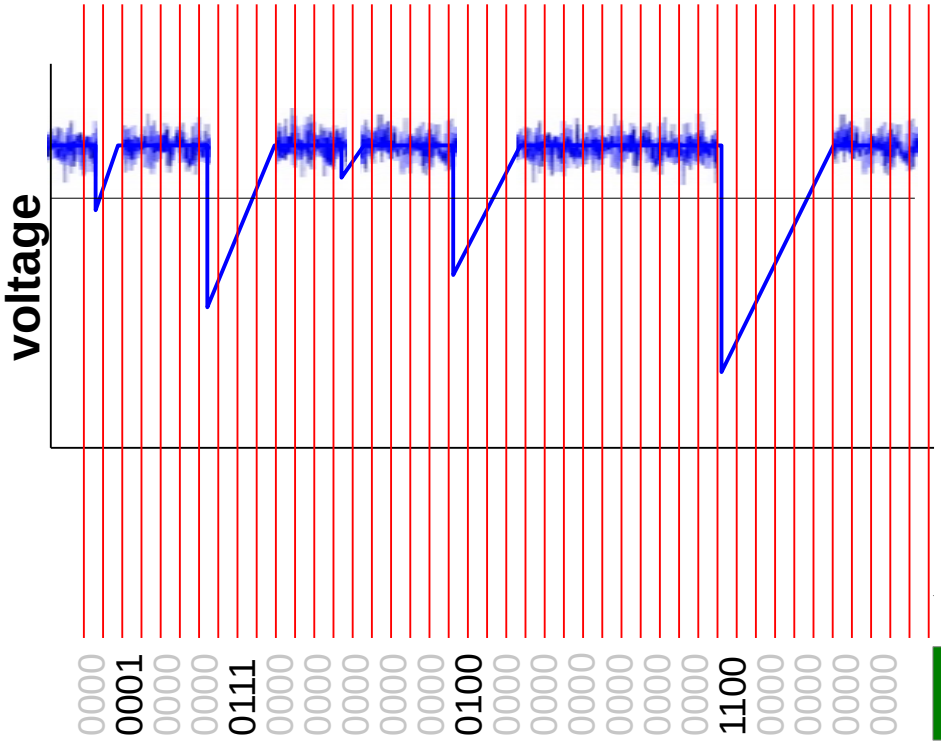
Pixel output



Bunch crossings

Digitize amplitude above threshold in each Bunch Crossing

On-Chip Storage and Trigger



On-chip memory ("FIFO")

Readout ~Gbps

Storage of all individual hits W/ ADC value (~40 Gbps for a 100Kpx chip)

Triggers (select 1/40 time slices)

Did I just say a chip is storing 40Gbps?

High rate pixel readout chips are memories (in addition to being pixel readout chips)

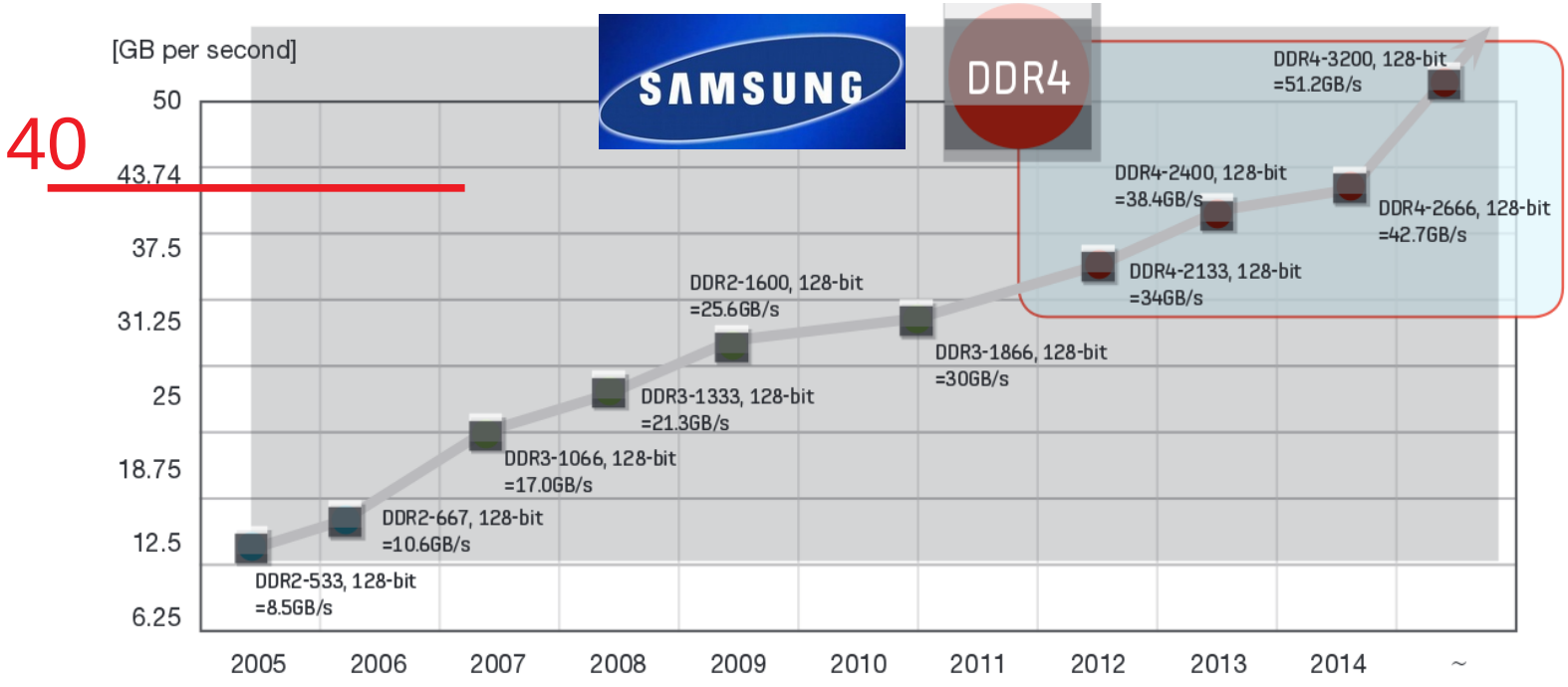


Figure 2. DDR4 higher performance compared with DDR3L and DDR2

Plot is for a memory module containing 8 silicon chips so B = b

(and this is not rad hard)

Silicon Detectors at Colliders

(and in orbit)

Fermi LAT

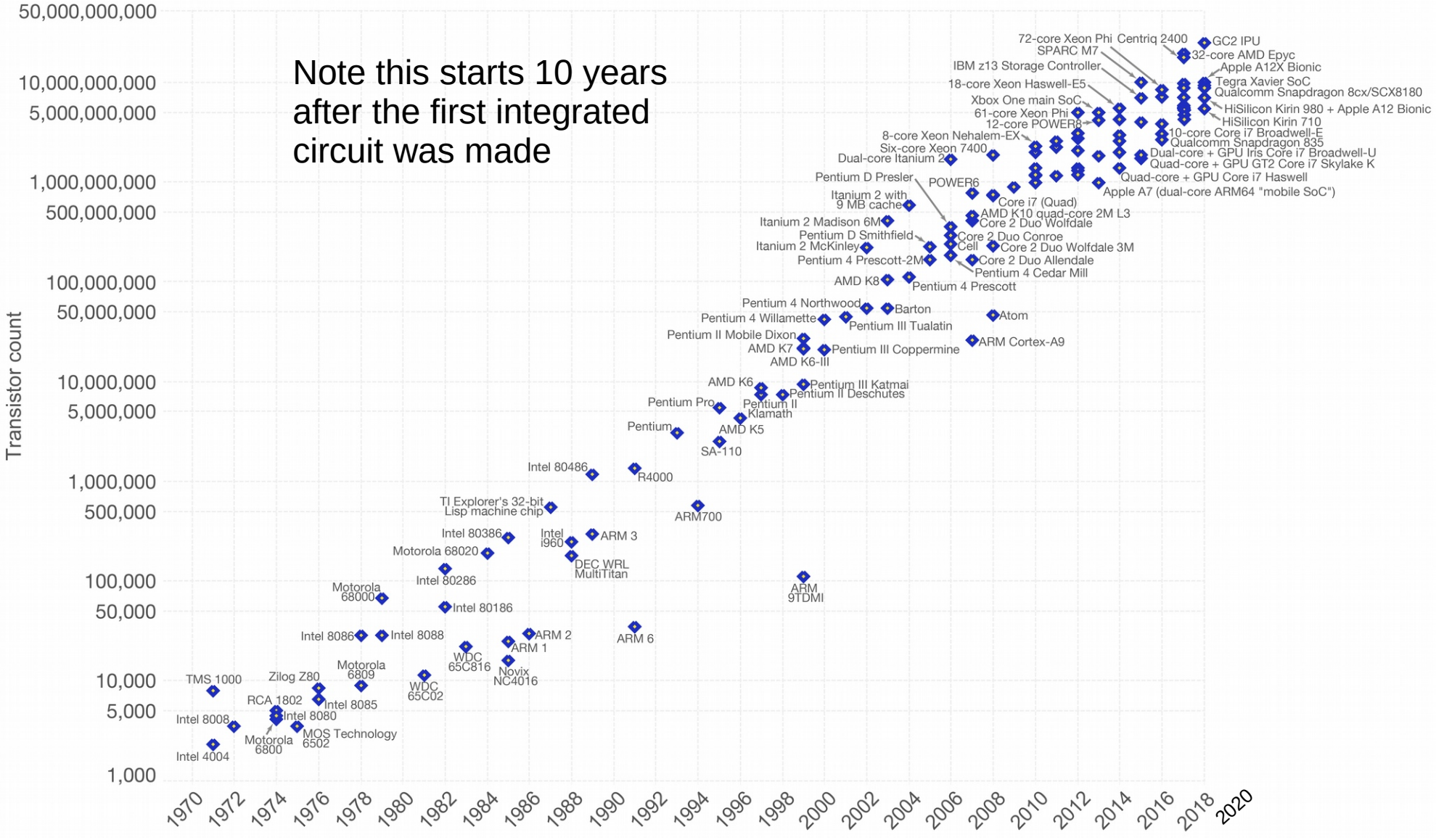
Strip Detectors		Hybrid Pixels	
1980	NA1	1999	Delphi
1981	NA11	2009	ATLAS
1982	NA14	2009	CMS
1990	MarkII	2015	ATLAS IBL
1990	DELPHI	2017	CMS
1991	ALEPH	2019	velopix
1991	OPAL	2025	ATLAS
1992	CDF SVX	2025	CMS
1993	L3		
1996	CDF SVX'	**CMOS Pixels**	
1998	CLEO III	2014	STAR
1999	BaBar	2019	ALICE
2001	CDF SVXII+ISL		
2009	ATLAS SCT	**CCDs**	
2009	CMS tracker	1993	VXD
2025	ATLAS ITK		
2025	CMS upgrade		

