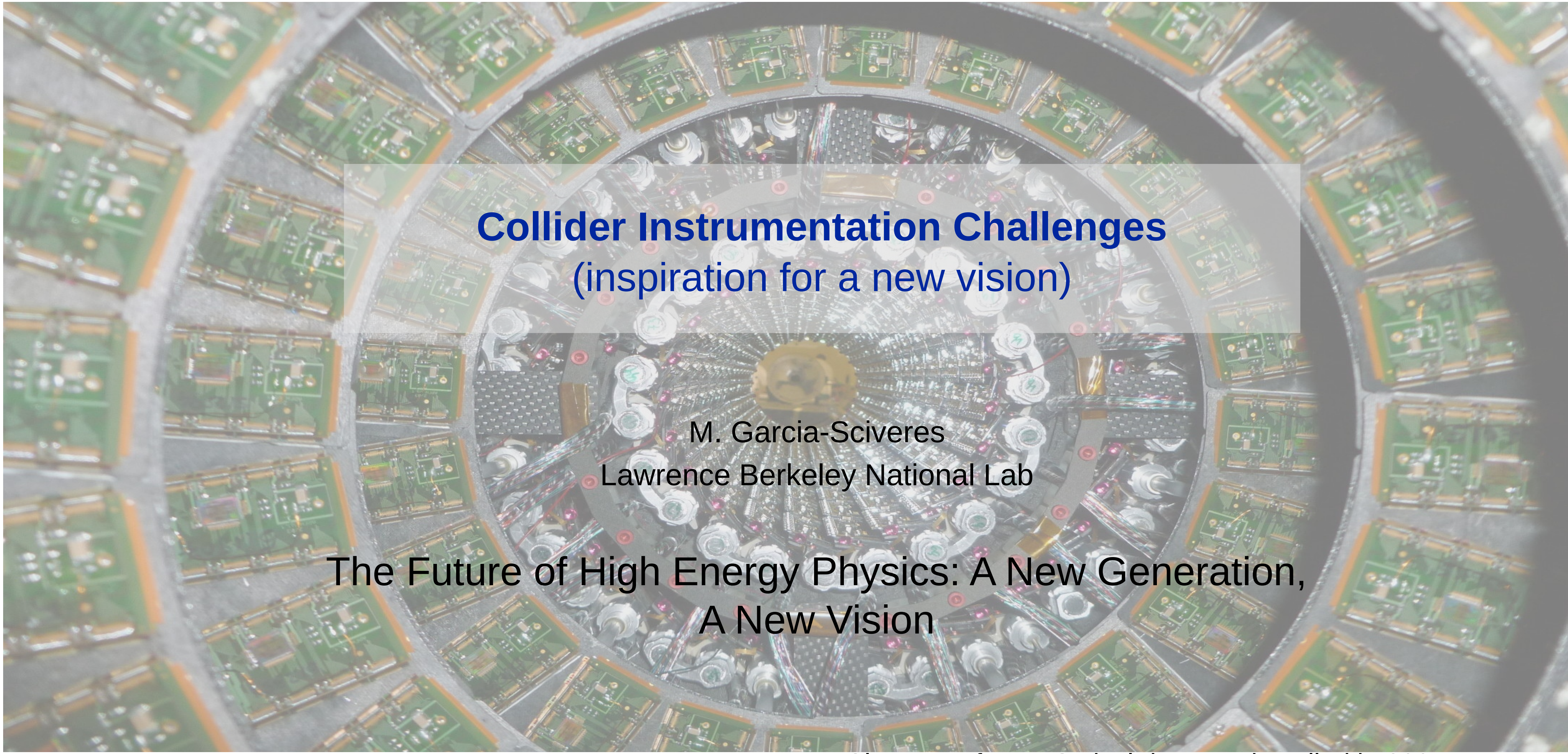
Collider Instrumentation Challenges
(inspiration for a new vision)

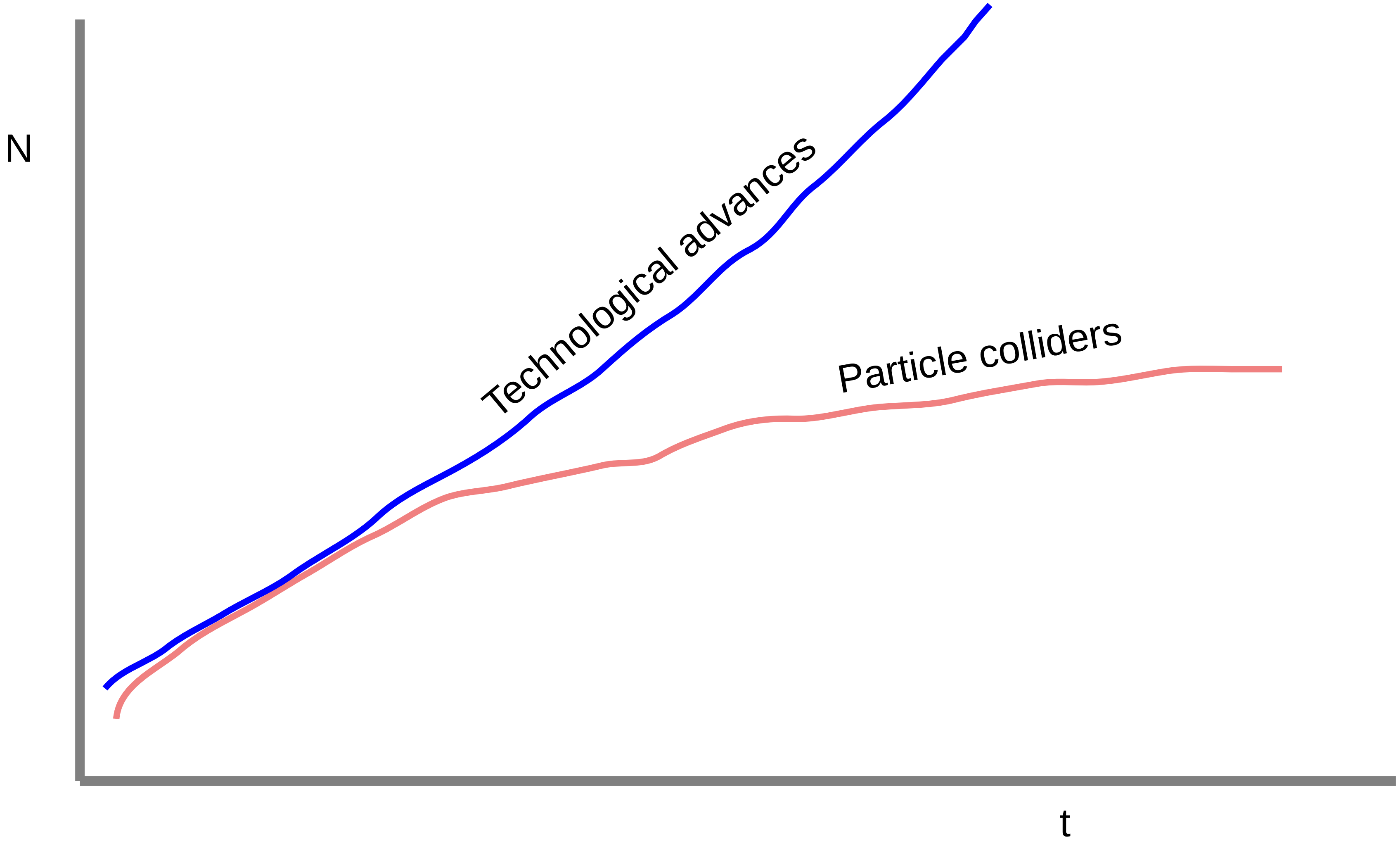
M. Garcia-Sciveres
Lawrence Berkeley National Lab

The Future of High Energy Physics: A New Generation,
A New Vision



Close-up of ATLAS pixel detector, installed in 2007

Main Message



Contents

- go to www.slideo.com and enter code 3393171
  to be ready for interactive polls

- A standard future collider detectors talk in 5 slides
  (mostly stolen from recent talk by Petra Merkel)
- Meanwhile, the CHIPS act and the end of Moore's Law
  - And generative AI, which is closely connected
- What is co-design? (in the context of CHIPS)
- Changing our design paradigm
- What will you do with new technology?
- Conclusions

- (Shameless plug of NIM volume on Microelectronics in HEP)

Future Collider Tracking Needs

Tracking Detectors

x = significant R&D is needed

Detector Requirements:

- driven by low mass and high granularity requirements
- increasingly moving to 4D tracking (throughout, or dedicated timing layer)

TRACKING	ILC	CLIC	FCC-ee	FCC-hh	MuC
spatial precision	x	x	x	x	x
low mass	x	x	x	x	x
low power	x	x	x	x	x
high rates				x	
ultrafast timing				x	x

GAS TRACKERS	ILC	CLIC	FCC-ee	FCC-hh	MuC
low X0	x	x	x		
ion backflow (TPC)	x	x	x		
high granularity	x	x	x		
dE/dx	x	x	x		

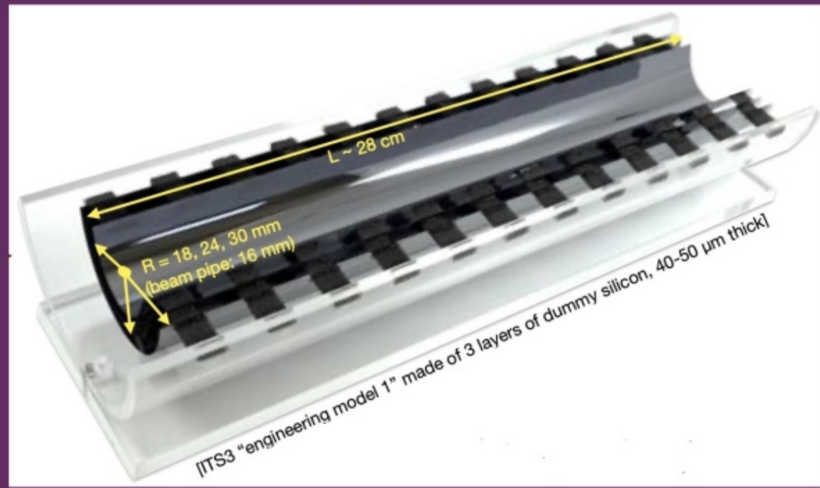
February 29th, 2024 Detectors for Future Colliders – Petra Merkel (Fermilab)

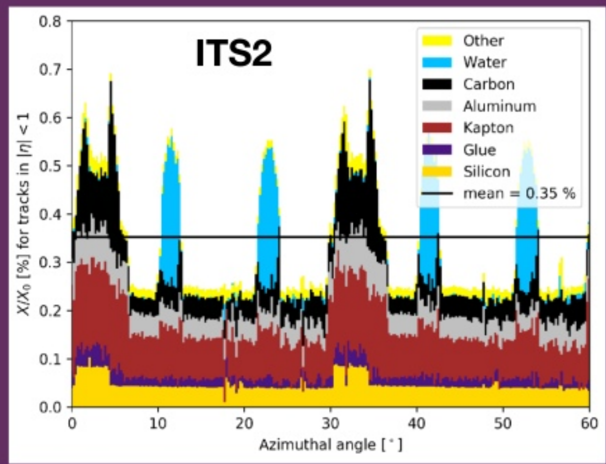
e+e- Collider physics reach is tied to tracker low mass

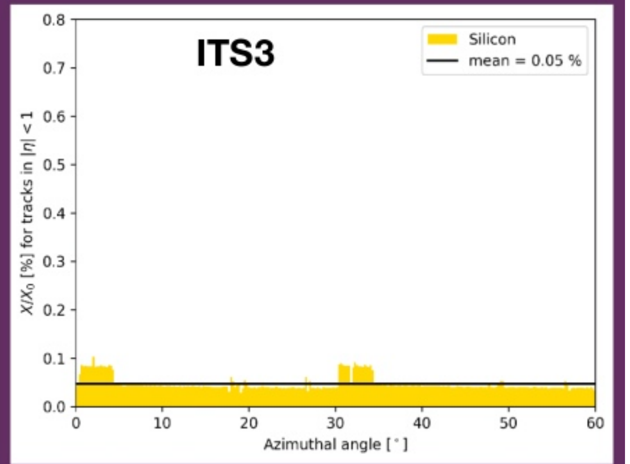
State-of-the-art: ALICE ITS3

A truly cylindrical vertex detector

- 300mm wafer-scale MAPS fabricated from smaller chips using stitching
  - Silicon thinned down to ≤50µm making them flexible; bent to target radii
  - mechanically held in place by carbon foam ribs
- Extremely low material budget: 0.05% X_0, homogeneous material distribution
- Planning to use air cooling (~8m/s)
- To be installed during CERN LS3