pixel

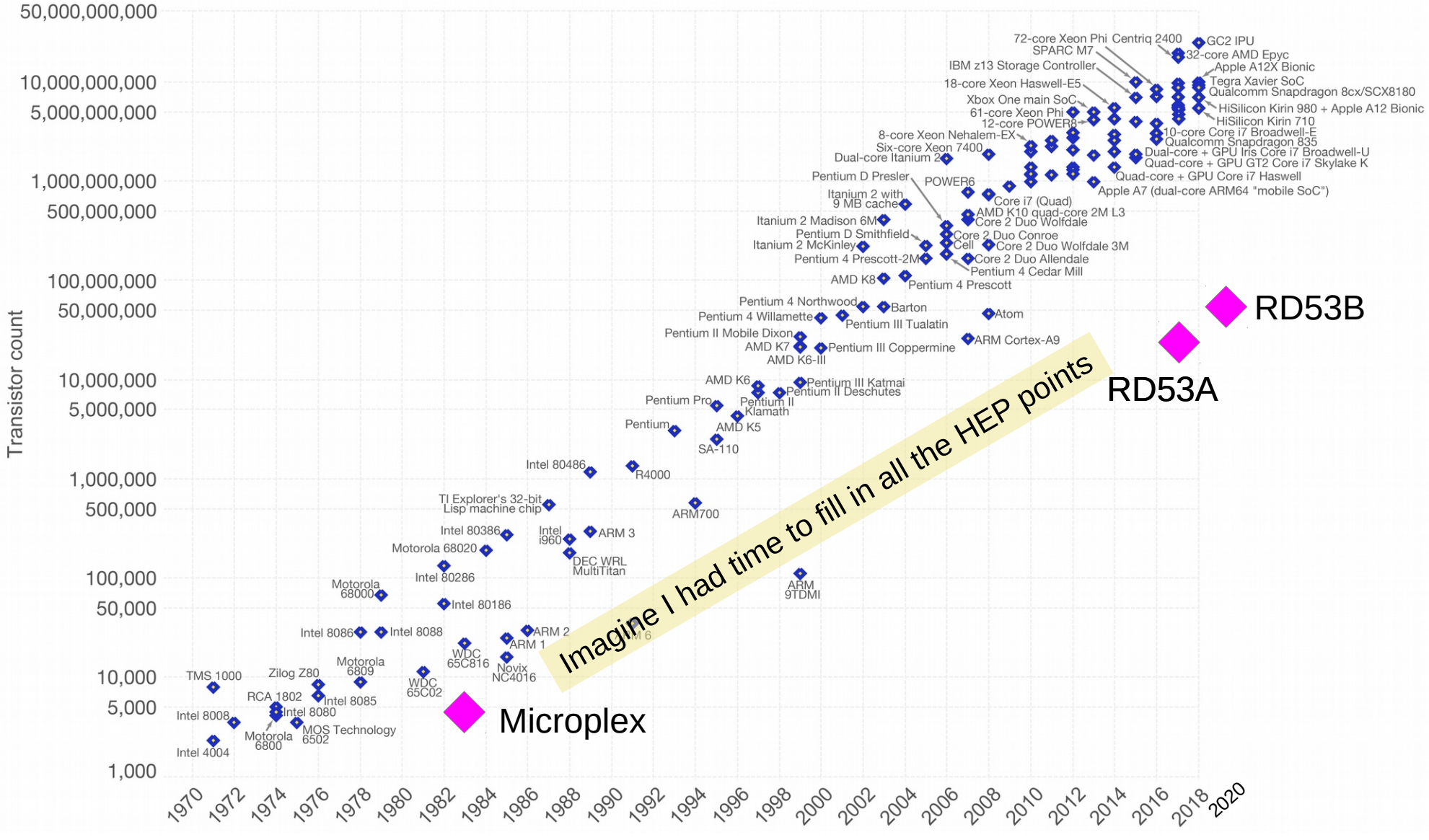
IBL

ITk

Computer Processor



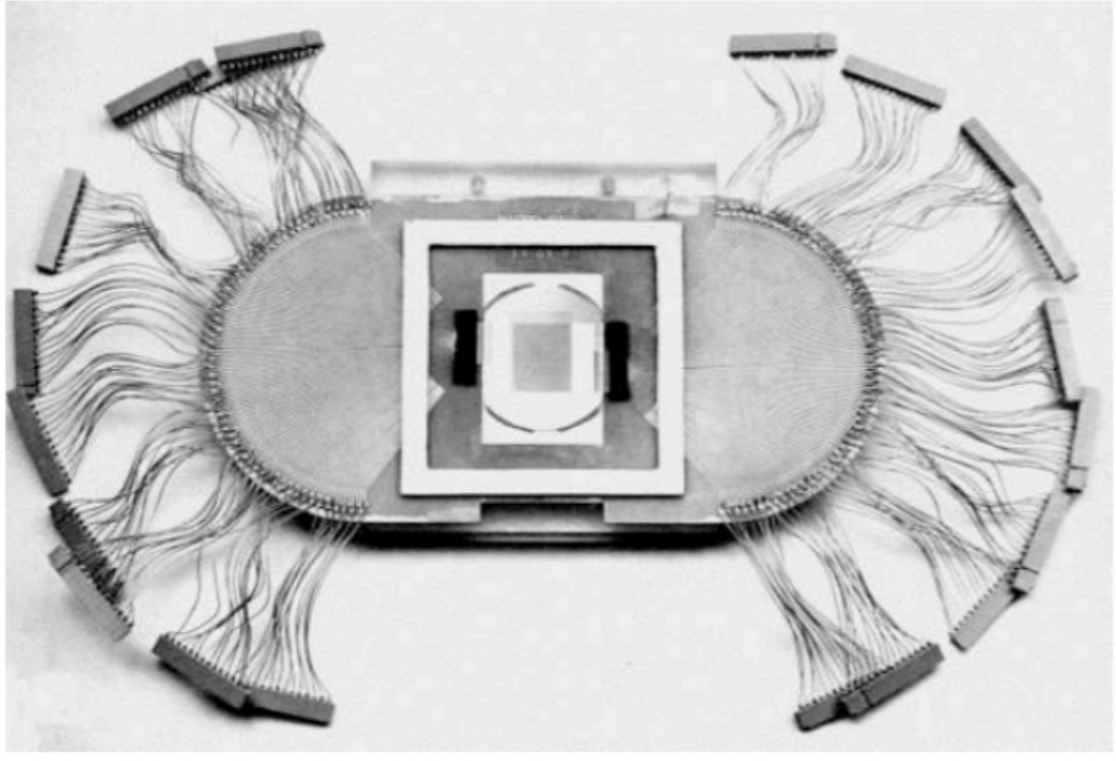
HEP Tracker Integrated Circuits



Why Microplex?

Because this was a silicon strip module before:

NA11, CERN 1981

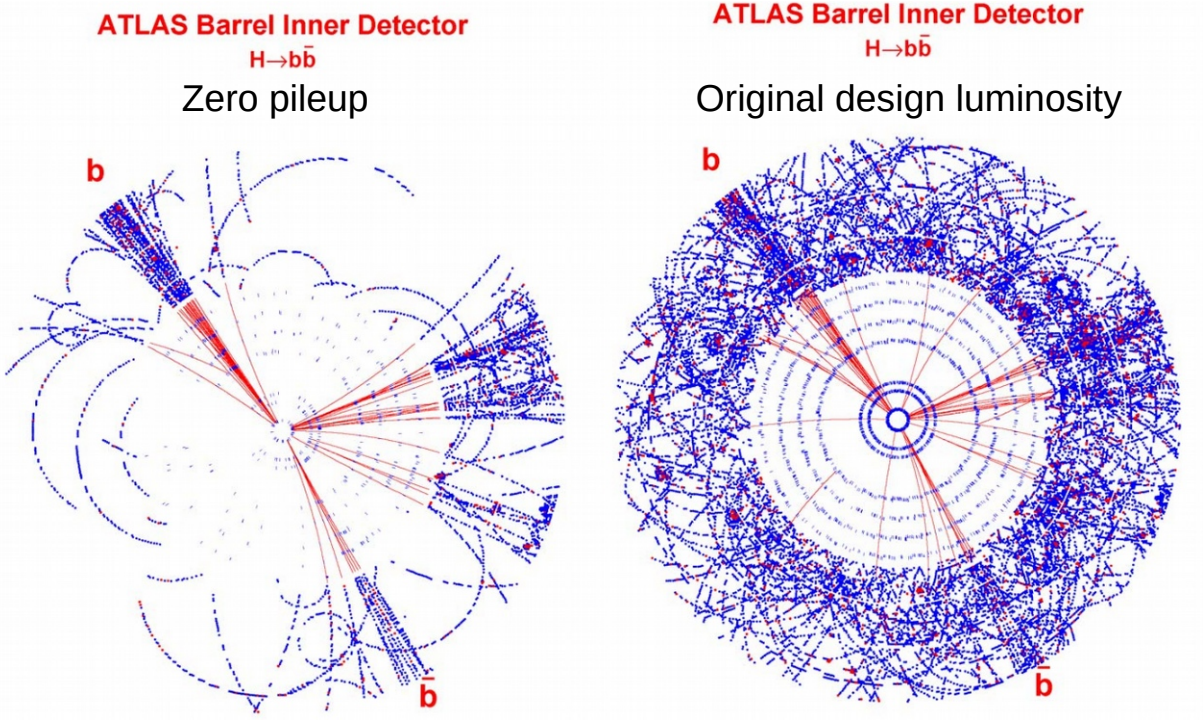


NIM205 (1983) 99

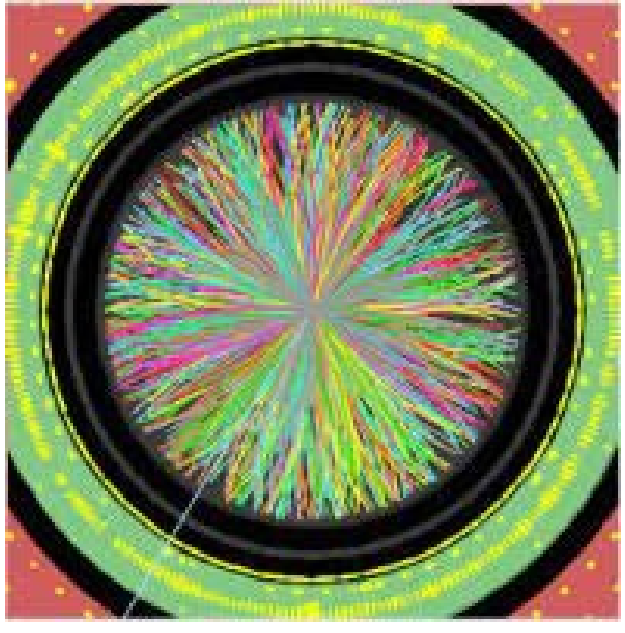
It did not scale

Why Microplex?

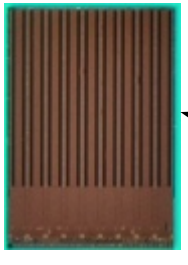
Original ATLAS motivation for pixels circa 1995



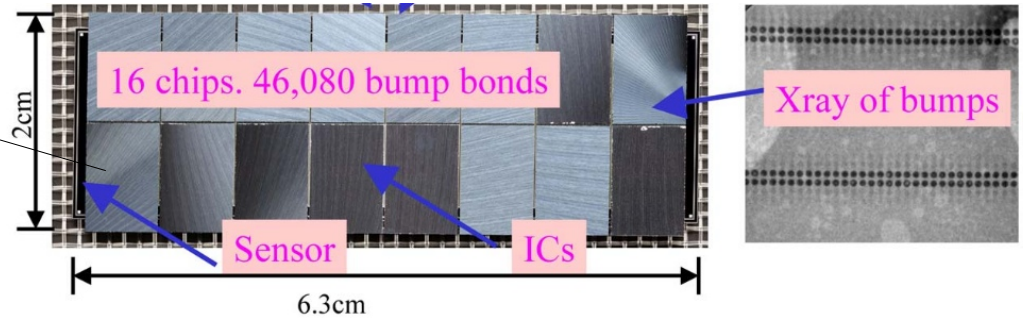
HL-LHC is far beyond



FE-I3 readout chip



Solution:



It did not scale.
A new readout chip solution had to be developed

Modern chip design needs large effort

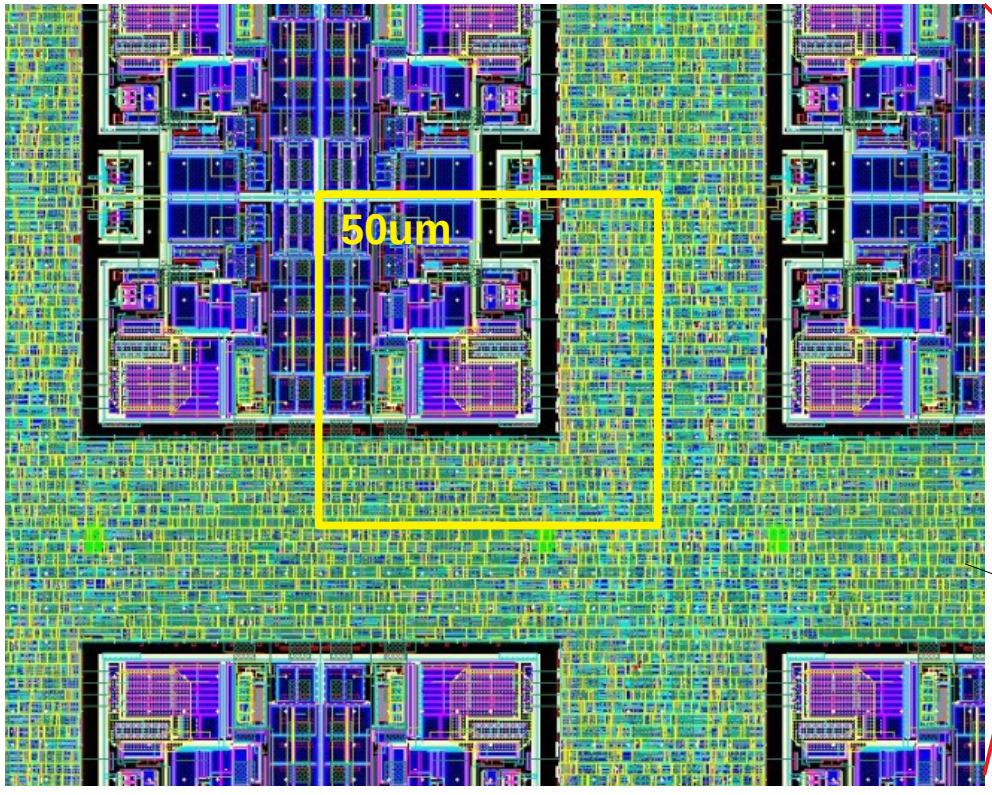
Typical INTEL design team

RD53 Hybrid Pixel Readout
100x higher rate and radiation

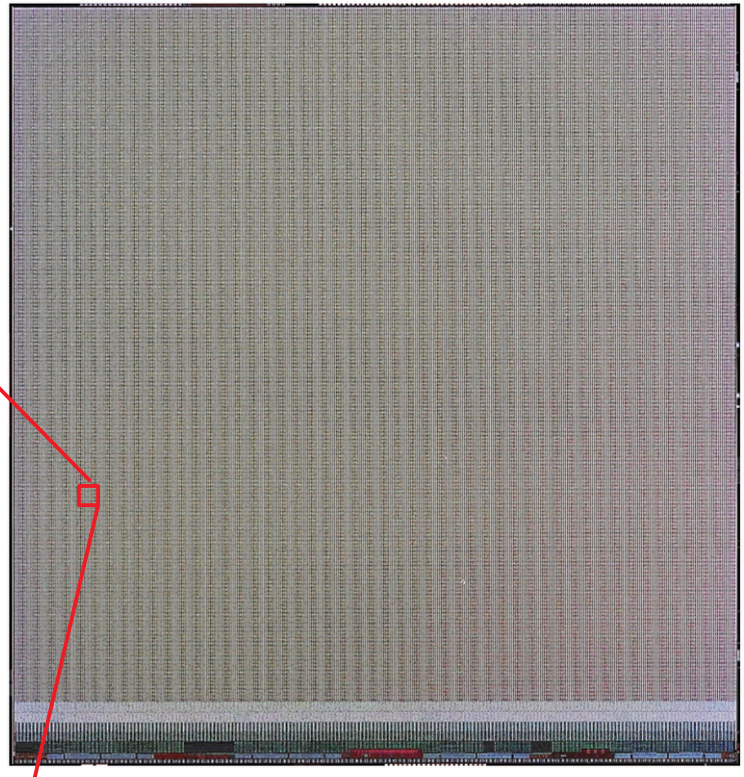
Cern.ch/rd53

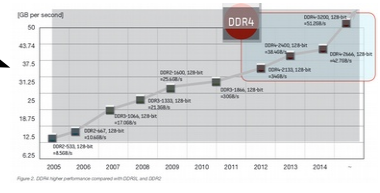
RD-53 Collaboration Home

RD-53 will design and produce the next generation of readout chips for the ATLAS and CMS pixel detector upgrades at the HL-LHC. More details can be found in the 2018 extension proposal and the original collaboration proposal.

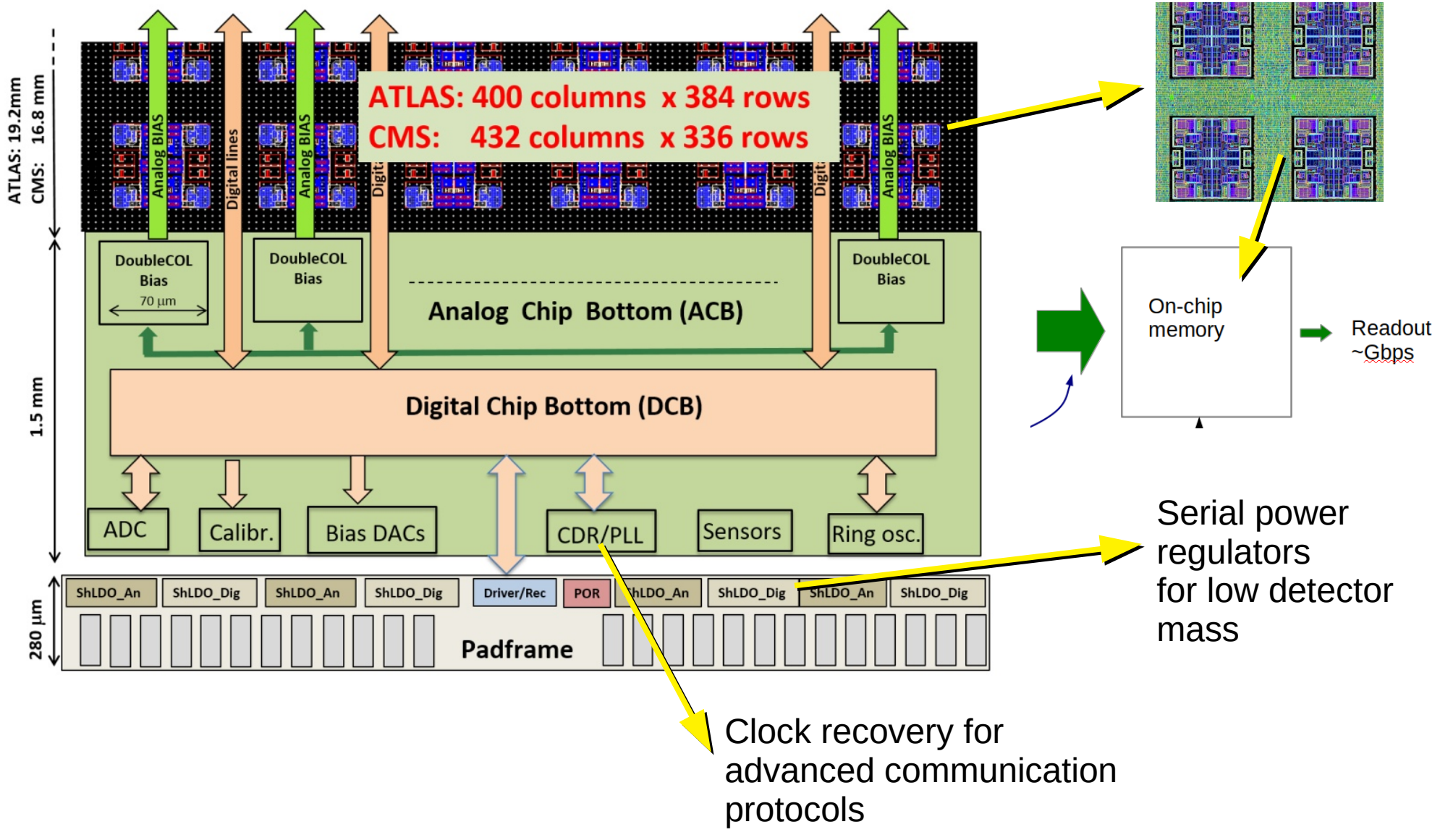


~1000 transistors

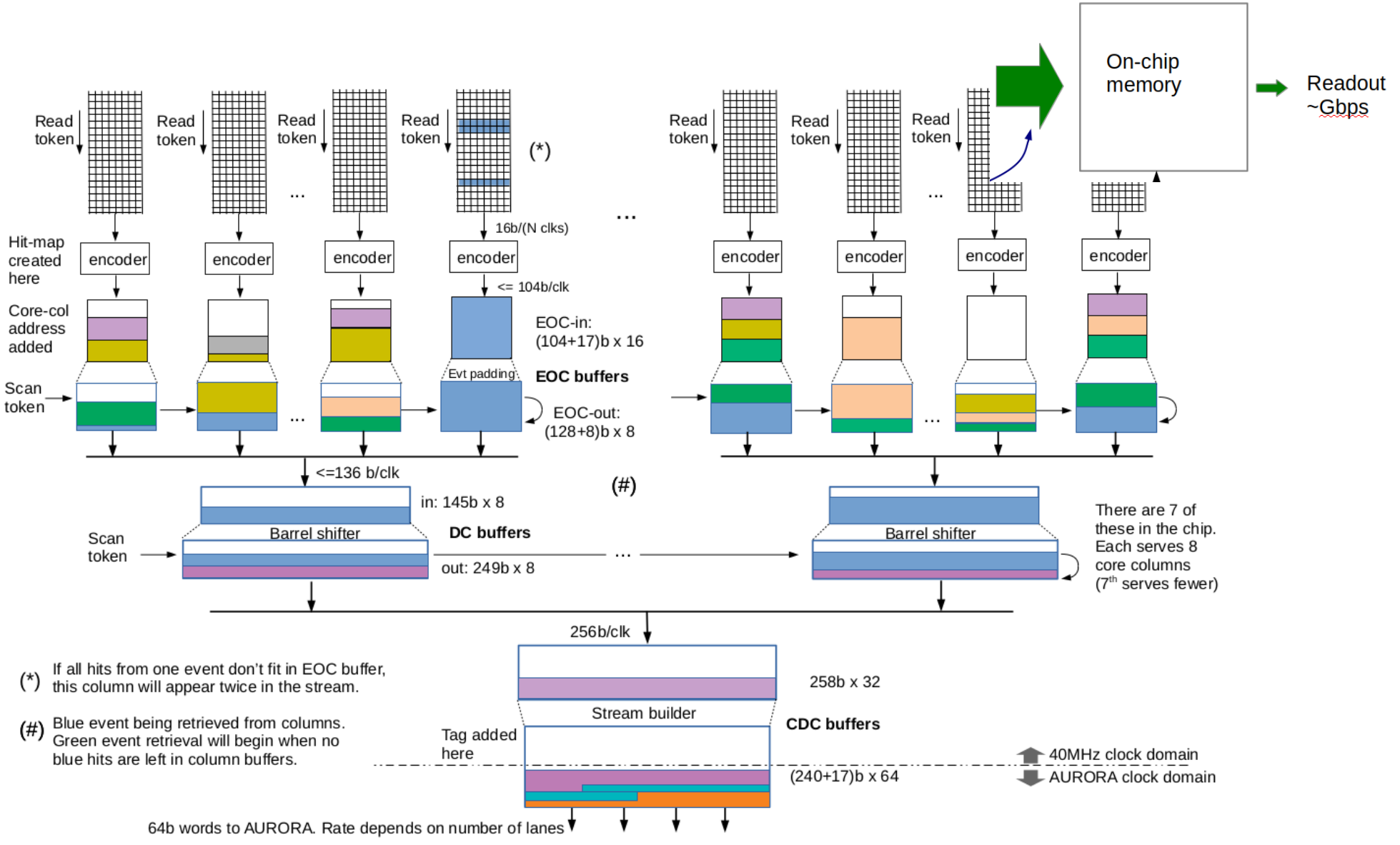




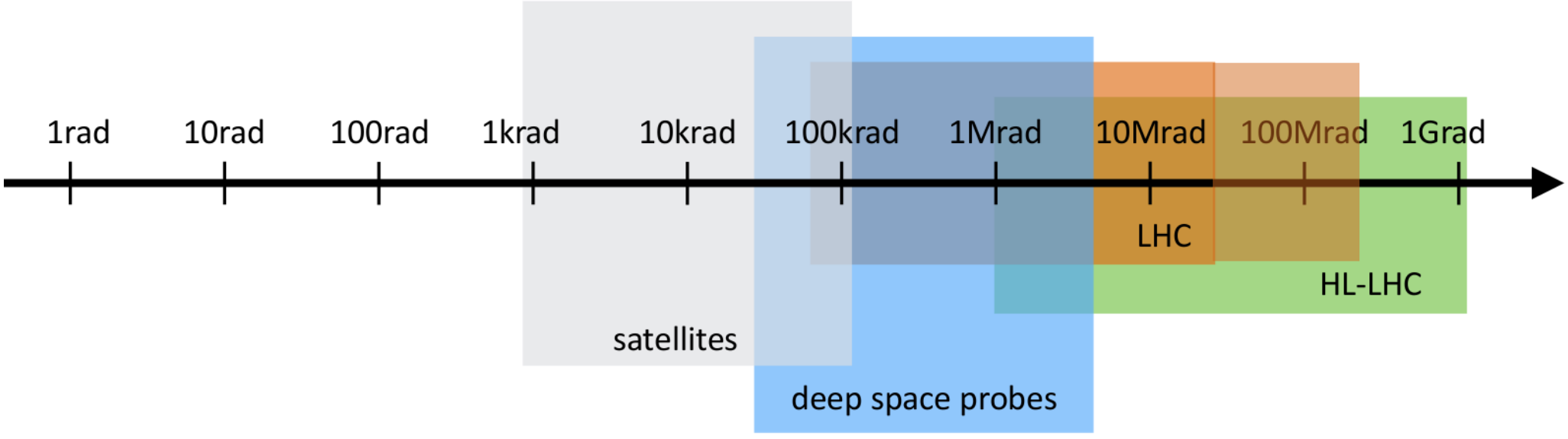
Complex system on chip



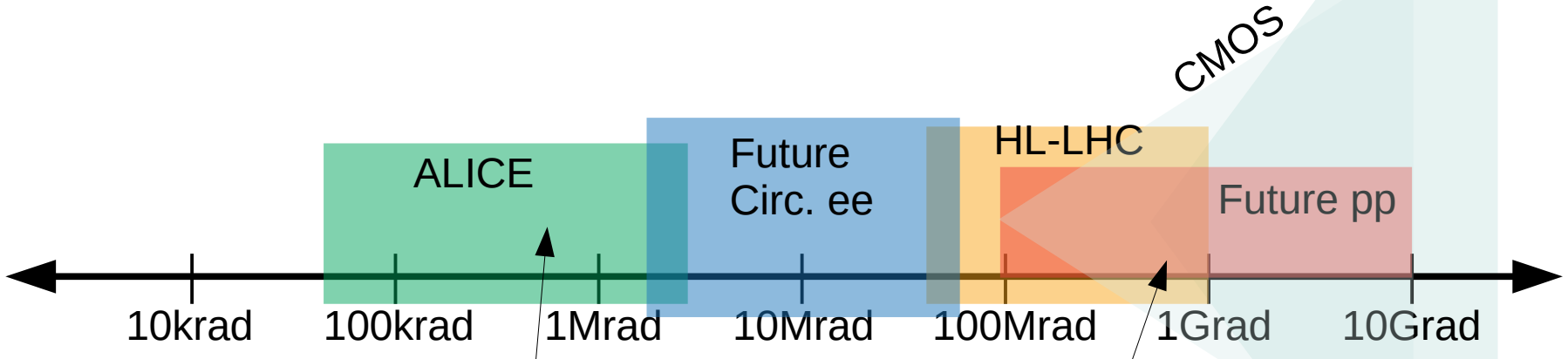
Example of non-trivial processing



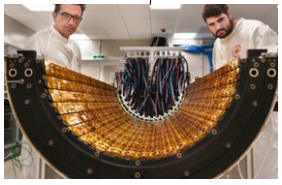
Radiation Environments



HEP IC Radiation Outlook

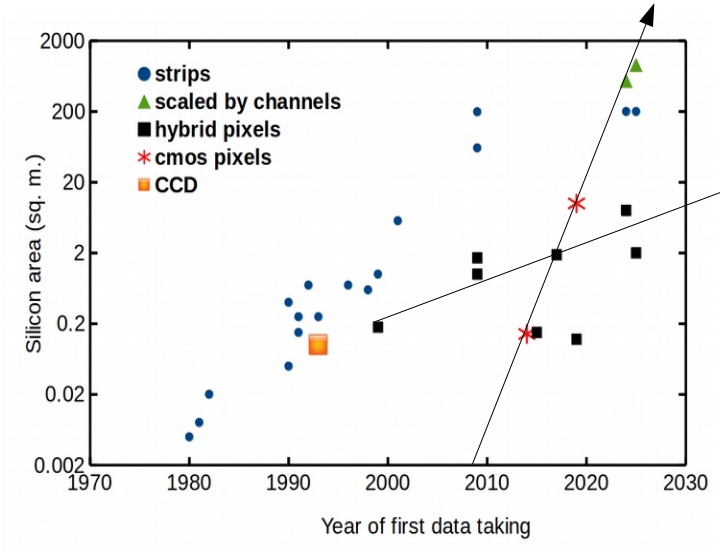


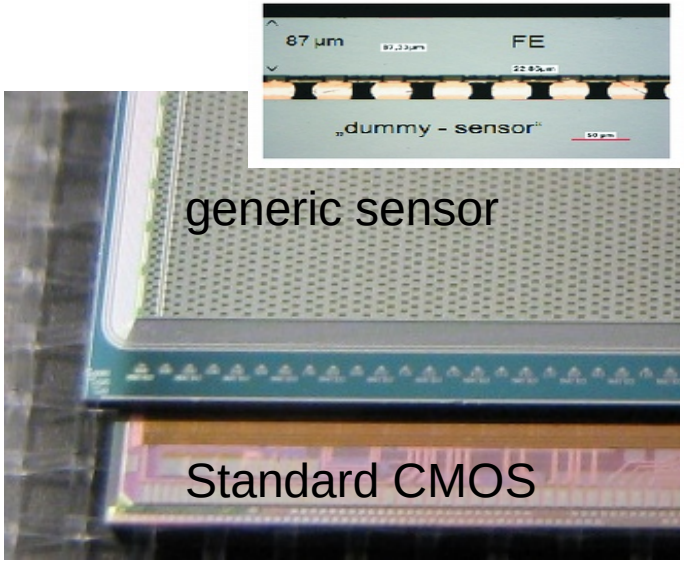
Inner Layer Dose

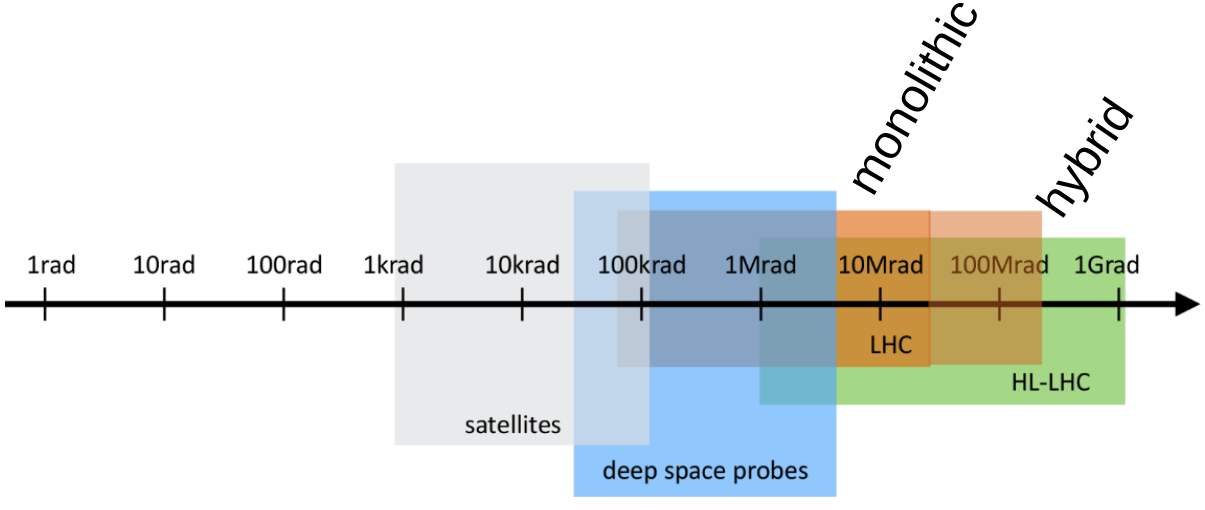


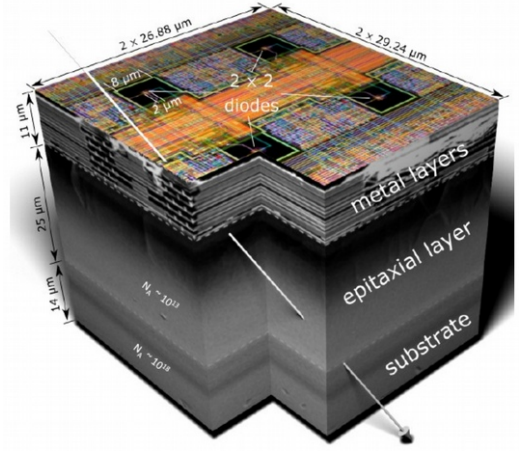
Temperature history
Process details
Dose rate
Dose history
Annealing
…

Trade-offs







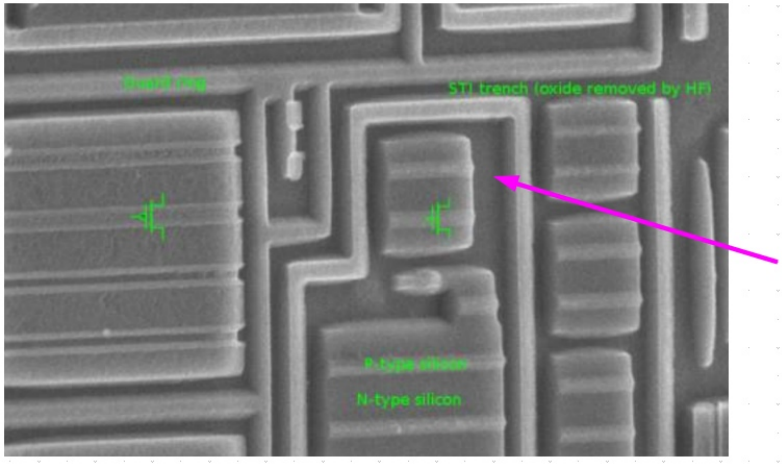


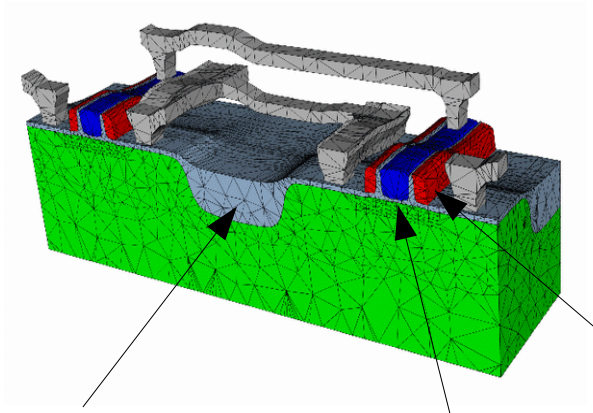
Highly customized non-portable process

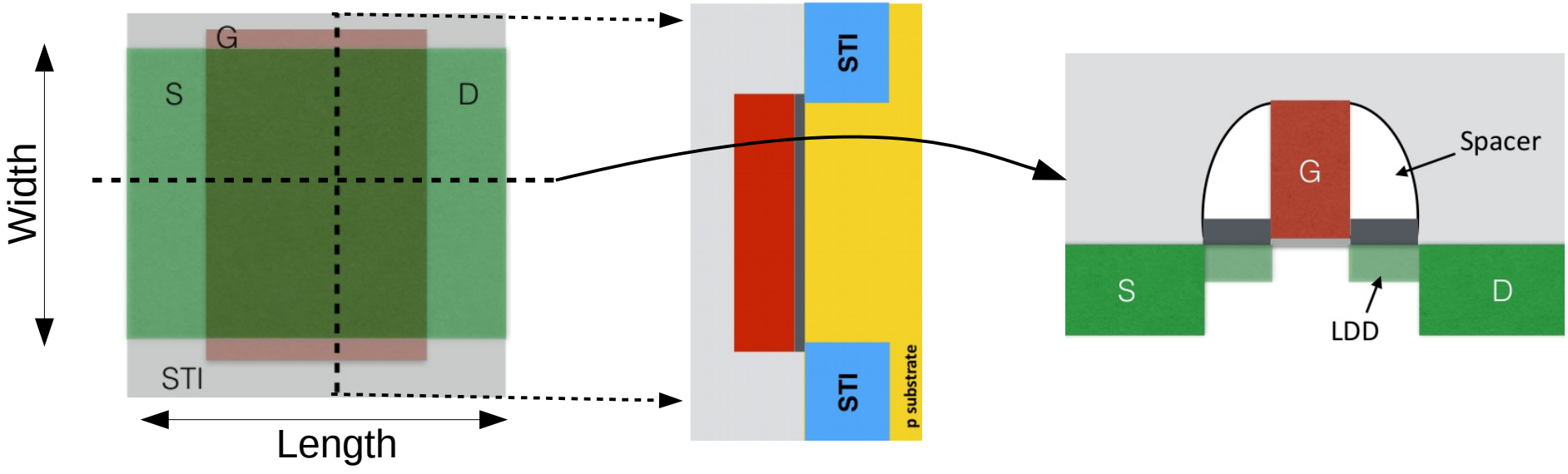