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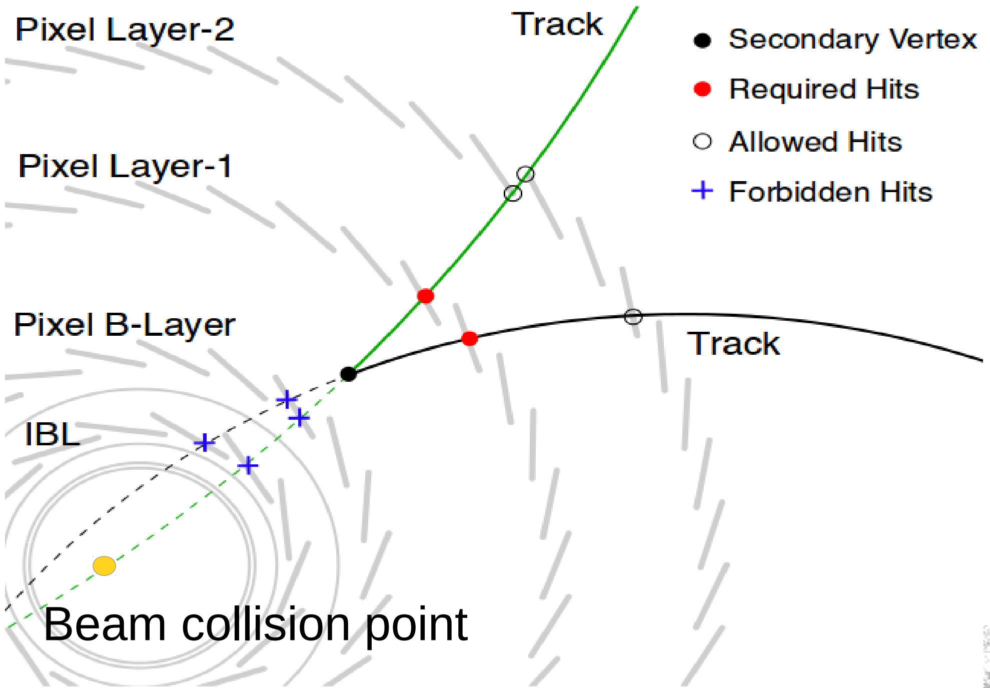
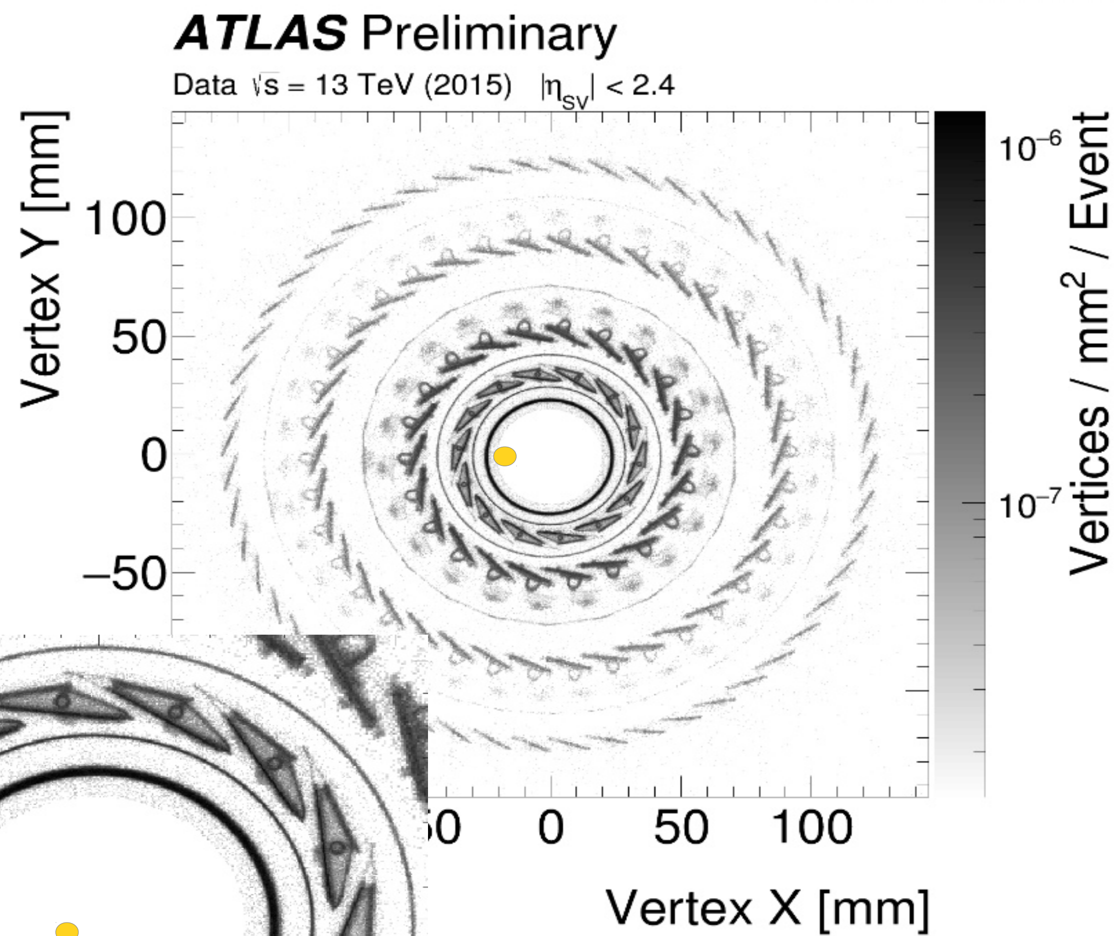
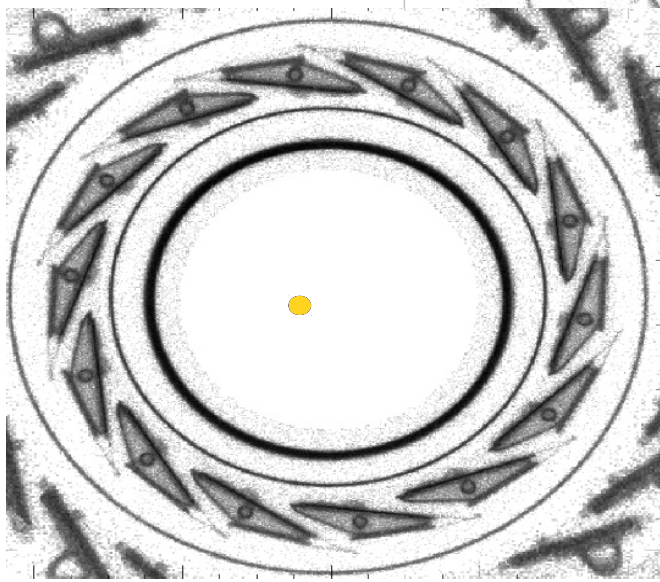
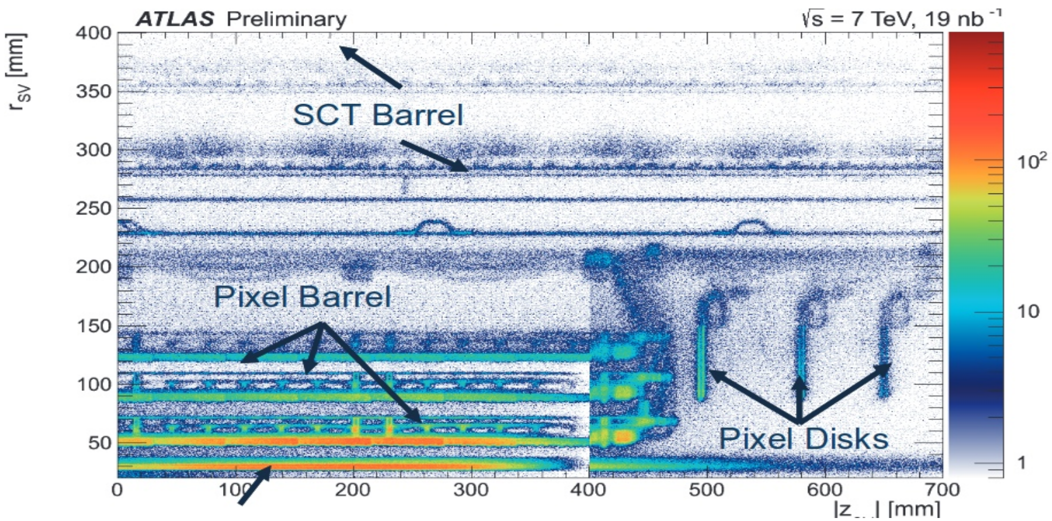
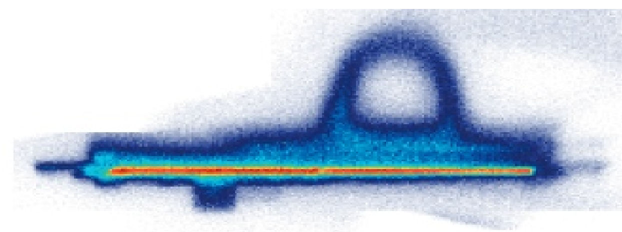
pp Collider mass can be higher, mu+mu- somewhere in between









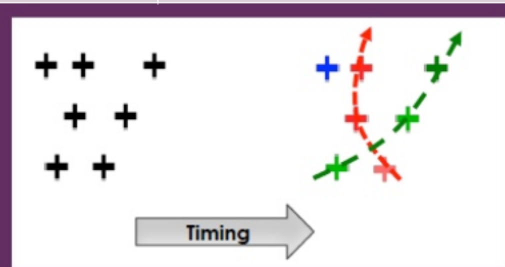


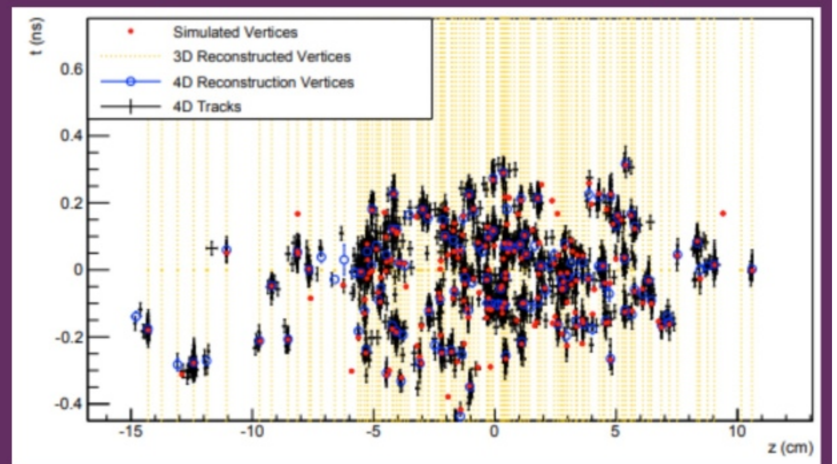
Everyone can make use of fast timing

4D Tracking

- 4D tracking: assign spatial and temporal coordinate to a hit
- Many time coordinates per track yield better performance, but require much more complex readout systems (=power)
- Some applications will be ok with limited set of timing points
- Power and cooling will determine 4D architecture (how many layers?), pixel size and temporal precision

Timing	(HL-LHC ~30ps)
100-1000 ps	ILC, CLIC
10-100 ps	FCC-ee, MuC
<10 ps	FCC-hh





Next!… Calorimetry

Calorimeter Choices

Project	~Earliest Start of data taking	Current Calorimeter options					
		Solid state	Scintilling tiles/strips	Crystals	Fibre based r/o (including DR)	Gaseous	Liquid Noble Gas
HL-LHC (>LS4)	2030			✔	✔		
SuperKEKb (>2030)	2030			✔			
ILC	2035	✔	✔			✔	
CLIC	2045	✔	✔				
CEPC	2035	✔	✔	✔	✔	✔	✔
FCC-ee	2045	✔	✔	✔	✔	✔	✔
EiC	2030		✔	✔	✔		
FCC-hh (eh)	>2050	✔	✔				✔
Muon Collider	> 2050	✔	✔	✔	✔	✔	
Fixed target	"continous"		✔	✔	✔		✔
Neutrino Exp.	2030		✔				(✔)

in most cases, final choices still to be made

I hope so!