IC Electronics Radiation Damage

- Change in effective doping is insignificant, because doping levels in CMOS transistors are very high.
- All radiation damage effects to CMOS are due to parasitic electric fields form charge trapped in oxides and oxide-silicon interfaces
- Meet the oxides:
  - Gate oxide
  - Field Oxide
  - Buried Oxide (only for SOI)
  - Shallow trench Isolation (STI)
  - Gate Spacer

STI, Gate, Spacer



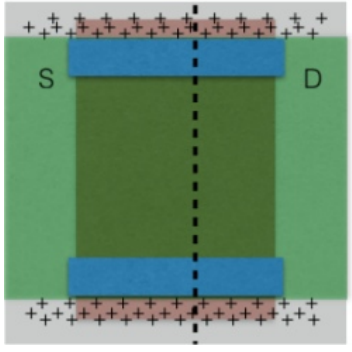


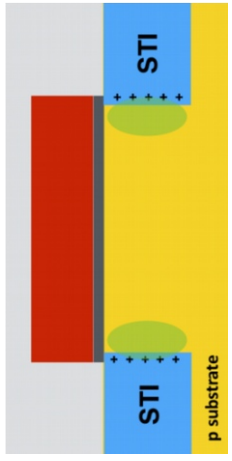


Radiation Induced Narrow Channel Effect

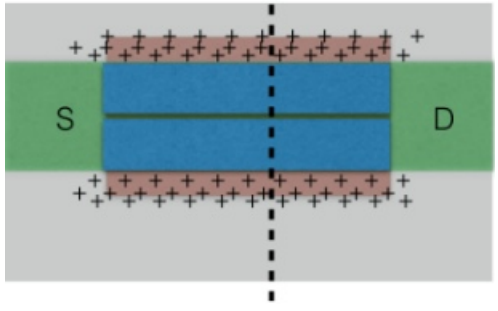
F. Faccio and G.Cervelli, "Radiation induced edge effects in deep submicron CMOS transistors", IEEE Trans. Nucl. Science, Vol.52, N.6 (2005) pp.2413-2420 http://dx.doi.org/10.1109/TNS.2005.860698

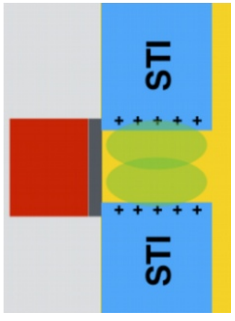
Wide Transistor

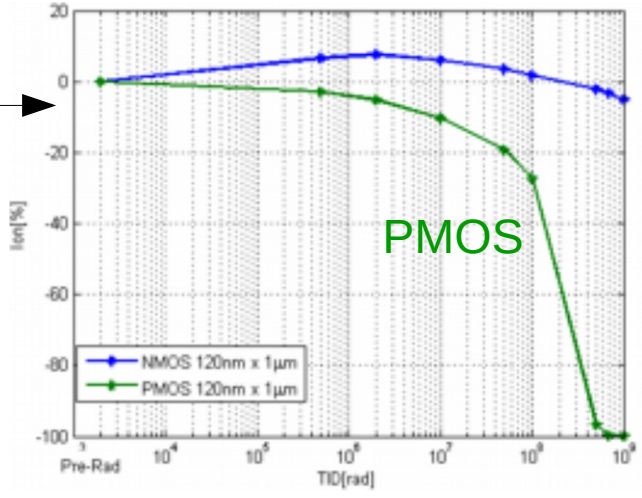




Narrowest Transistor





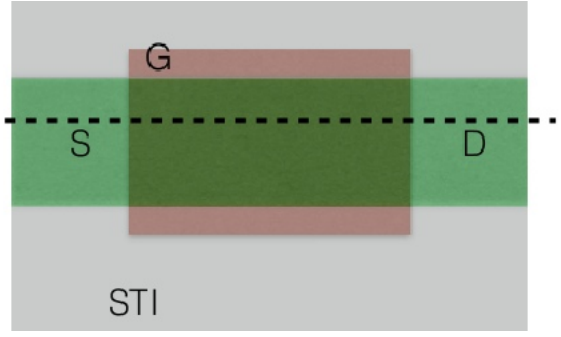


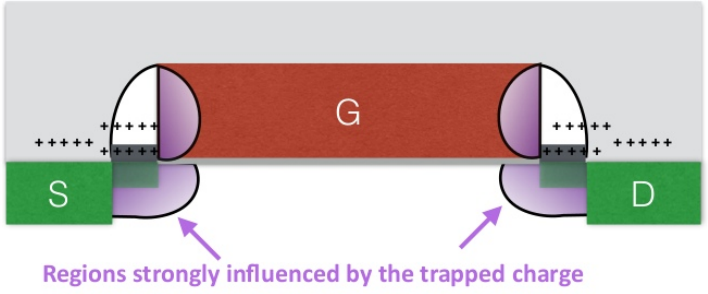
1Grad

Radiation Induced Short Channel Effect

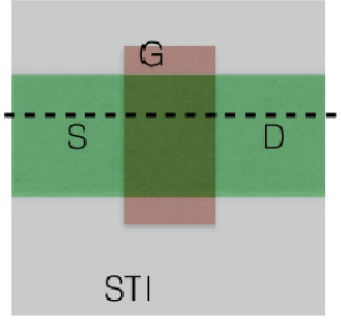
F. Faccio et al., "Radiation-Induced Short Channel (RISCE) and Narrow Channel (RINCE) Effects in 65 and 130 nm MOSFETs," IEEE Trans. Nucl. Science, Vol.62 , N.6 (2015) http://dx.doi.org/10.1109/TNS.2015.2492778

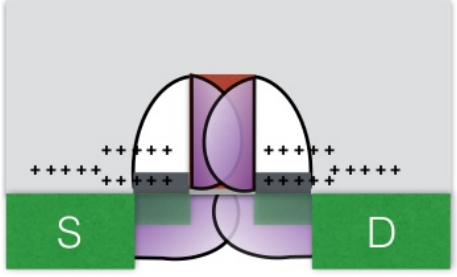
Long Transistor

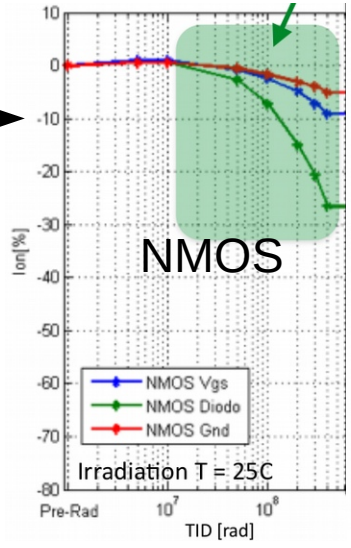


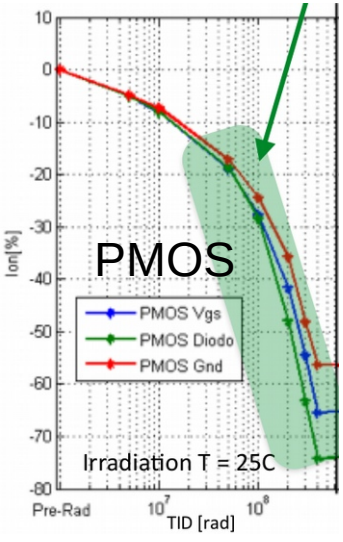


Shortest Transistor





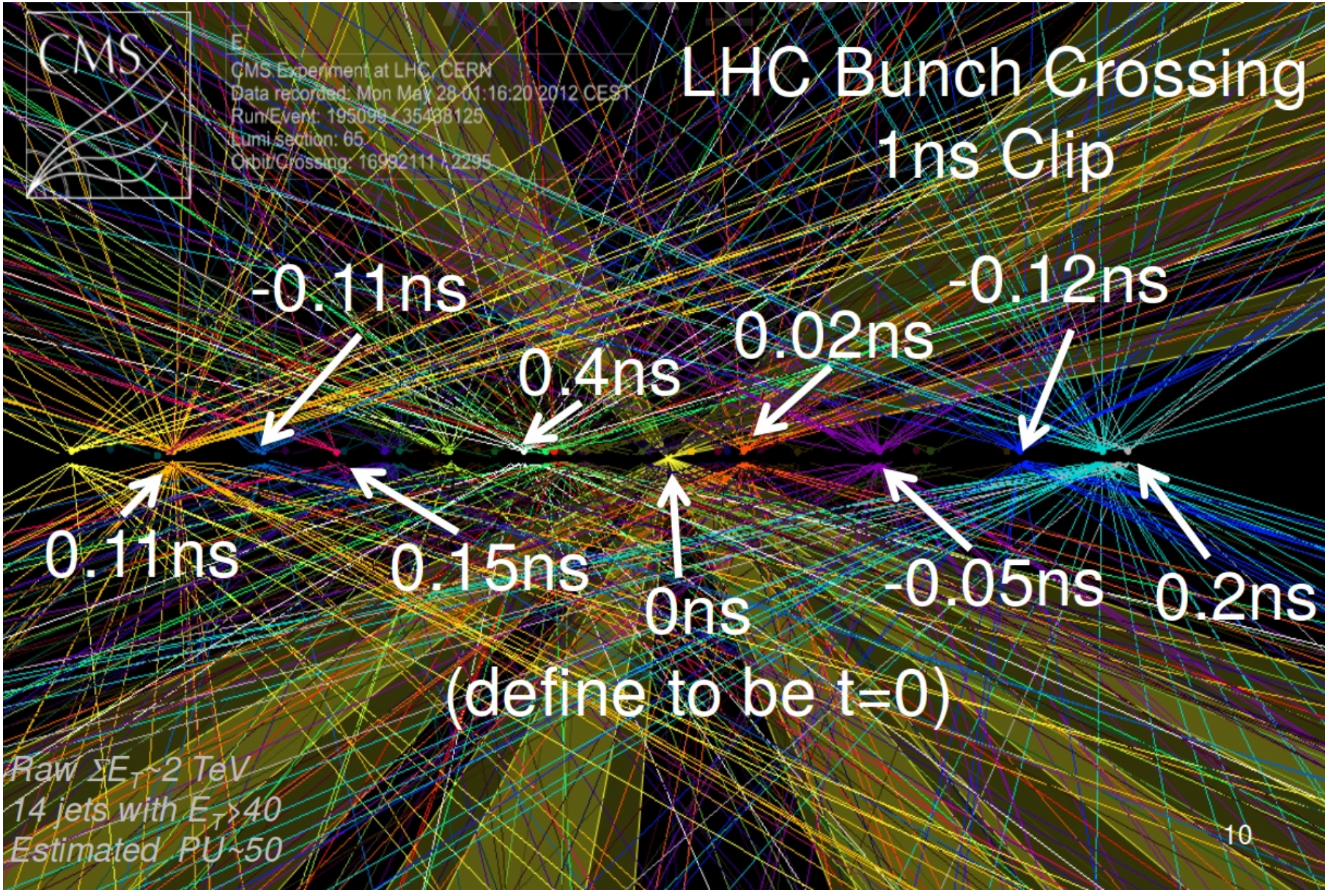




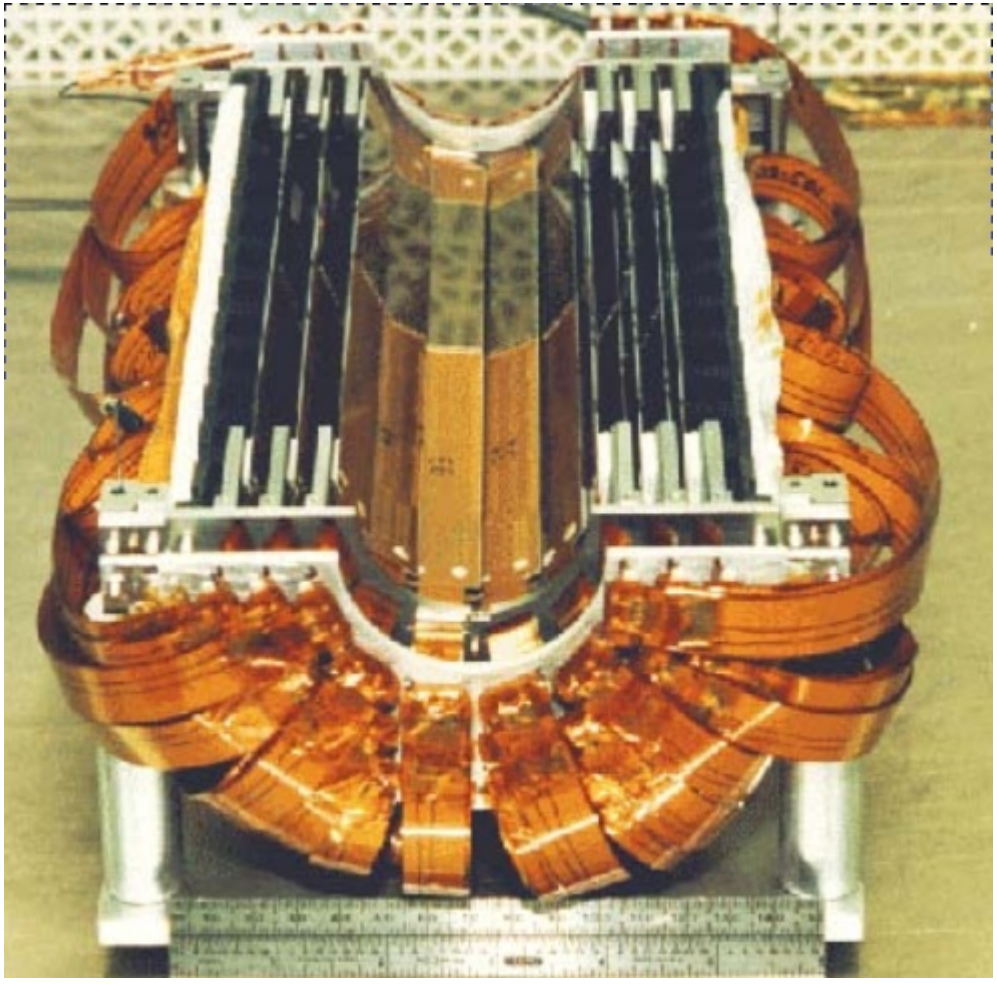
Recap

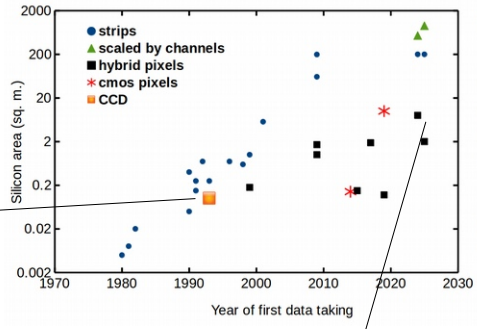
- Imaging particles is an inverse problem to typical imaging
- Need to surround the source of particles with senors – large area of silicon needed
- Plus frame rate is in the MHz
- => Custom ICs needed
- CMOS sensors for particle detection scale better to large areas, but hae limited rate and radiation hardness and need highly customized fabrication process.
- Hybrid detectors can use standard CMOS for readout (custom design but not custom process) and radiation optimized sensors.
- Design of radiation hard ASICs is a cottage industry in HEP

A future direction



The Rate Extremes



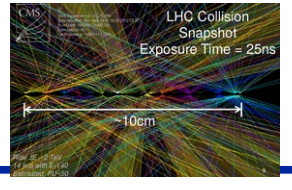


SLD VXD

- Silicon area: 0.12 m²
- 300M pixels (20μm x 20μm)
- But only 350,000 Z decays recorded
- => most pixels were never hit by real collision particle!