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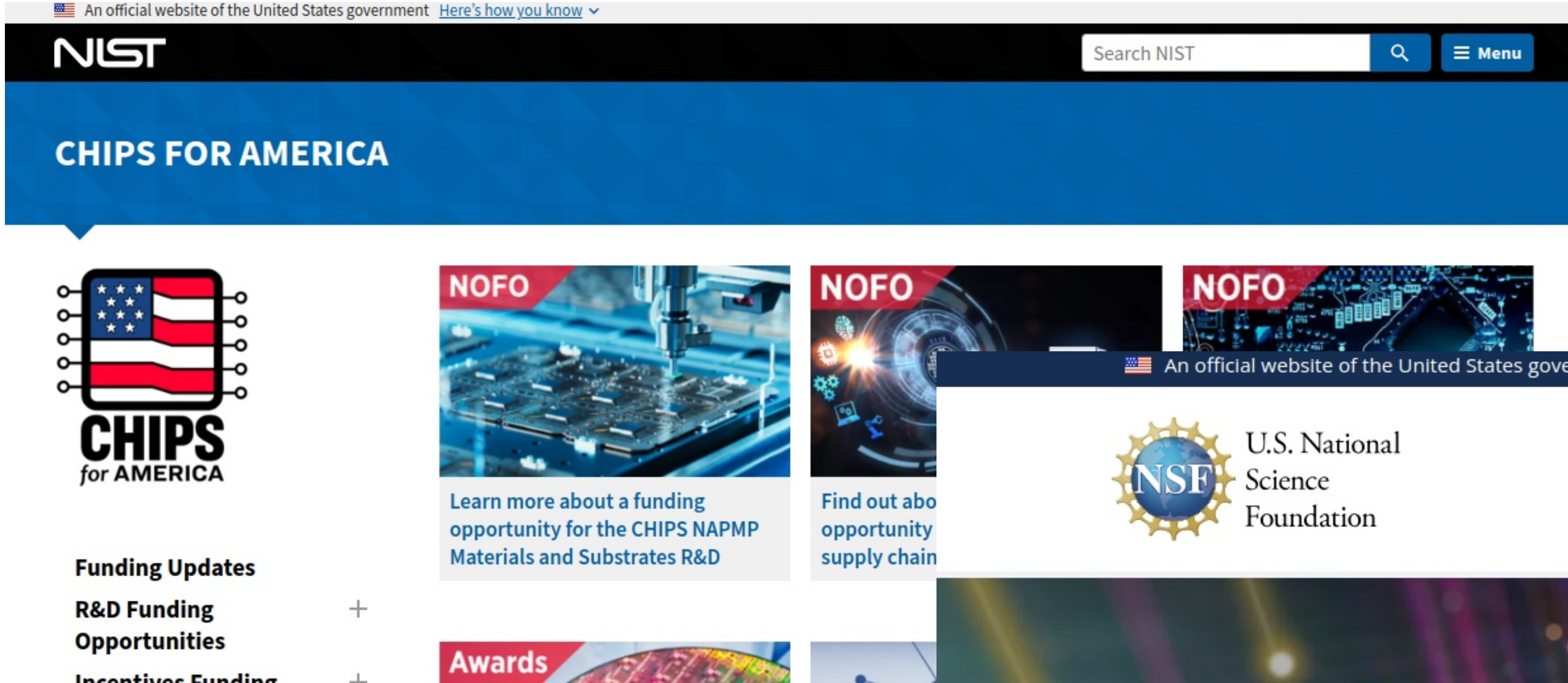
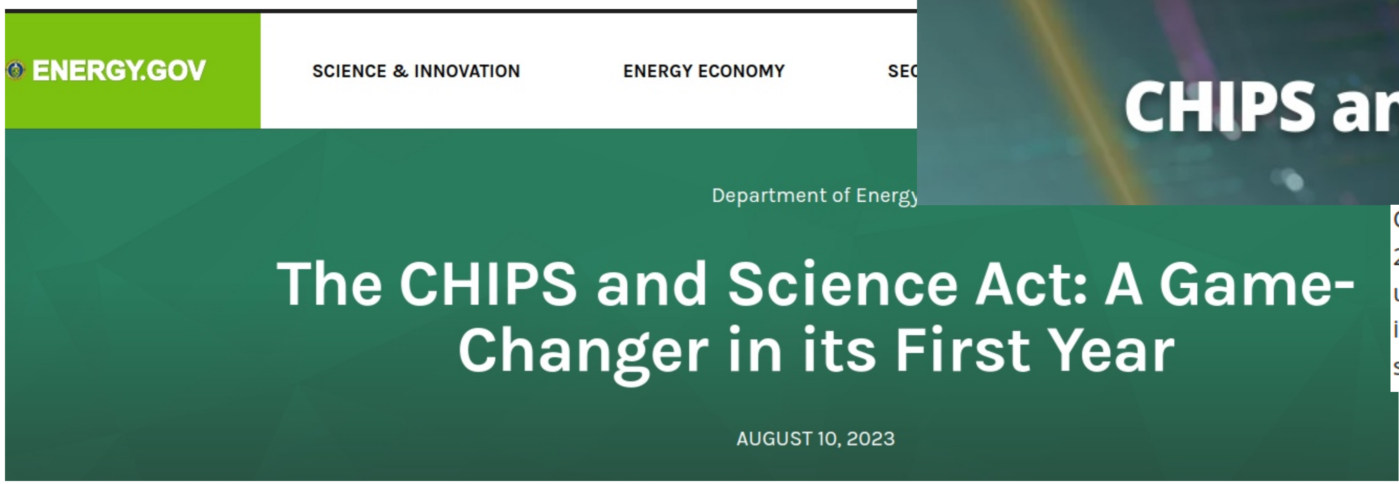
Meanwhile...

280B for manufacturing
13B for semiconductor research
174B for public sector research

(authorized, not appropriated)

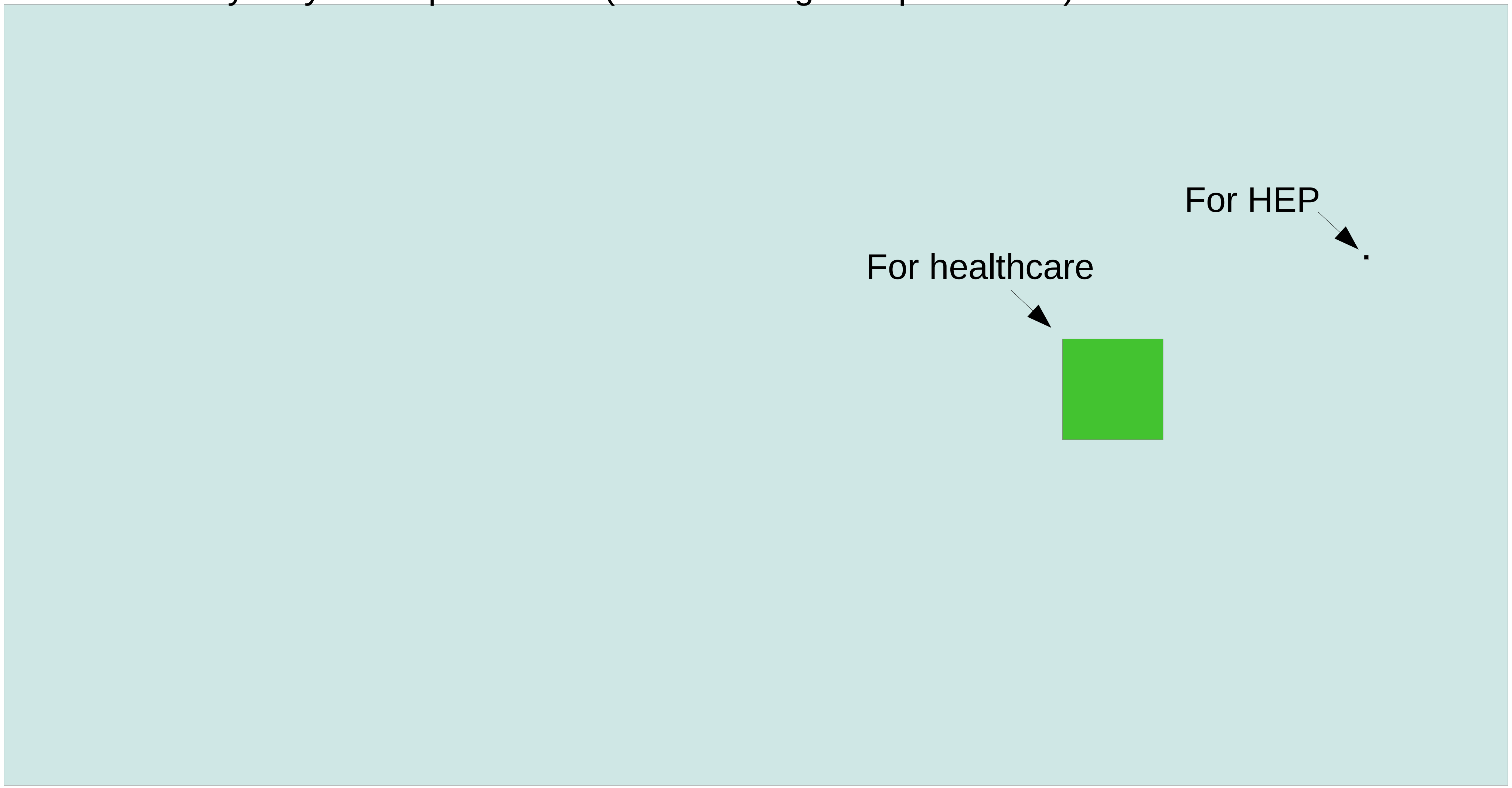




(P5 report referenced)

Context for where we fit in

TSMC yearly wafer production (50% of the global production)

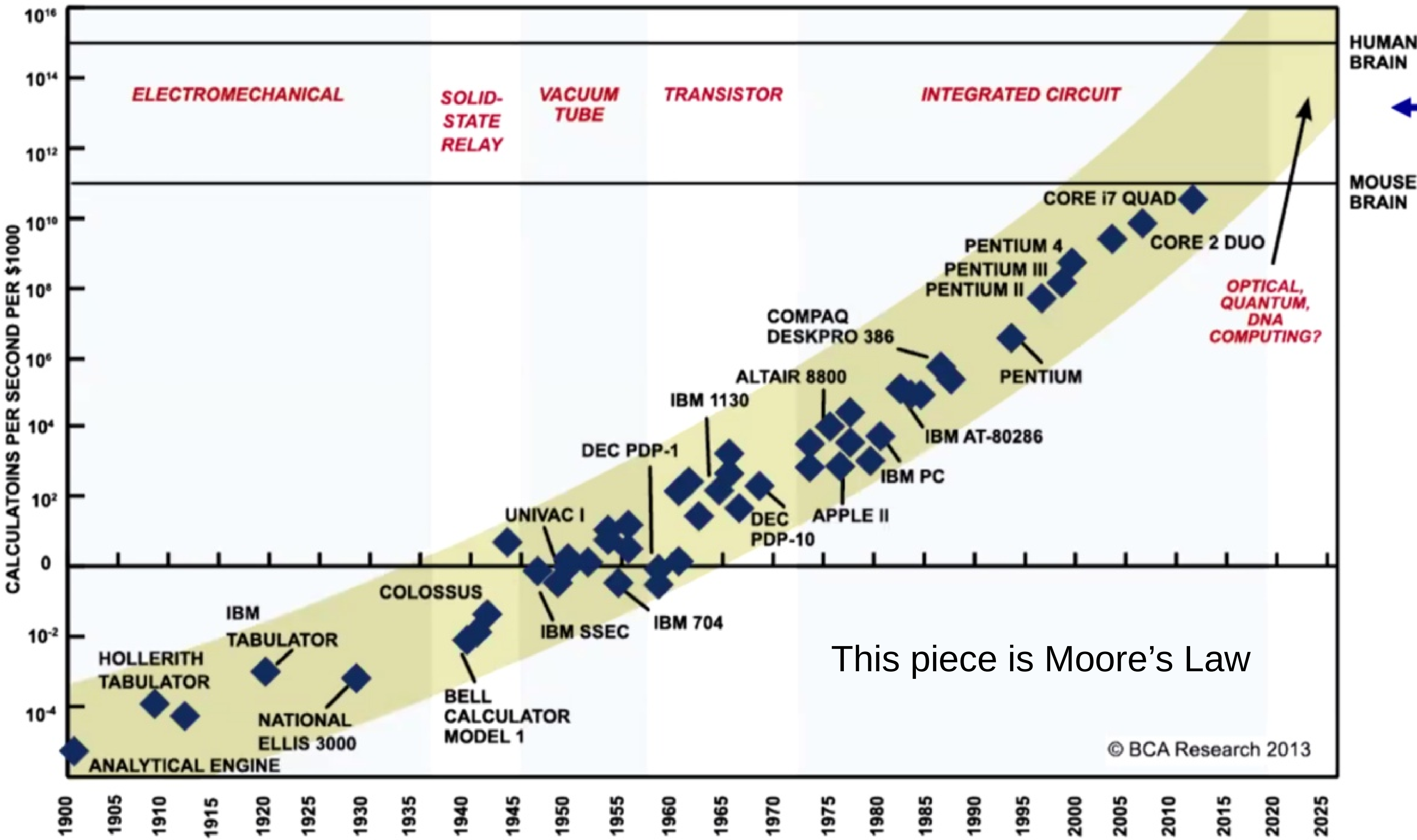


Let’s take a poll

What technology applications outside of HEP do you work on?

https://wall.sli.do/event/4tXP5F8RPMAarzUoCfMfCx?section=ba952af7-e655-43f8-b31c-0a5022720aac

History of computing

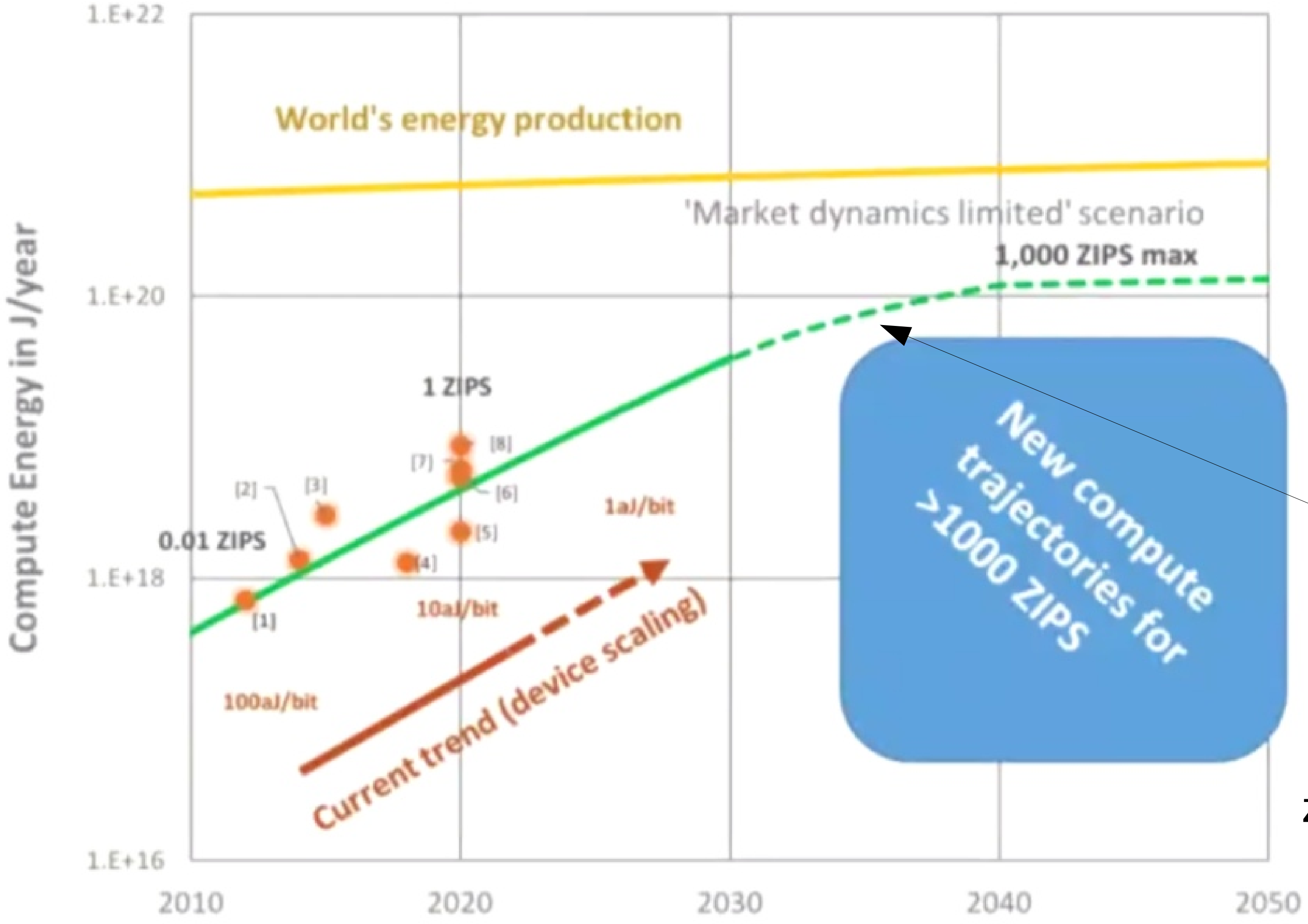


SOURCE: RAY KURZWEIL, "THE SINGULARITY IS NEAR: WHEN HUMANS TRANSCEND BIOLOGY", P.67, *THE VIKING PRESS*, 2006. DATAPOINTS BETWEEN 2000 AND 2012 REPRESENT BCA ESTIMATES.