HL-LHC

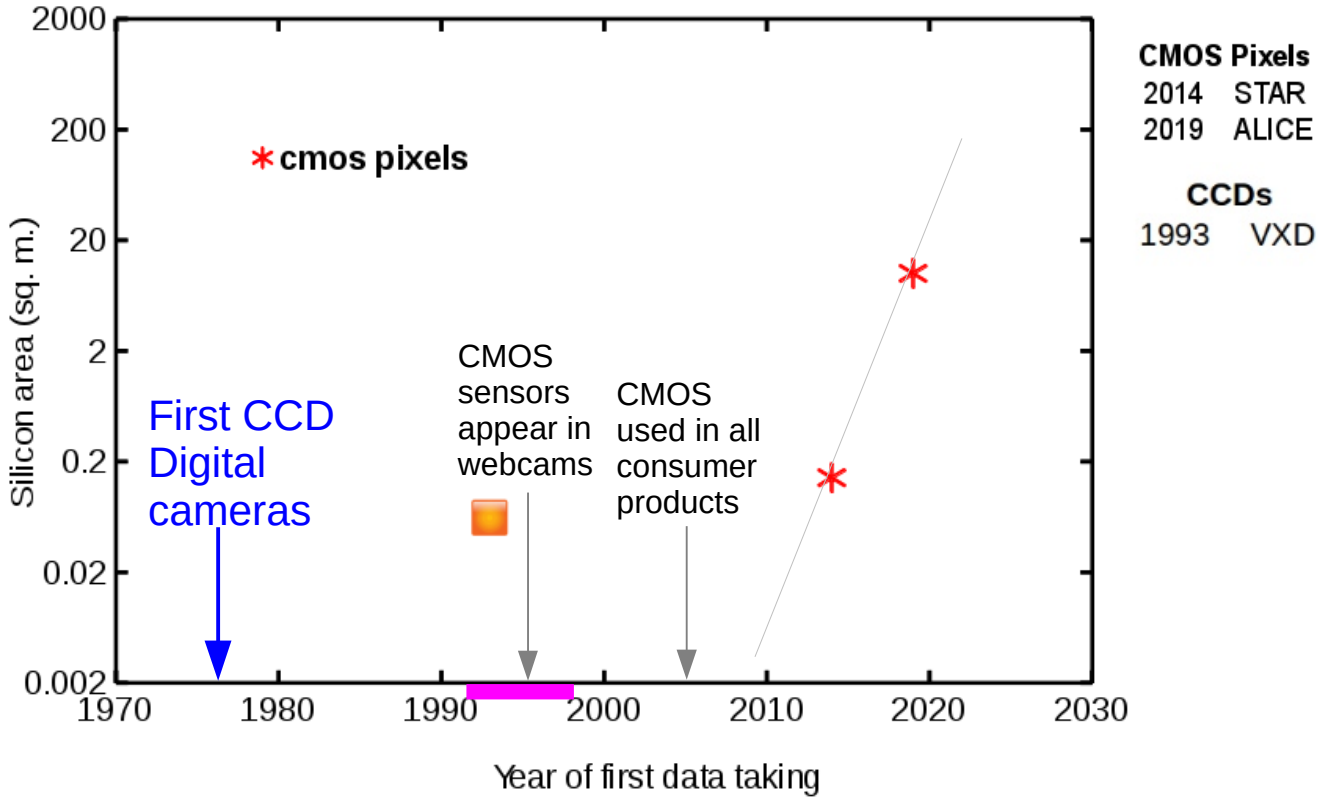
- Inner layers of ATLAS and CMS high luminosity upgrades will see 10 collision particles in every Si atom!



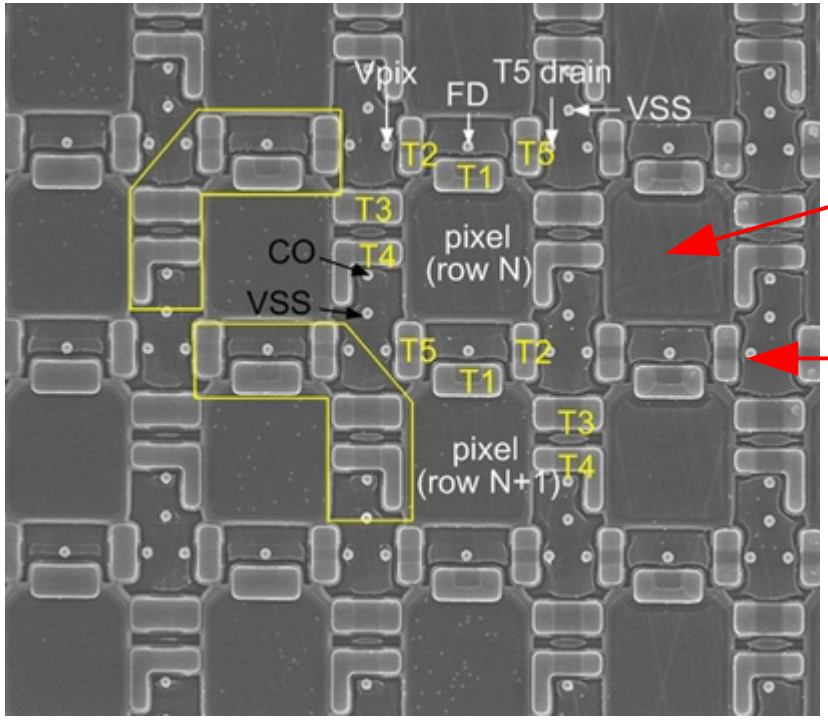
X 10^{16}

B A C K U P

Connection to Consumer Electronics



Close-up of CMOS camera sensor



Photodiode covers about half the pixel area in this example

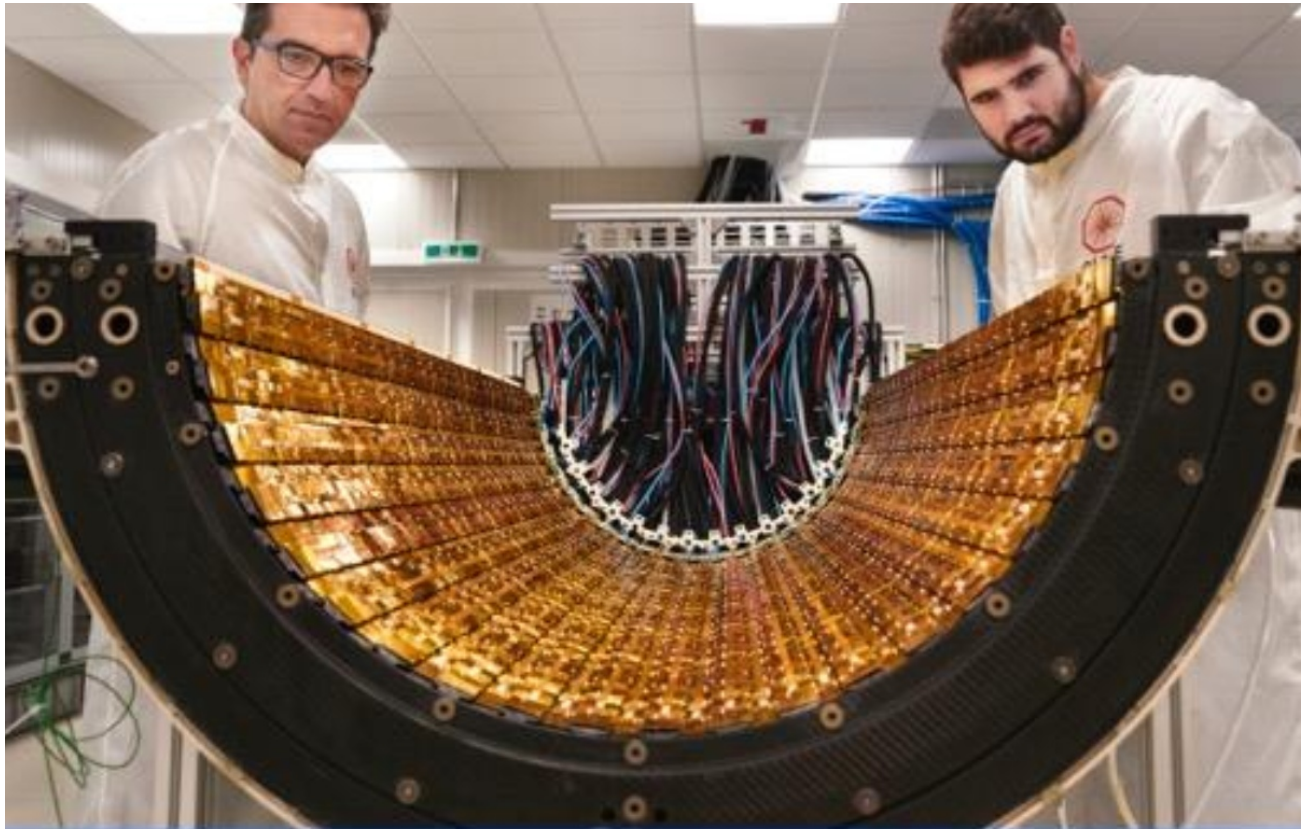
Metal traces have been removed. They run over the transistors leaving photodiode exposed

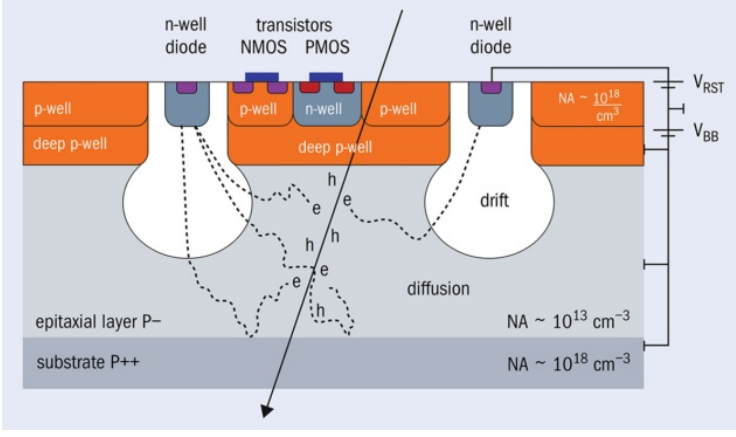
For particle tracking need 100% fill factor

Need low enough noise that can detect a single particle

Need radiation hardness

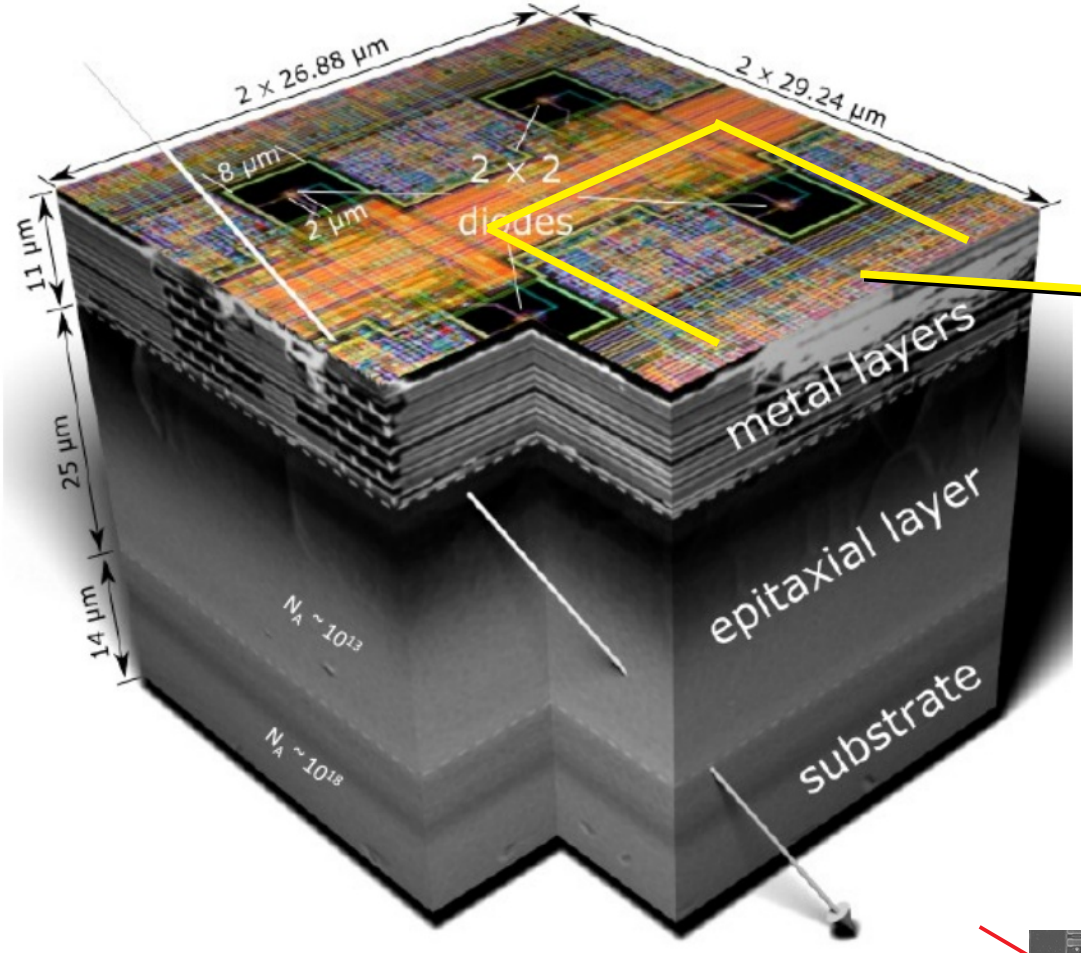
ALICE just installed a 10m^2 tracker made of CMOS sensors

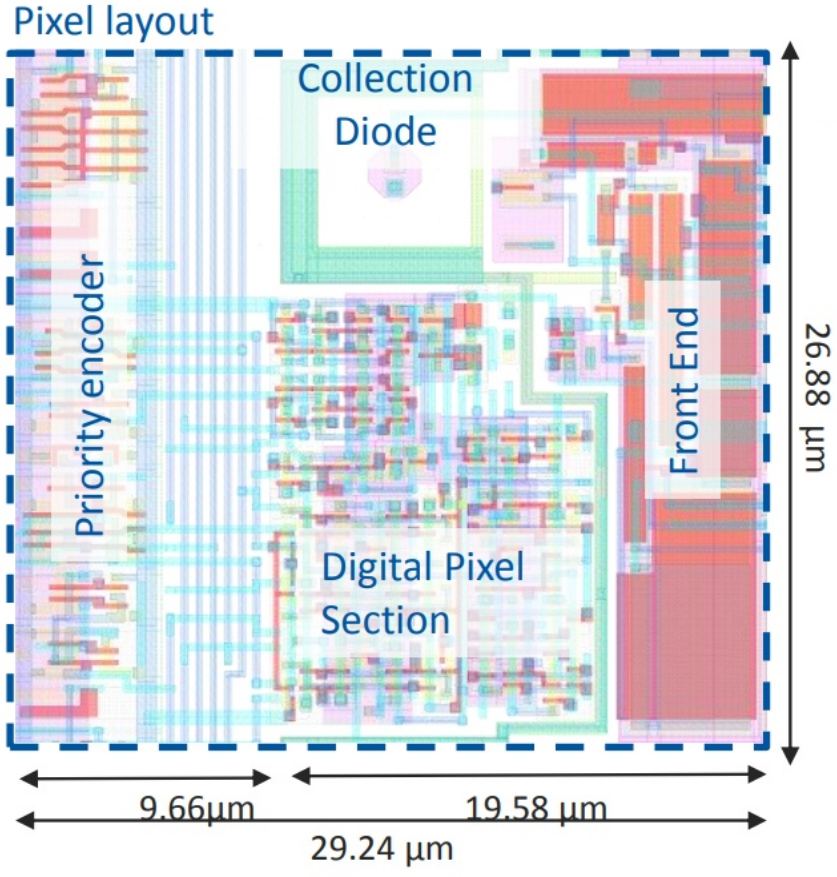


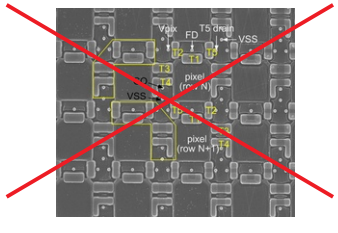


Highly customized CMOS process. Proprietary. Not portable

ALPIDE sensor chip- not a simple 3T pixel

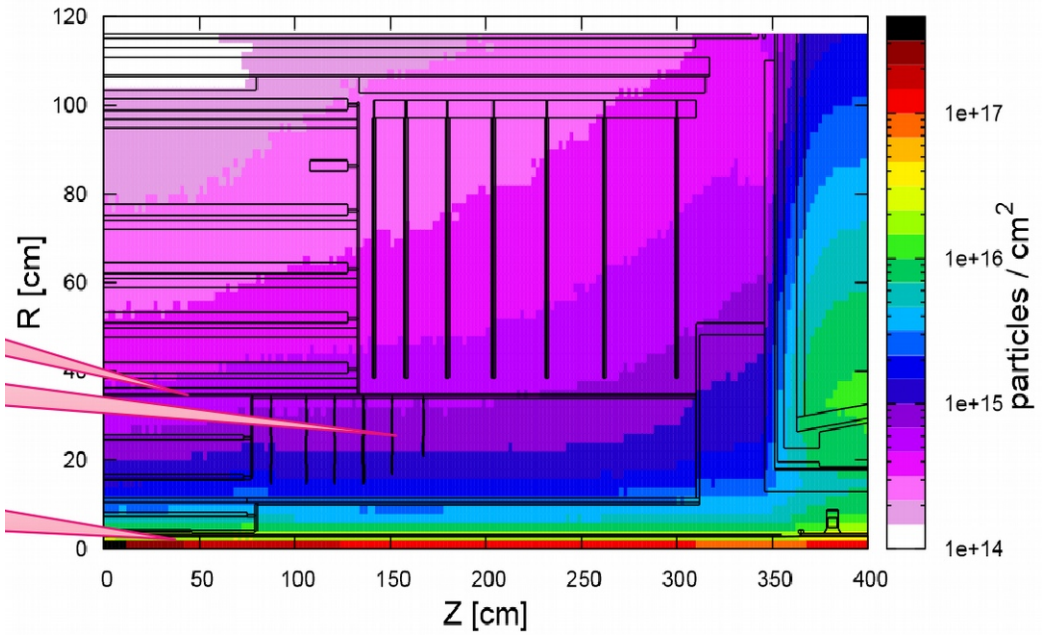






~100 transistors

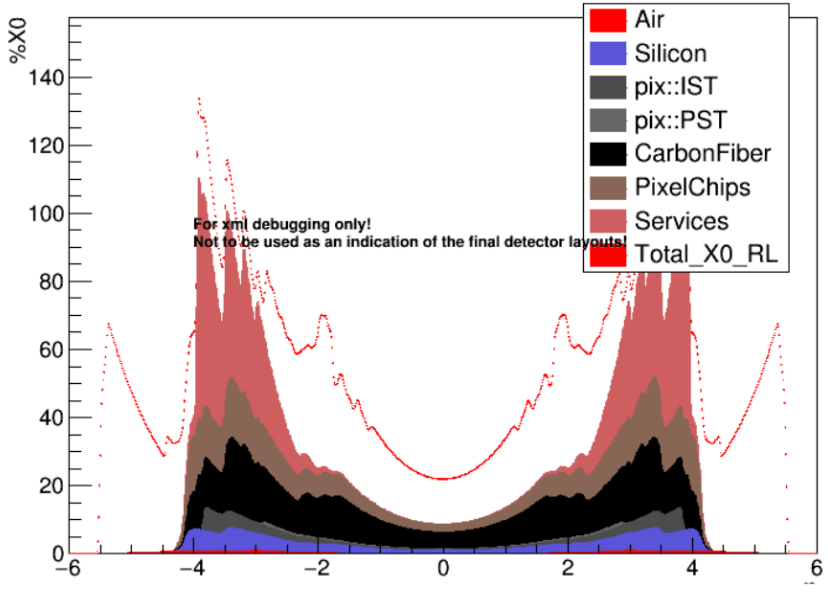
Limited Readout Bandwidth



100 MRad

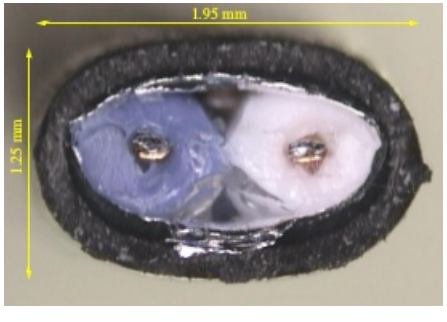
200 MRad

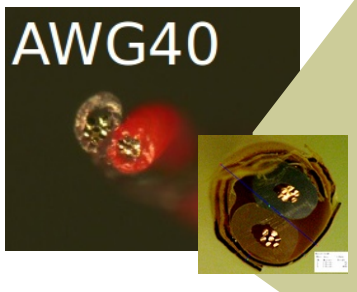
1 GRad

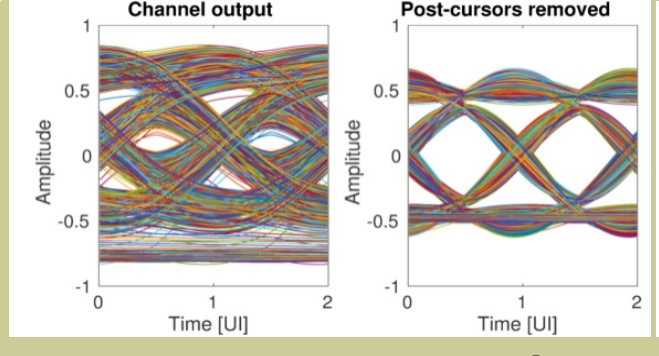


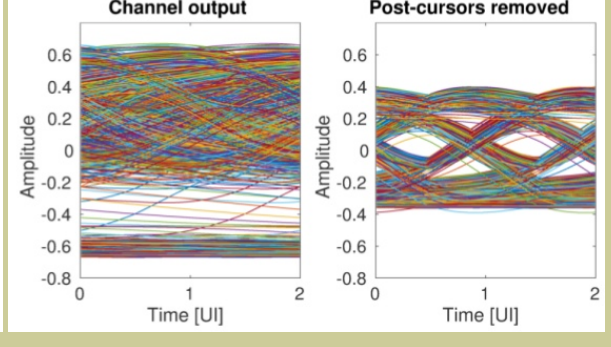
Can’t use optical transmitters

Can’t use heavy shielded cables



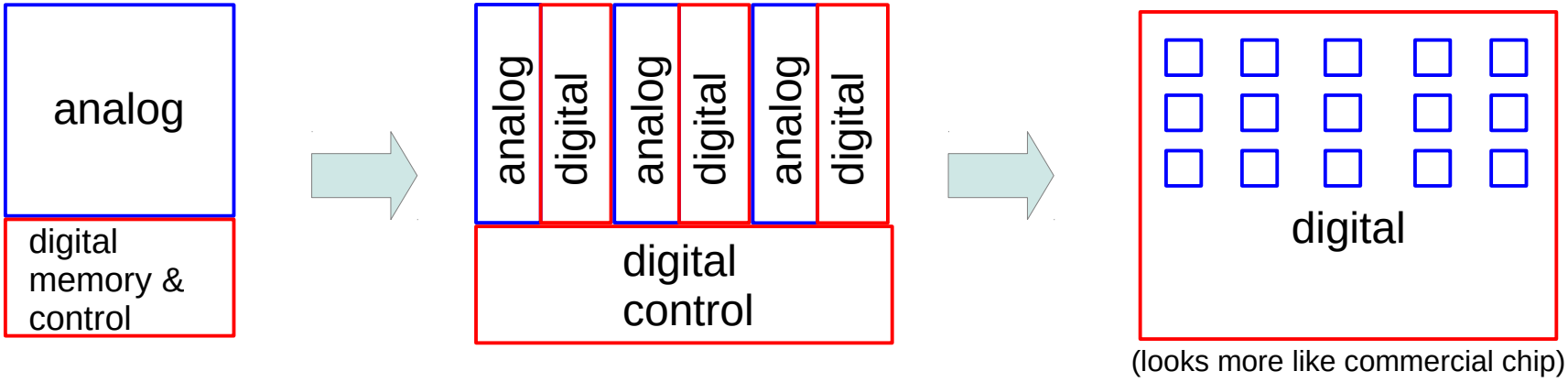






3m **5Gbps Simulation** **5m**

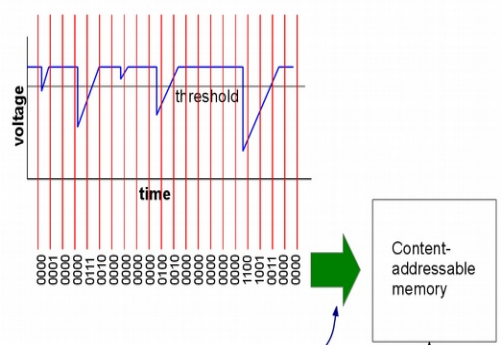
Readout Chip Evolution

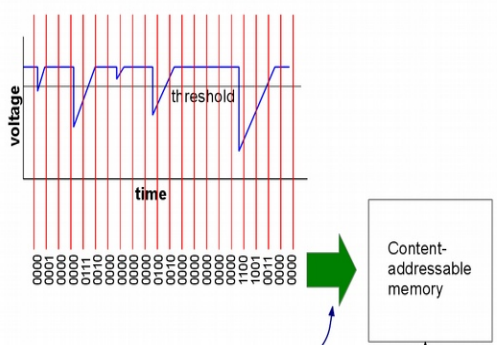


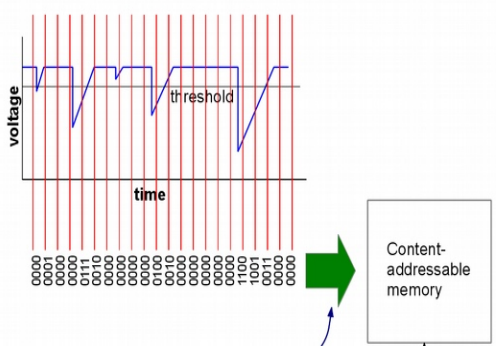