← **ChatGPT**

timing not an accident
We are at an Interesting point in time

Power used = The motivation for CHIPS



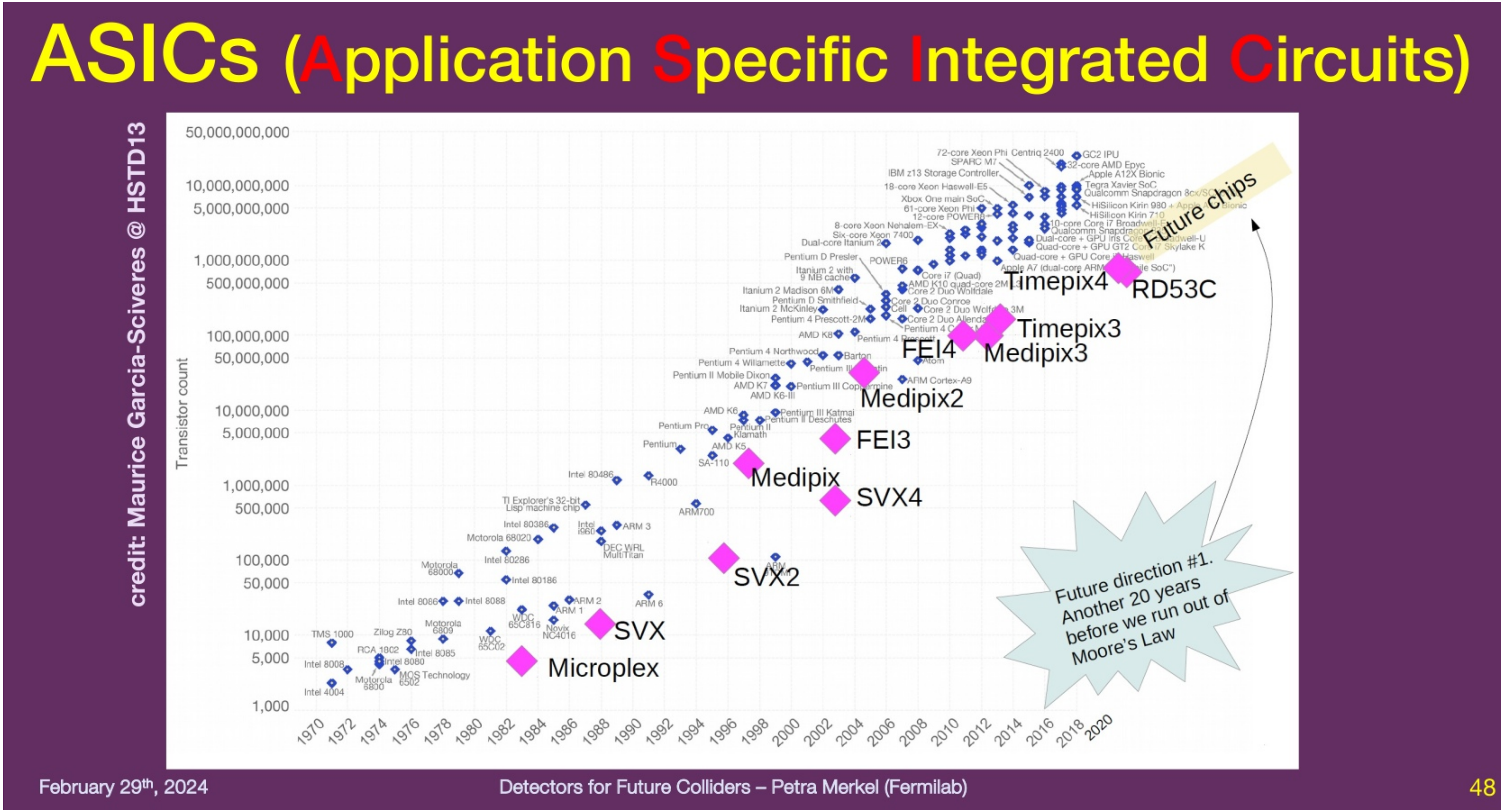
Semiconductor Research Corp. Decadal Plan for Semiconductors

fun fact, the brain also consumes 20% of the body's power

Big technology shift will happen In the time frame we're talking about

$z=10^{21}$

We follow technology trends too

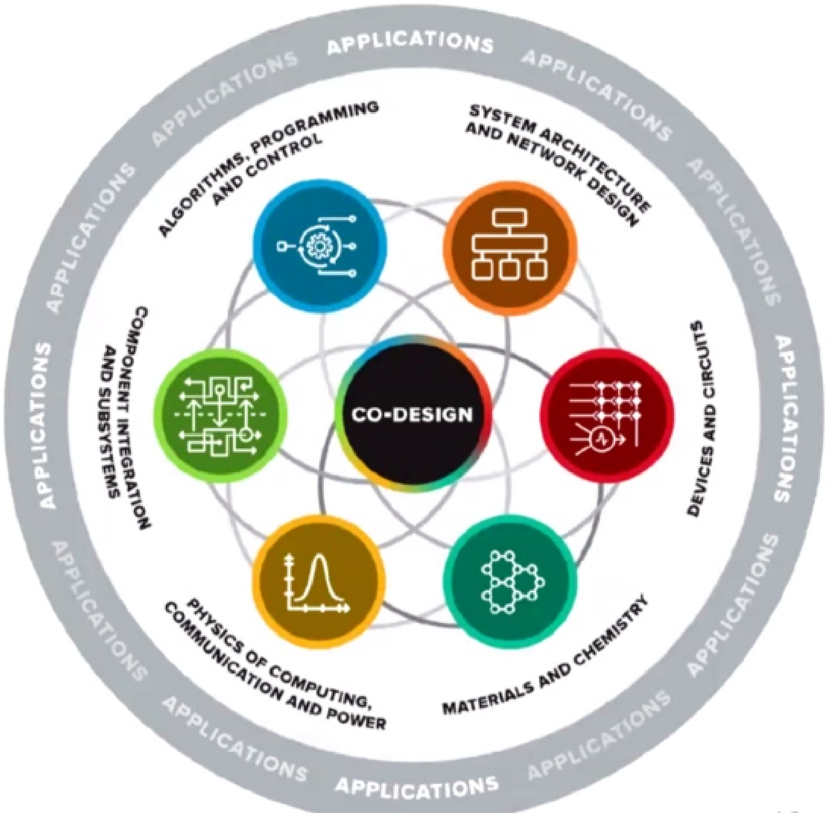


The technology shift

Future Semiconductor R&D

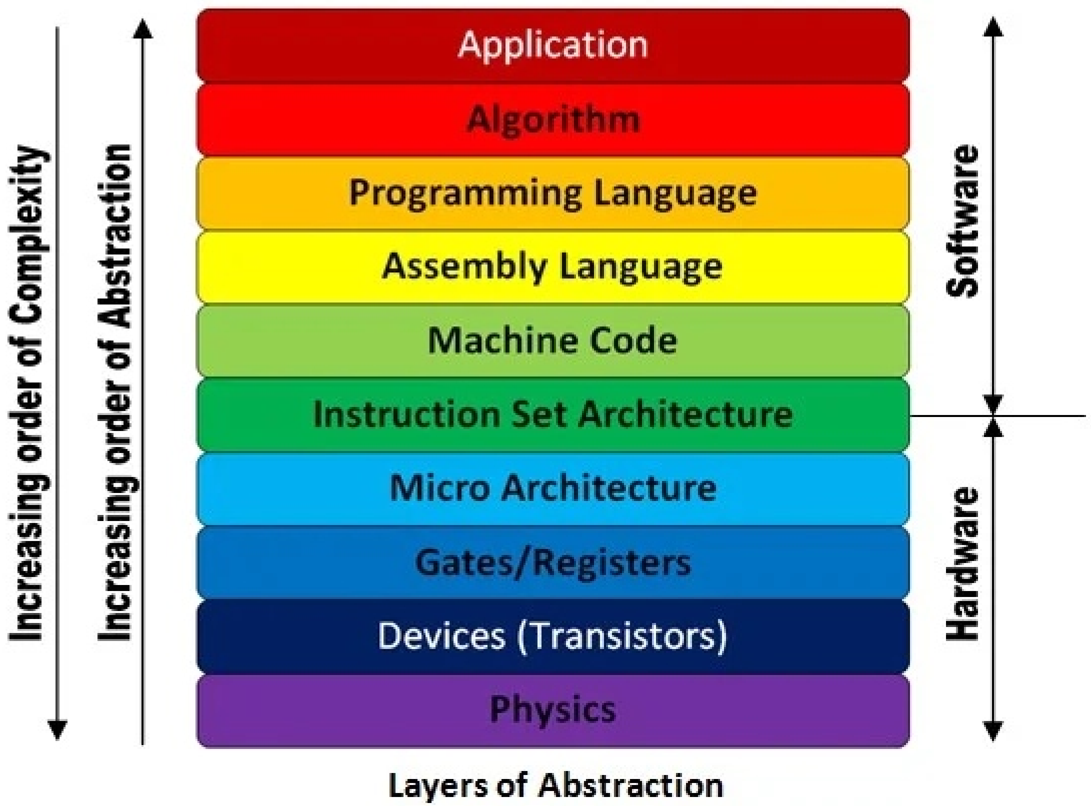
Report of the Office of Science Workshop on Basic Research Needs for Microelectronics, Oct 2018

- **A new paradigm is needed to advance computing:**
  - **Innovations in materials, devices & architectures driven by applications**



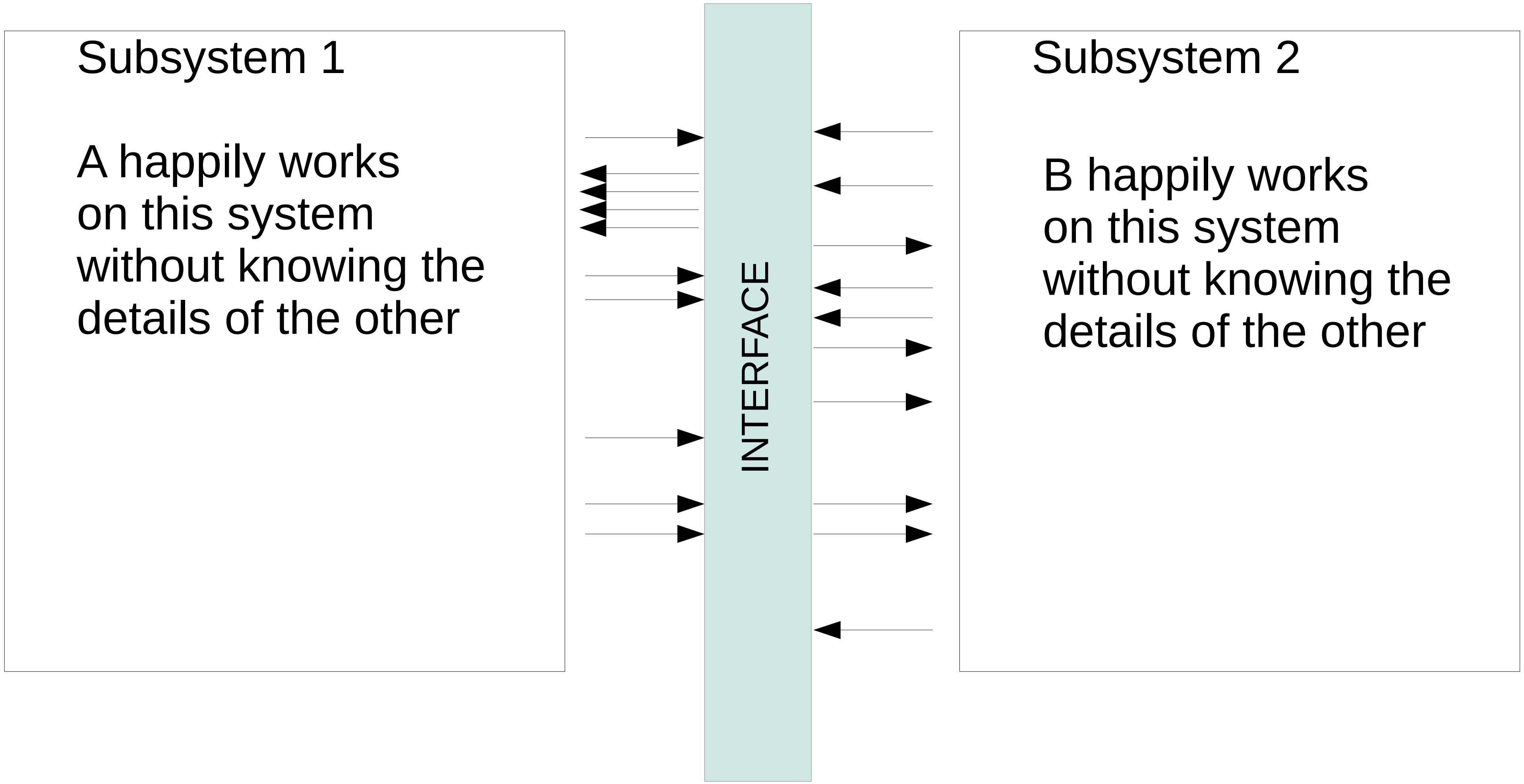
Co-design = the technology stack is suddenly the problem

How electronics are developed, made, and used.



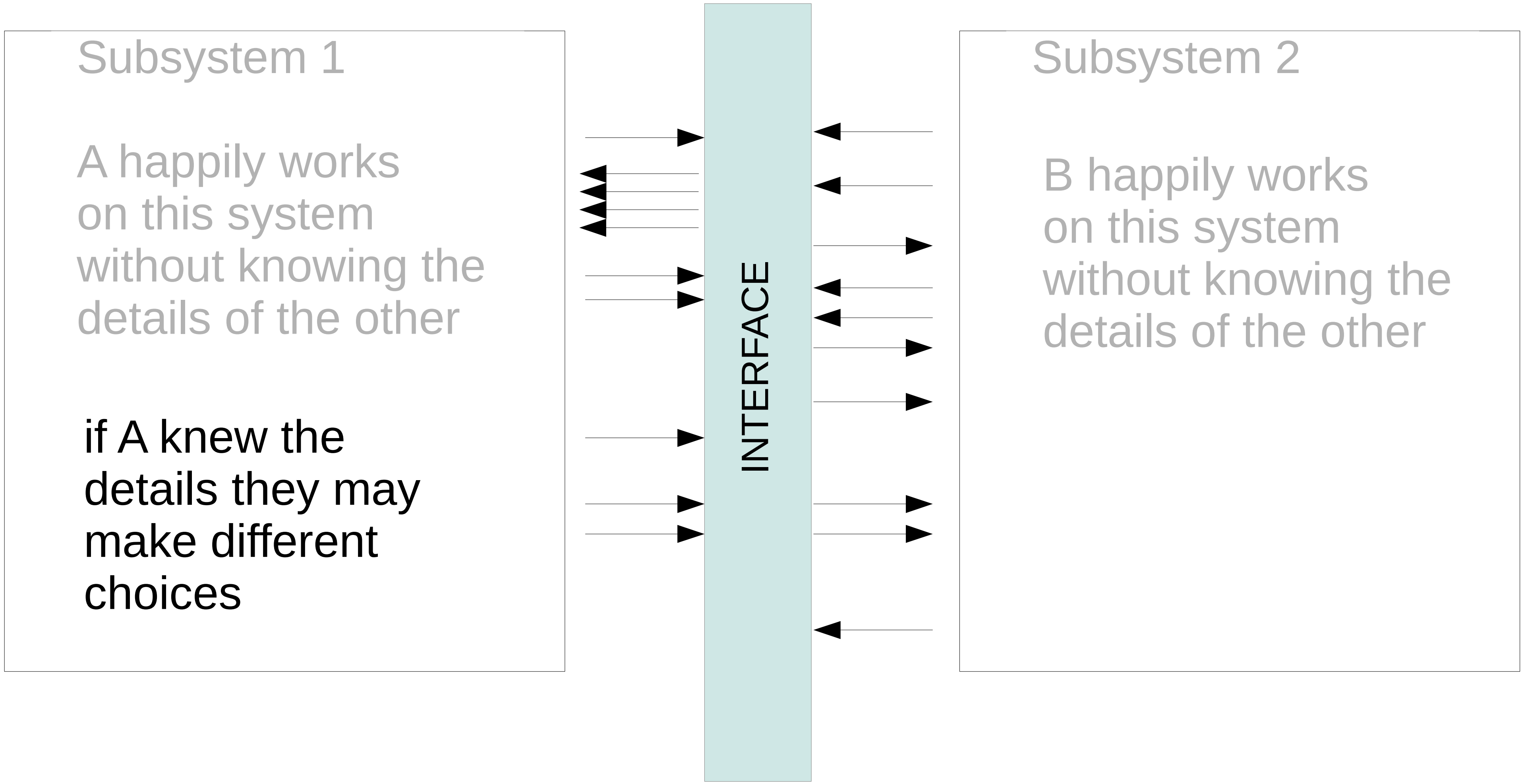
It combines independently optimized pieces instead of performing a global optimization
And that misses opportunities for increased performance

Systems and Interfaces



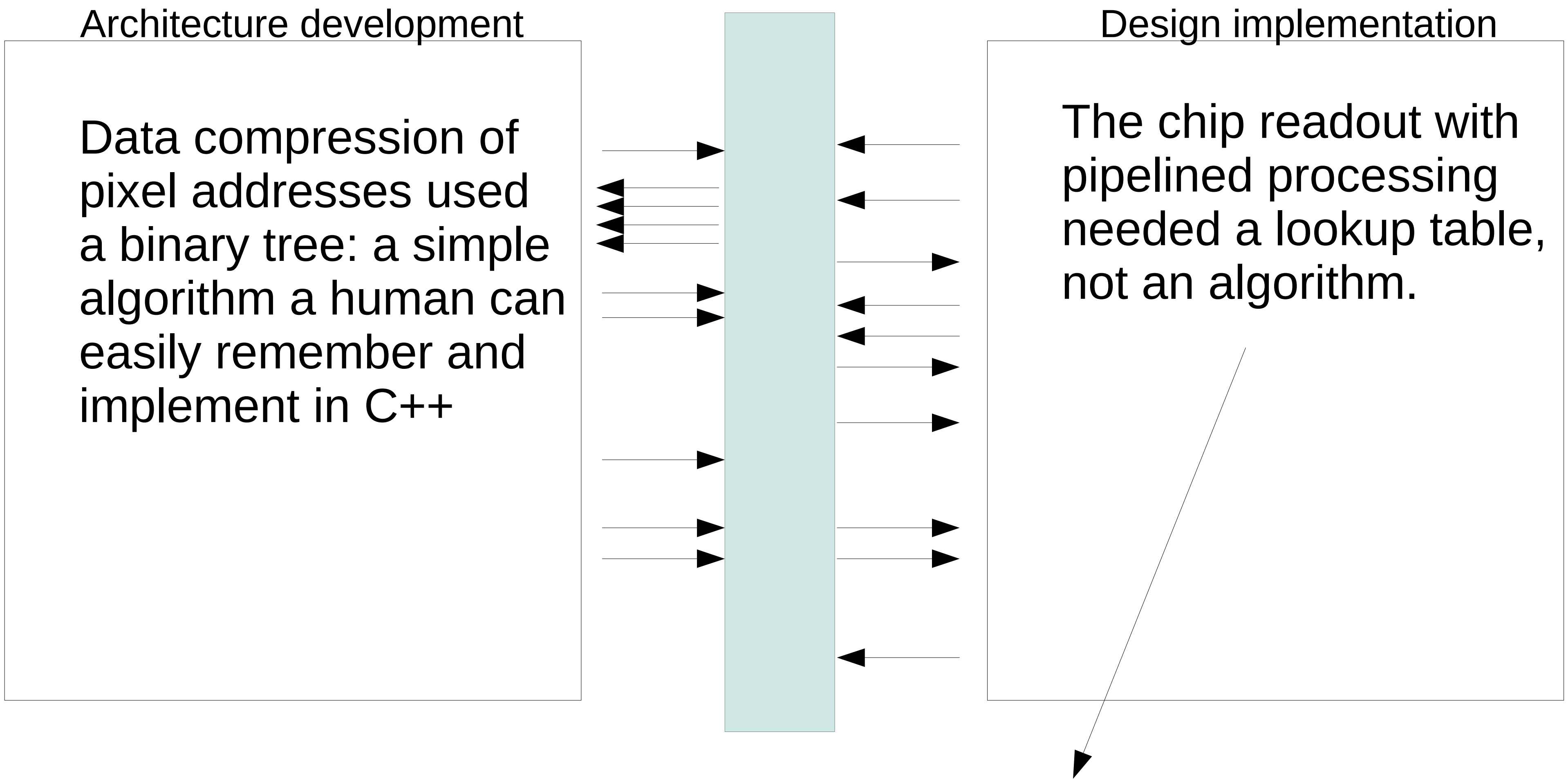
The interface ensures 1 and 2 will work together
BY IMPOSING CONSTRAINTS

CoDesign and Interfaces



The interface ensures 1 and 2 will work together
BY IMPOSING CONSTRAINTS

A HEP example from the RD53 chip



Given the information that address compression is implemented with a lookup table,
A more efficient compression than the binary tree encoding can be found in an afternoon.
But by then we were stuck with the binary tree codes.

Image sensor pixel size example

Wikipedia
The Free Encyclopedia

Search Wikipedia | Search

Diffraction-limited system

Optics Express Vol. 18, Issue 6, pp. 5861-5872 (2010) • https://doi.org/10.1364/OE.18.005861

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Microlens performance limits in sub-2µm pixel CMOS image sensors

Yijie Huo, Christian C. Fesenmaier, and Peter B. Catrysse

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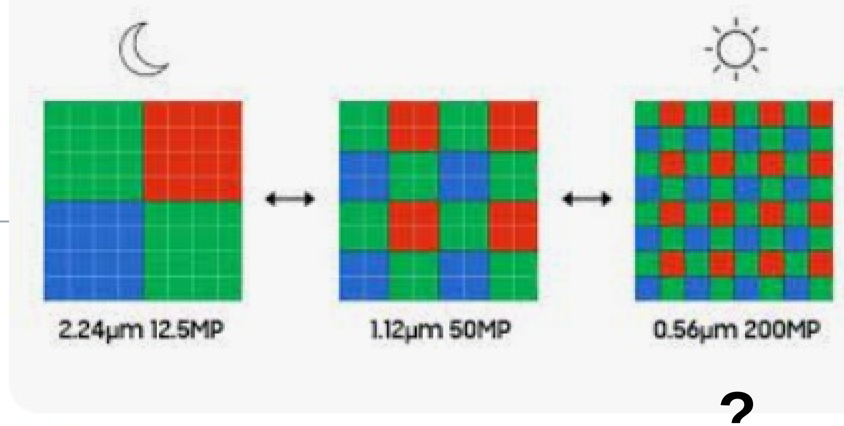
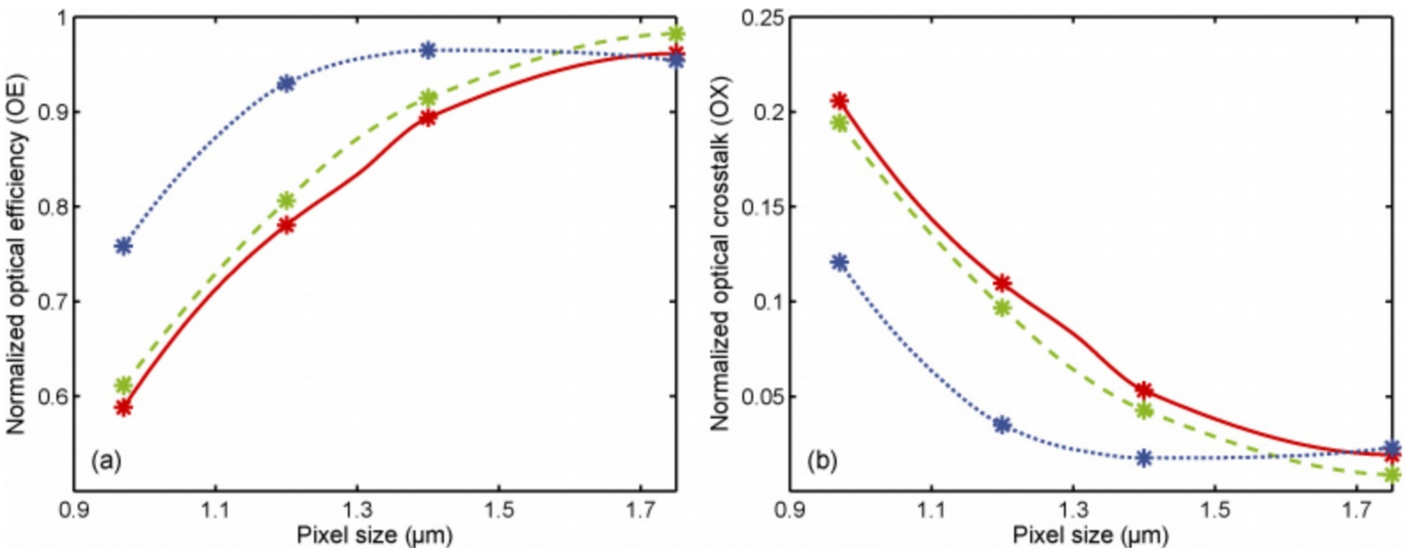


?