10 yrs ago

today

Future





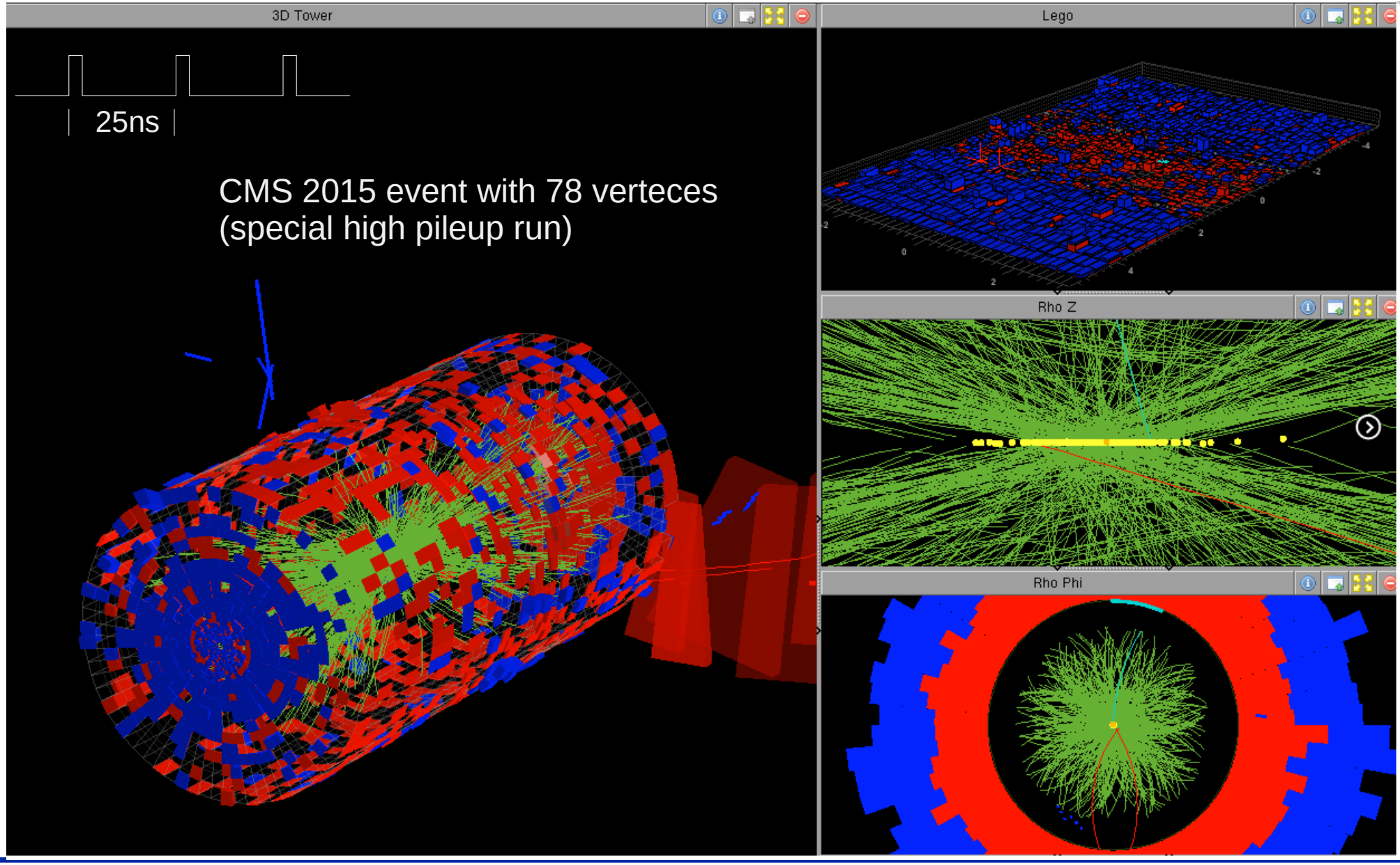


<1Gb/s /cm^2

5Gb/s /cm^2

40Gb/s /cm^2

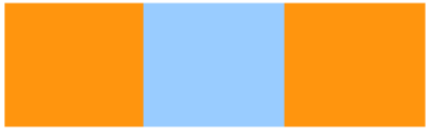
What Images Look Like



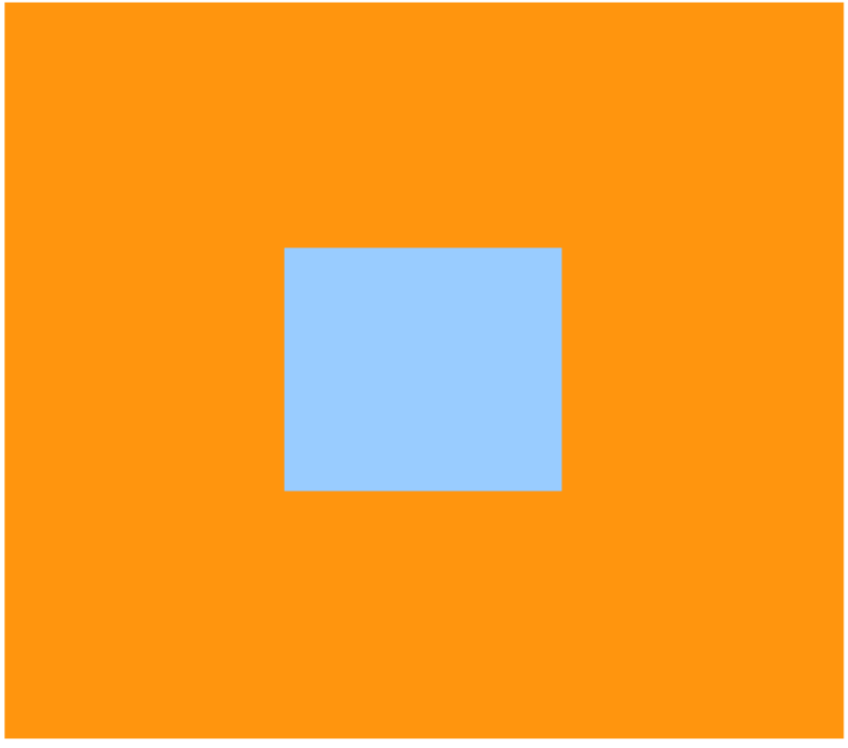
Rad Hard Logic Density Scaling

65nm

130nm

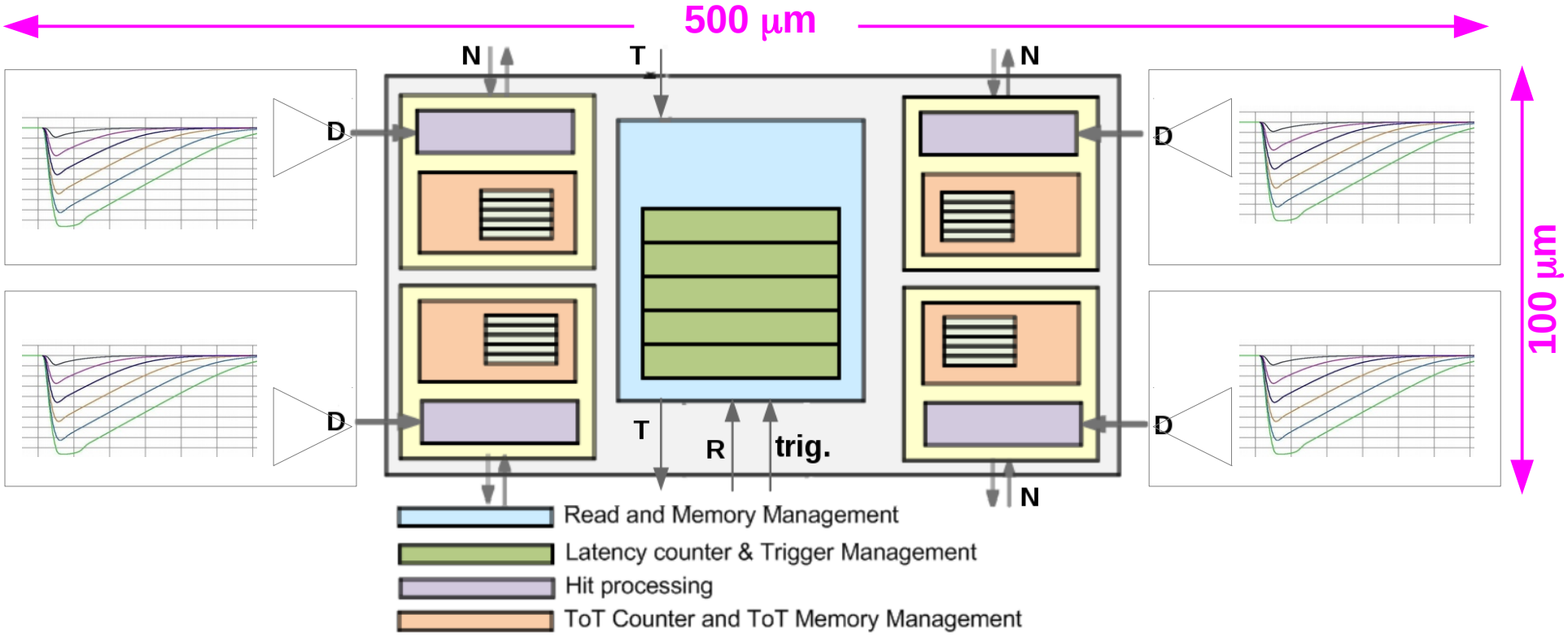


0.25um
ELT



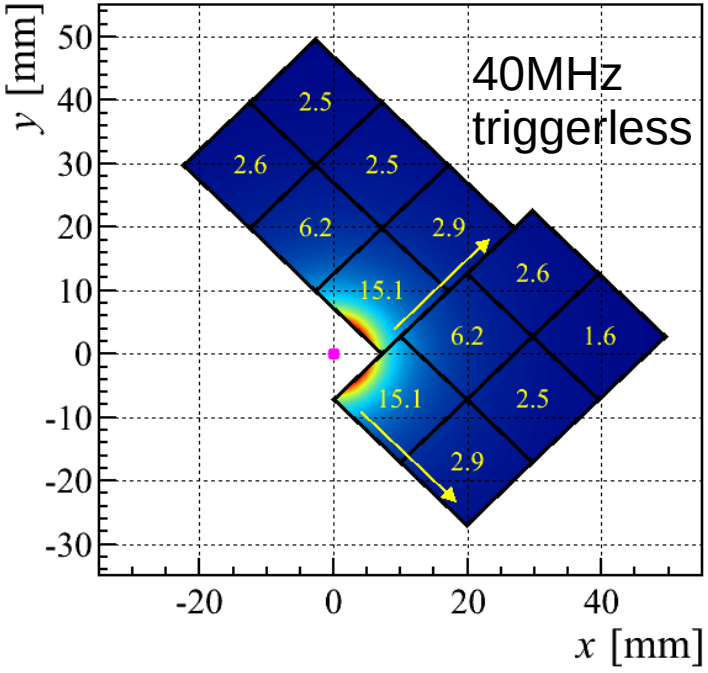
FE-I4 Digital Region

- **Digital block is shared with 4 inputs- each form an identical analog pixel.**

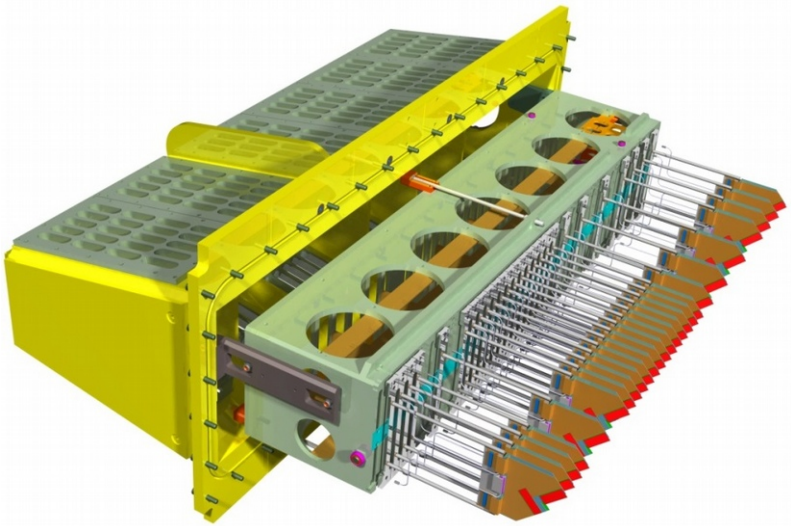


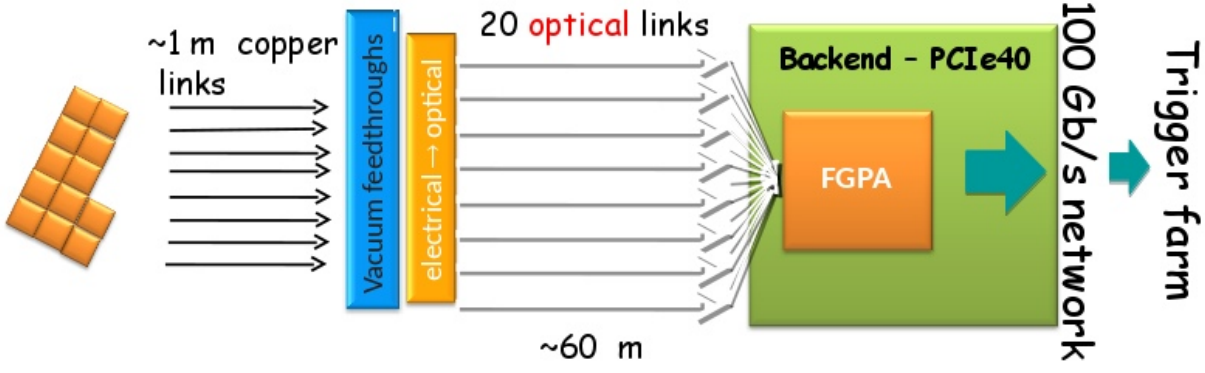
Velopix triggerless readout

Readout chips in LHCb Velopix plane
Output data rate per chip in Gbps



Velopix half with 26 planes





- Geometry looks like data flow diagram
- Lots of room outside physics acceptance
- Can have many cables out of each chip