Samsung Semiconductor
ISOCELL HP3 | Mobile Image Sensor ...



Diffraction Limit determines minimum useful pixel size. End of story?

What if you model the sensor and incident light as one single system?

- (co-design approach)
- Photon absorption is a quantum process.
- Have to consider Hamiltonian of photon field and detector material

Calculation results in a new detector type

https://doi.org/10.1038/s42005-023-01193-1

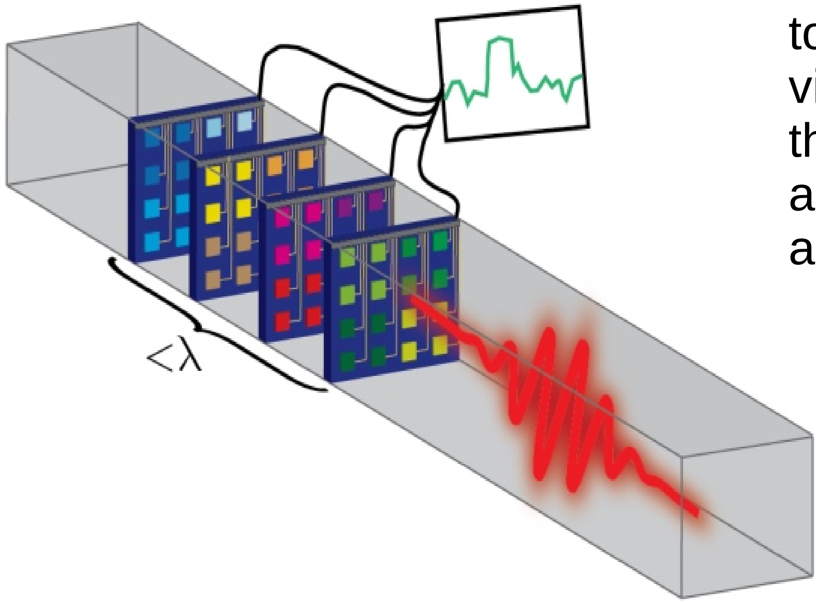
Nanoscale Architecture for Frequency-Resolving Single-Photon Detectors

Steve M. Young, Mohan Sarovar, and François Léonard*

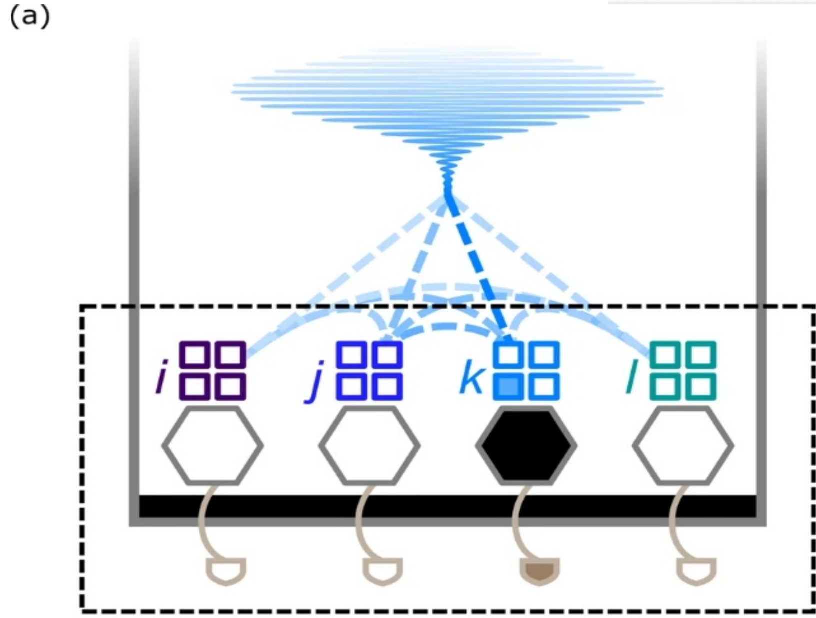
Sandia National Laboratories, Livermore, CA, 94551, USA

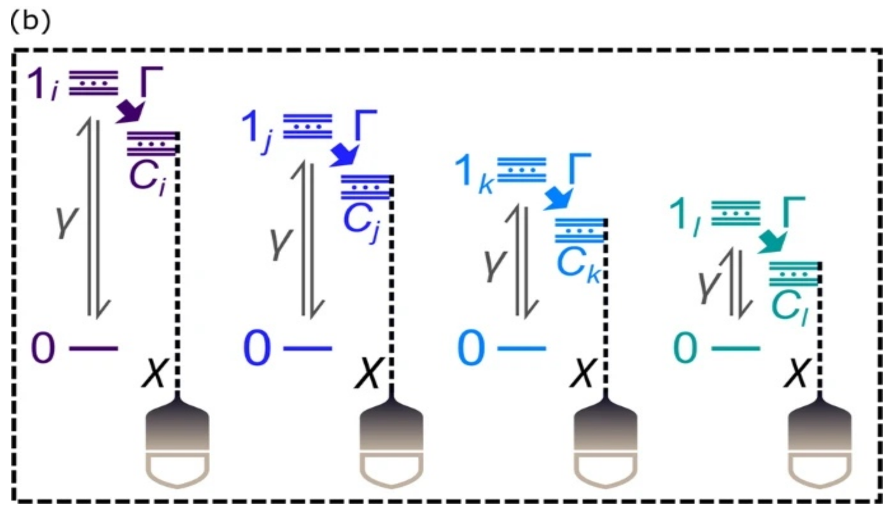
May 2022

concept



Readout analogous to qubit readout, via shelving states that prevent back action on photon absorption states

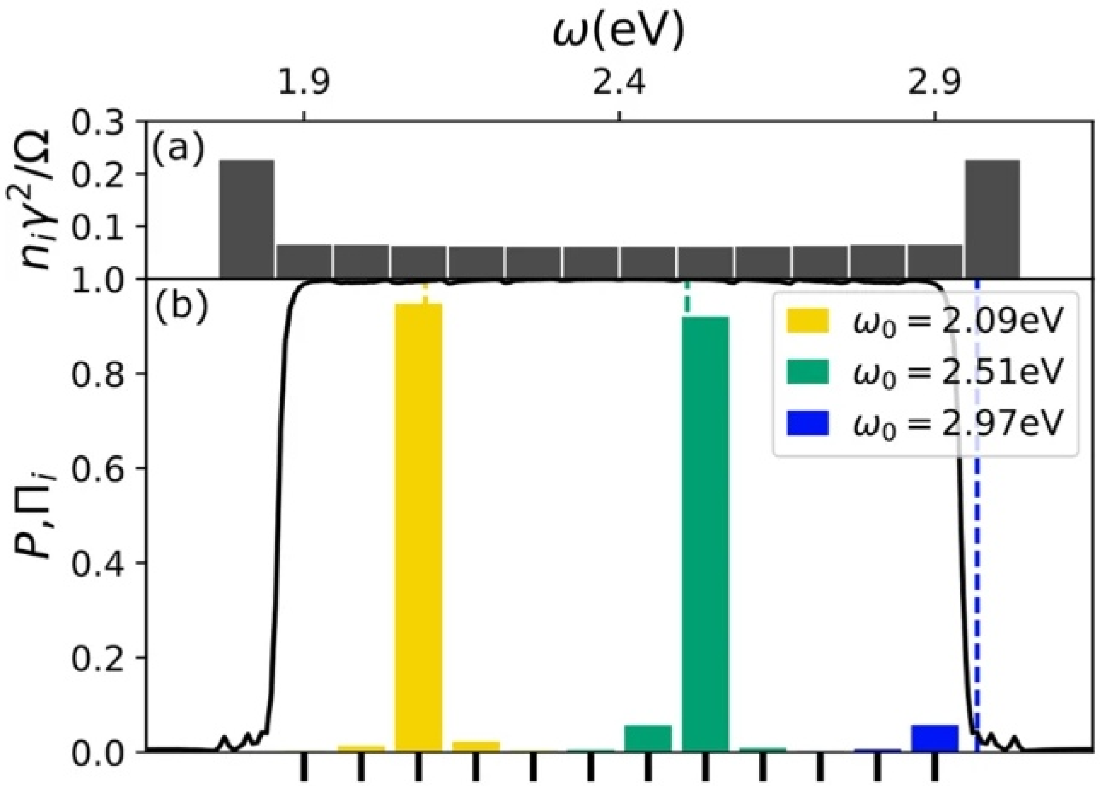




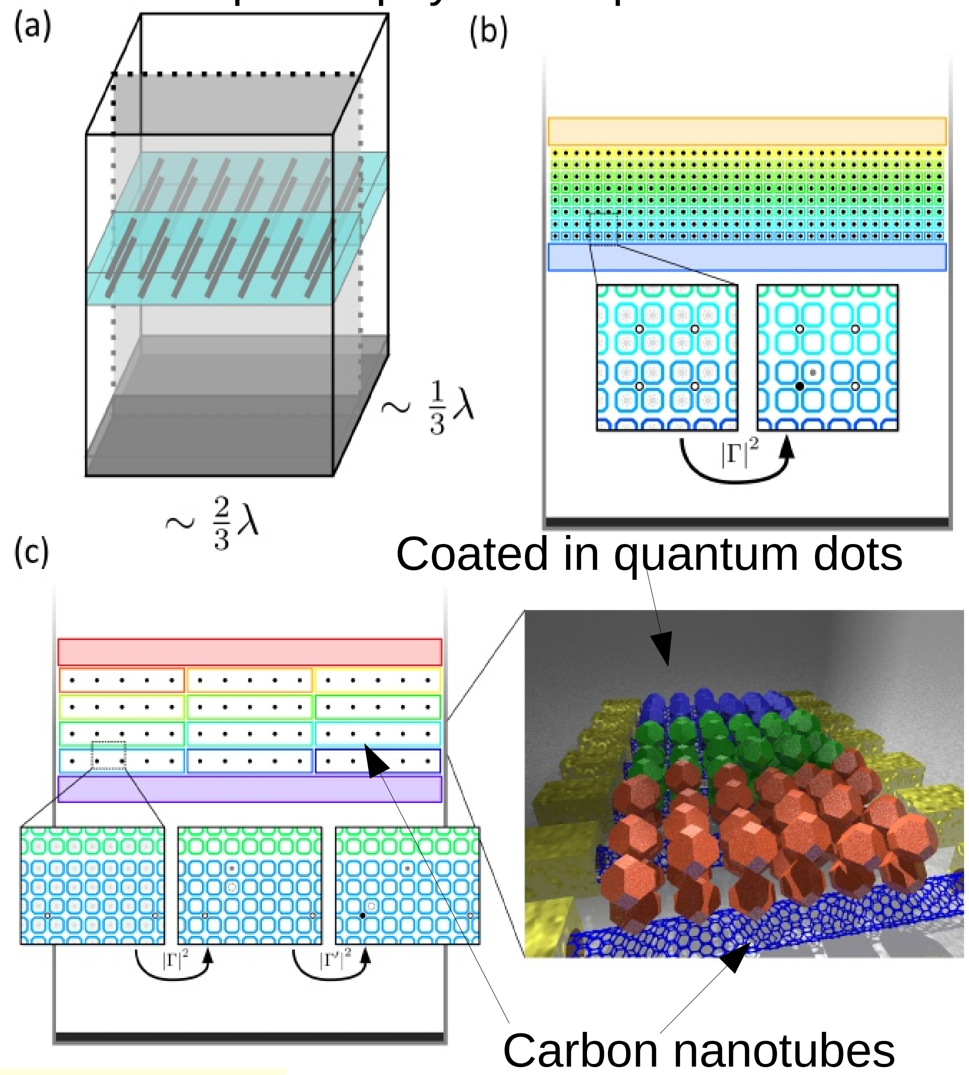
Does not need to be super cold

With 100% QE and spectrally resolved single photon sensitivity

Modeling quantum efficiency and spectral resolution

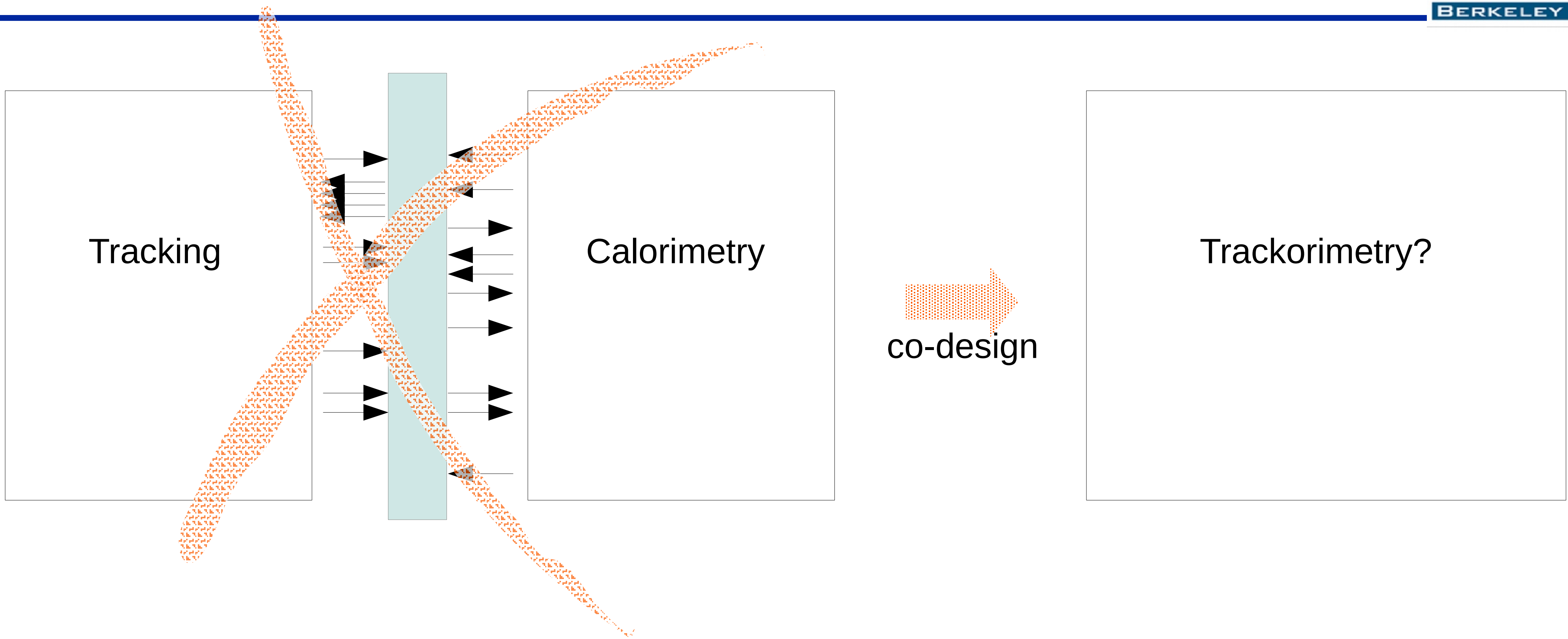


Proposed physical implementation



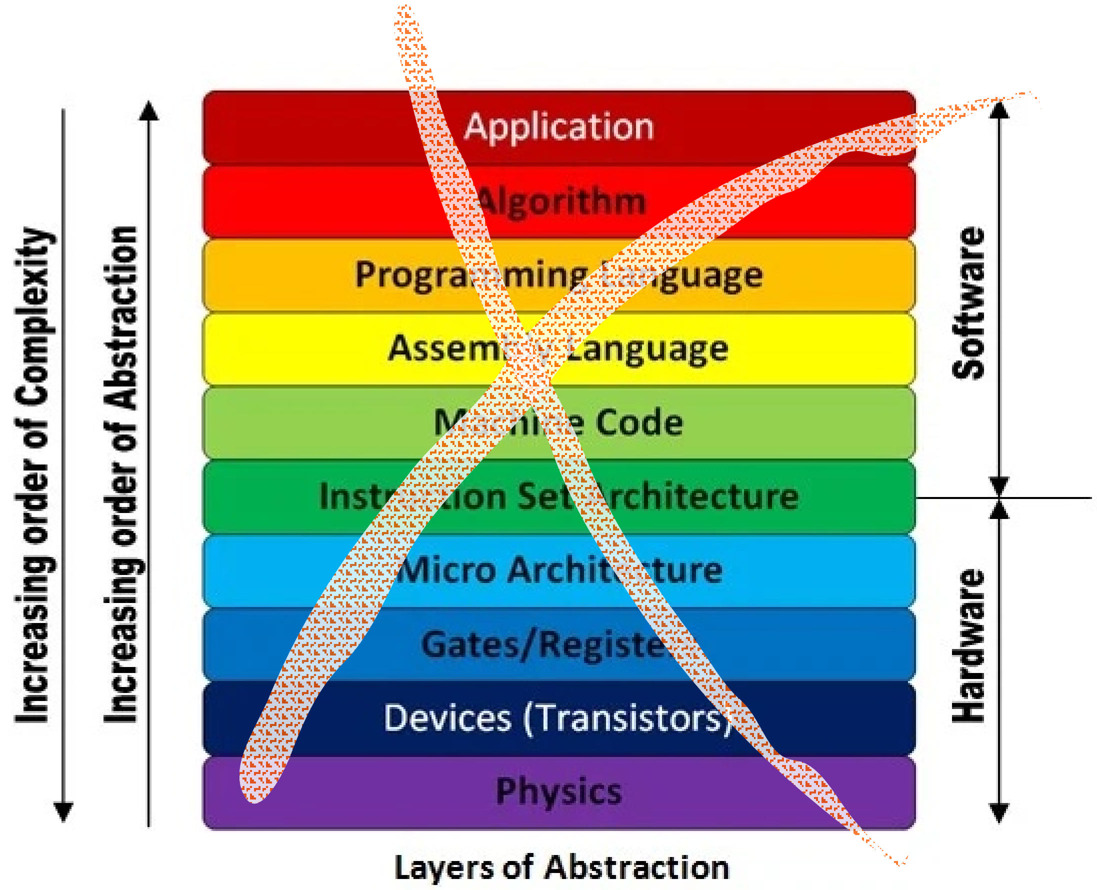
Ongoing project: details beyond scope of this talk

Back to the standard FC detectors talk



Already dE/dX is calorimetry with a tracker, and particle flow is tracking with a calorimeter,
But what opportunities are being missed with separate groups developing separate subdetectors?

Ultimate co-design



Unlikely that one person can know all the details of the full technology stack,
Or of the detector + collider + analysis stack

System Interfaces were invented to allow humans to work complex designs

...But why does it have to be humans any more?
Generative AI can learn all the details and maybe identify the co-design opportunities
This is not currently part of our design process

What will you do with new technology?

- Generative AI has already arrived
- Many others are just around the corner
  - Room temperature superconductivity
    (remember LK99? One of those sensational media frenzy items.
    The limelight moved away, but LK99 and R.T.S. development are not dead)
  - Ultra low power electronics
  - Photonic computing
  - Metamaterial coatings
  - Precision, wafer-scale self-assembly
  - …
- POLL:
  Which new technology (above ones or others) will have the greatest impact on future detectors?

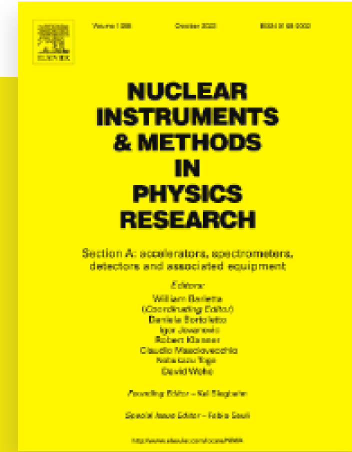
https://wall.sli.do/event/4tXP5F8RPMAarzUoCfMfCx?section=ba952af7-e655-43f8-b31c-0a5022720aac

Conclusion

- A lot of work already done on future collider detector designs
- Mostly assuming present technology and design methods
- (example ILC designs predate ALICE ITS3 development and are already obsolete compared to ITS3 R&D)
- Technology and design methods WILL CHANGE A LOT between now and detector construction
- Maybe dream about what a physically limited detector can do rather than a technology limited one...

- PS: very high precision measurements may require something incompatible with a general purpose detector.

Fairly new reference material



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Microelectronics in High Energy Physics

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Particle physics experiments: From photography to integrated circuits

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Front-end electronics for silicon strip trackers: Architectures and evolution

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Hybrid pixel readout integrated circuits

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Monolithic CMOS Sensors for high energy physics — Challenges and perspectives

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ASIC survival in the radiation environment of the LHC experiments: 30 years of struggle and still tantalizing

Federico Faccio

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Radiation tolerant optoelectronics for high energy physics

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ASICs for LHC intermediate tracking detectors

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[b] *Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, CA 95064, USA*

Cryogenic electronics for noble liquid neutrino detectors

Hucheng Chen *, Veljko Radeka

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Analog-to-digital converters and time-to-digital converters for high-energy physics experiments

Ping Gui

Southern Methodist University, Dallas, TX, USA

Radiation-hard ASICs for data transmission and clock distribution in High Energy Physics

Paulo Moreira *, Szymon Kulis

CERN, European Center for Nuclear Research, Switzerland

BACKUP

FCC-ee Precision EW

Alain Blondel[1], Patrick Janot[2]: FCC-ee overview: new opportunities create new challenges 7

Table 3. Measurement of selected precision measurements at FCC-ee, compared with present precision. The systematic uncertainties are initial estimates, aim is to improve down to statistical errors. This set of measurements, together with those of the Higgs properties, achieves indirect sensitivity to new physics up to a scale Λ of 70 TeV in a description with dim 6 operators, and possibly much higher in specific new physics (non-decoupling) models.

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)$ ($\times 10^3$)	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z ($\times 10^3$)	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ ($\times 10^4$)	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
σ_{had}^0 ($\times 10^3$) (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
N_ν ($\times 10^3$)	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b ($\times 10^6$)	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^b, 0$ ($\times 10^4$)	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic ($\mu\nu_\mu\nu_\tau$) B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

= where systematics are not dominated by beam energy or luminosity

Or theory

Blondel and Janot
arXiv:2106:13885v2 Dec 2021

Slide from C. Haber at MIT FCC-ee workshop this week

FCC-ee Precision EW

Observable	Best Present value	Source	FCC-ee Stat	FCC-ee Syst*	Leading error*	NLE
R_ℓ^Z (x 10^3)	20725 +/-33 +/-20 +/-5	ALEPH	0.06	0.2-1	Acceptance for leptons	
R_b (x 10^6)	216340 +/-670 +/-600	DELPHI	0.3	<60	B tag efficiency?	
A_{FB}^b (x 10^4)	1000 +/-27 +/- 11	ALEPH	0.02	1-3	Jet charge	
τ Lifetime (fs)	290.17 +/-0.53 +/-0.33	Belle	0.001	0.04	Radial alignment	Asymmetry
τ mass (MeV)	1776.91 +/- 0.12 $^{+0.10}_{-0.13}$	BES	0.004	0.04	Momentum scale	
τ leptonic ($\mu\nu_\mu\nu_\tau$) B.R. (%)	17.319 +/- 0.070 +/-0.032	ALEPH	0.0001	0.003	e/μ/h separation**	Bkg, τ-selection**

*From Blondel and Janot

- Standard statistical error improves by a factor of ~500
- They assume less than scaling by statistics

➢ Changed present values from PDG averages to best single value to see also statistical and systematic errors

➢ Also, to understand how to improve systematics, it seems best to focus on the best single experiment, and try to understand what systematics they faced

➢ ** all ID's are equal at ~0.02 contribution to sys error

Slide from C. Haber at MIT FCC-ee workshop this week

FCC-ee Precision EW

Theory systematics

Observables	Present value	FCC-ee stat.	FCC-ee current syst.	FCC-ee ultimate syst.	Theory input (not exhaustive)
m_Z (keV)	91187500 ± 2100	4	100	10 ?	Lineshape QED unfolding Relation to measured quantities
Γ_Z (keV)	2495500 ± 2300 [*]	4	25	5 ?	Lineshape QED unfolding Relation to measured quantities
σ^0_{had} (pb)	41480.2 ± 32.5 [*]	0.04	4	0.8	Bhabha cross section to 0.01% $e^+e^- \to \gamma\gamma$ cross section to 0.002%
N_ν ($\times 10^3$) from σ_{had}	2996.3 ± 7.4	0.007	1	0.2	Lineshape QED unfolding $(\Gamma_{\nu\nu}/\Gamma_{\ell\ell})_{SM}$
R_ℓ ($\times 10^3$)	20766.6 ± 24.7	0.04	1	0.2 ?	Lepton angular distribution (QED ISR/FSR/IFI, EW corrections)
$\alpha_s(m_Z)$ ($\times 10^4$) from R_ℓ	1196 ± 30	0.1	1.5	0.4 ?	Higher order QCD corrections for Γ_{had}
R_b ($\times 10^6$)	216290 ± 660	0.3	?	< 60 ?	QCD (gluon radiation, gluon splitting, fragmentation, decays, …)

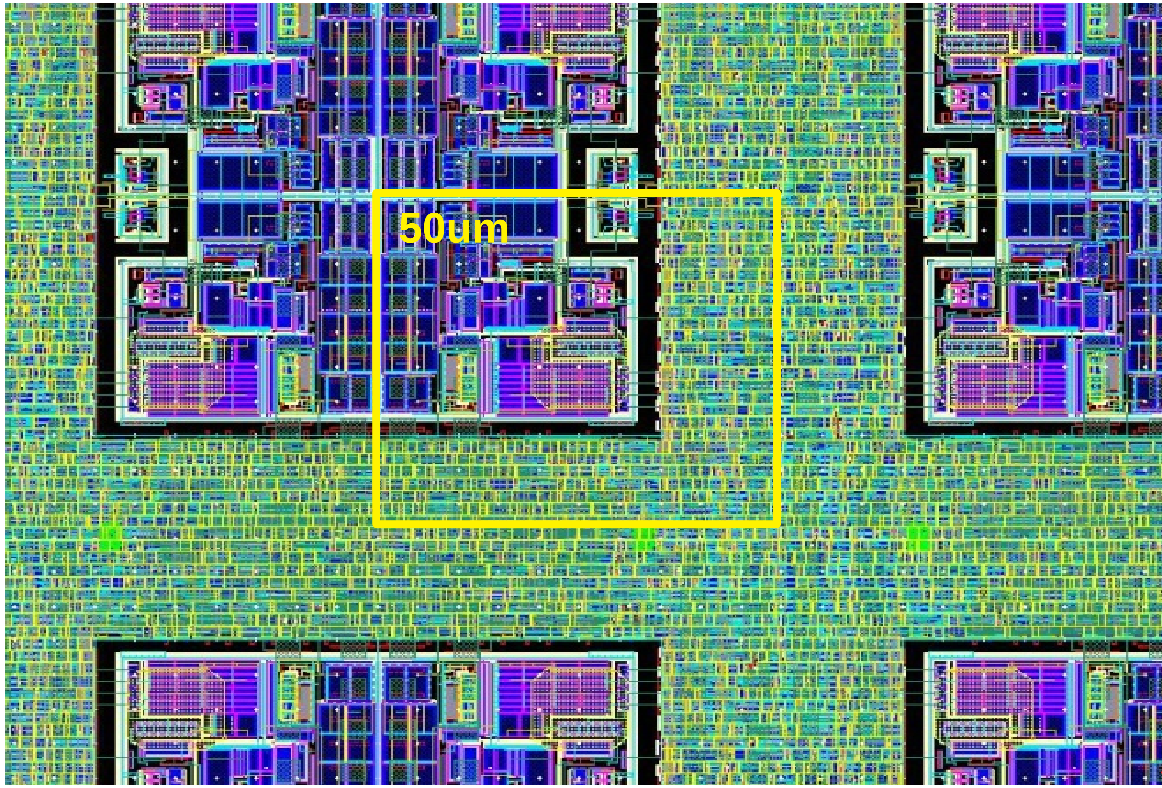
From: P.Janot talk at FCC theory workshop in June 2022

RD53 Hybrid Pixel Readout
100x higher rate and radiation

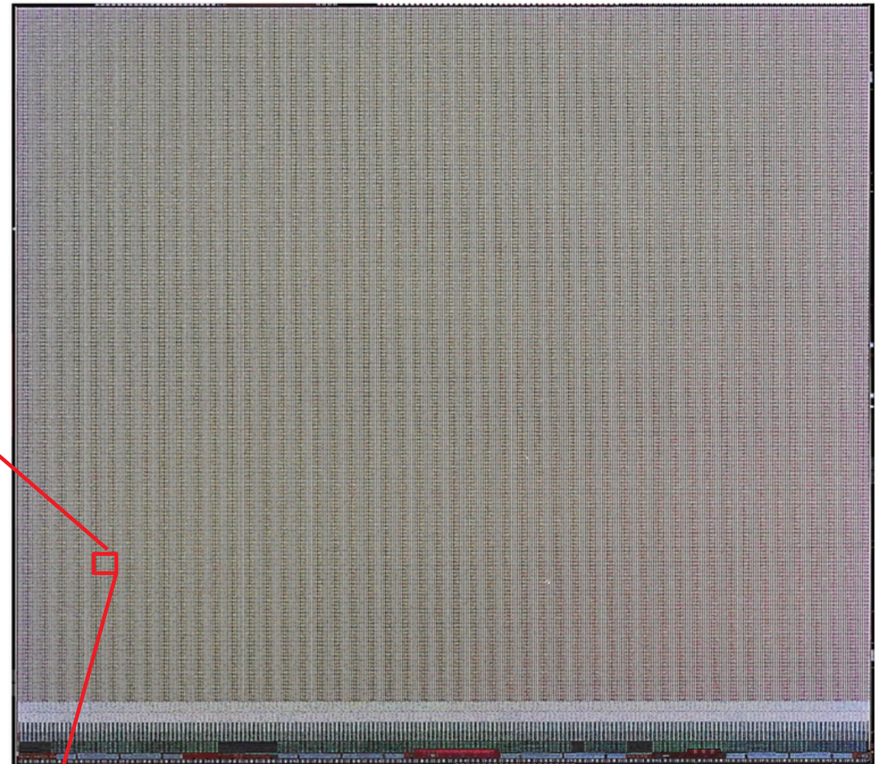
Cern.ch/rd53

RD-53 Collaboration Home

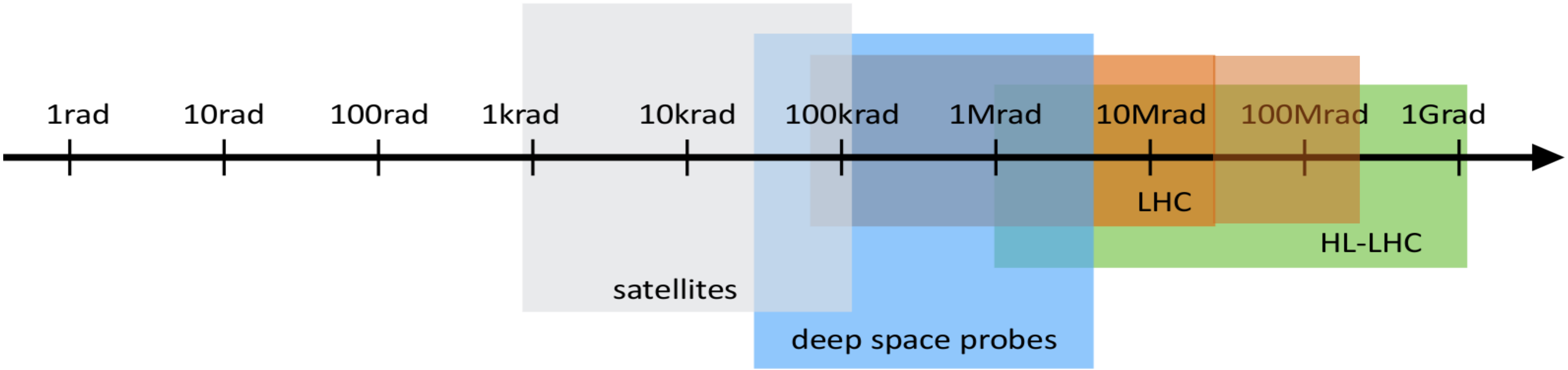
RD-53 will design and produce the next generation of readout chips for the ATLAS and CMS pixel detector upgrades at the HL-LHC. More details can be found in the 2018 extension proposal and the original collaboration proposal.



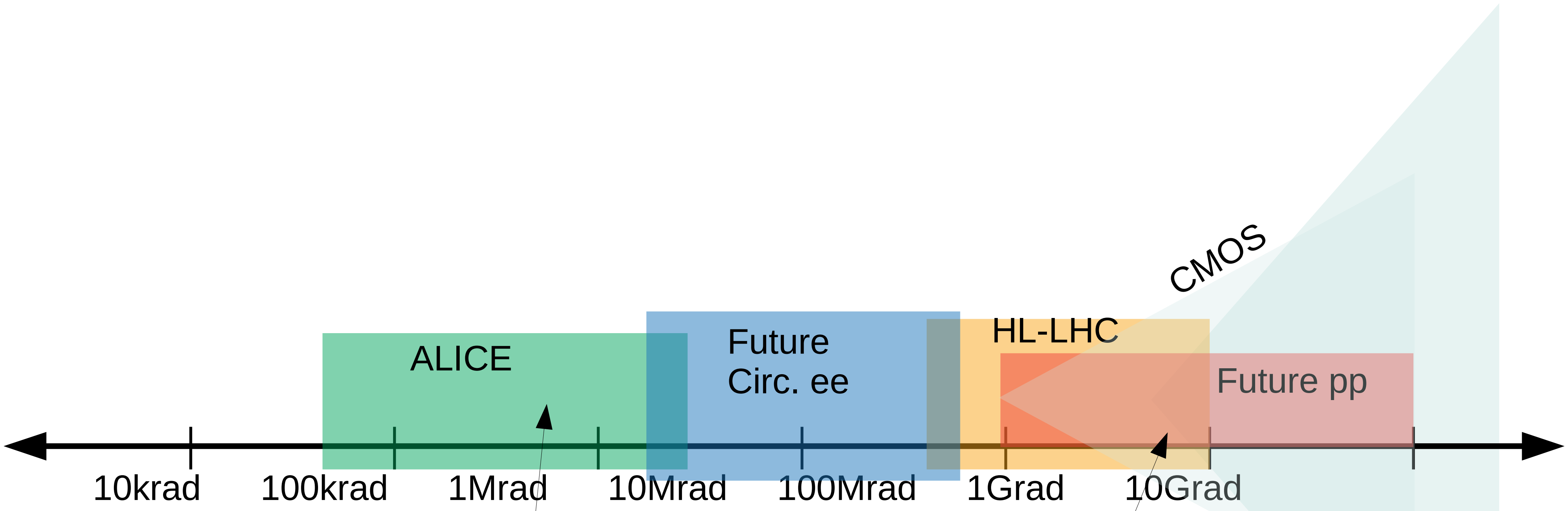
~1000 transistors



Radiation Environments

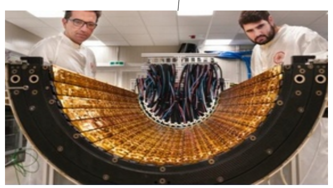


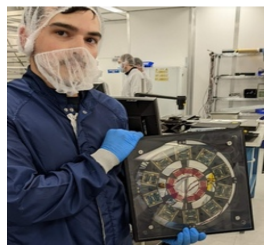
HEP IC Radiation Outlook



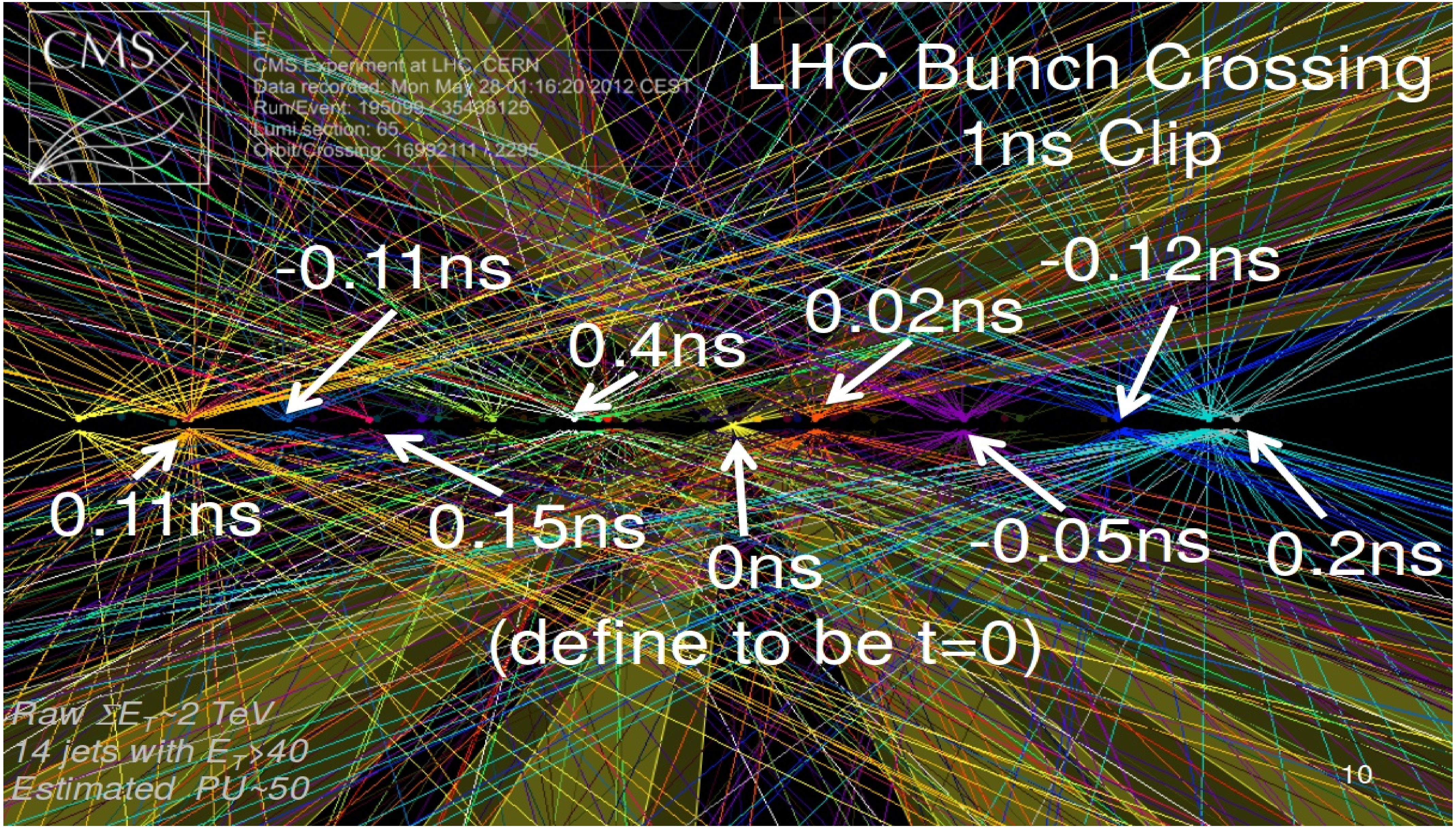
Inner Layer Dose

Temperature history
Process details
Dose rate
Dose history
Annealing
…





A future direction



8-Pixel address maps from full sim

L0 central most probable maps

Hitmap	Number of occurrences	Probability	Cumulative
10000000	112507	0.107	0.107
00000001	112021	0.106	0.213
11000000	72585	0.069	0.282
00000011	71430	0.068	0.350
00000010	41231	0.039	0.389
00001000	41206	0.039	0.428
00000100	41080	0.039	0.467
01000000	40968	0.039	0.506
00010000	39965	0.038	0.544
00100000	39806	0.038	0.581
00001100	39359	0.037	0.619
01100000	39054	0.037	0.656
00000110	39015	0.037	0.693
00011000	37448	0.036	0.728
00110000	37373	0.035	0.764
00000111	33691	0.032	0.796
11100000	33337	0.032	0.827
11110000	17193	0.016	0.844
00001111	17047	0.016	0.860
00001110	16714	0.016	0.876
00011100	16606	0.016	0.891
01110000	16420	0.016	0.907

Binary tree vs better lookup tables

Data Set	H (bits)	Bin. Tree (bits/map)	Huffman(L0) (bits/map)	3-6-14 (bits/map)
L0 central	4.69	5.83	4.71	5.13
L3 outer ring	4.17	5.12	4.47	5.00
L4 inner ring	4.29	5.27	4.50	5.03

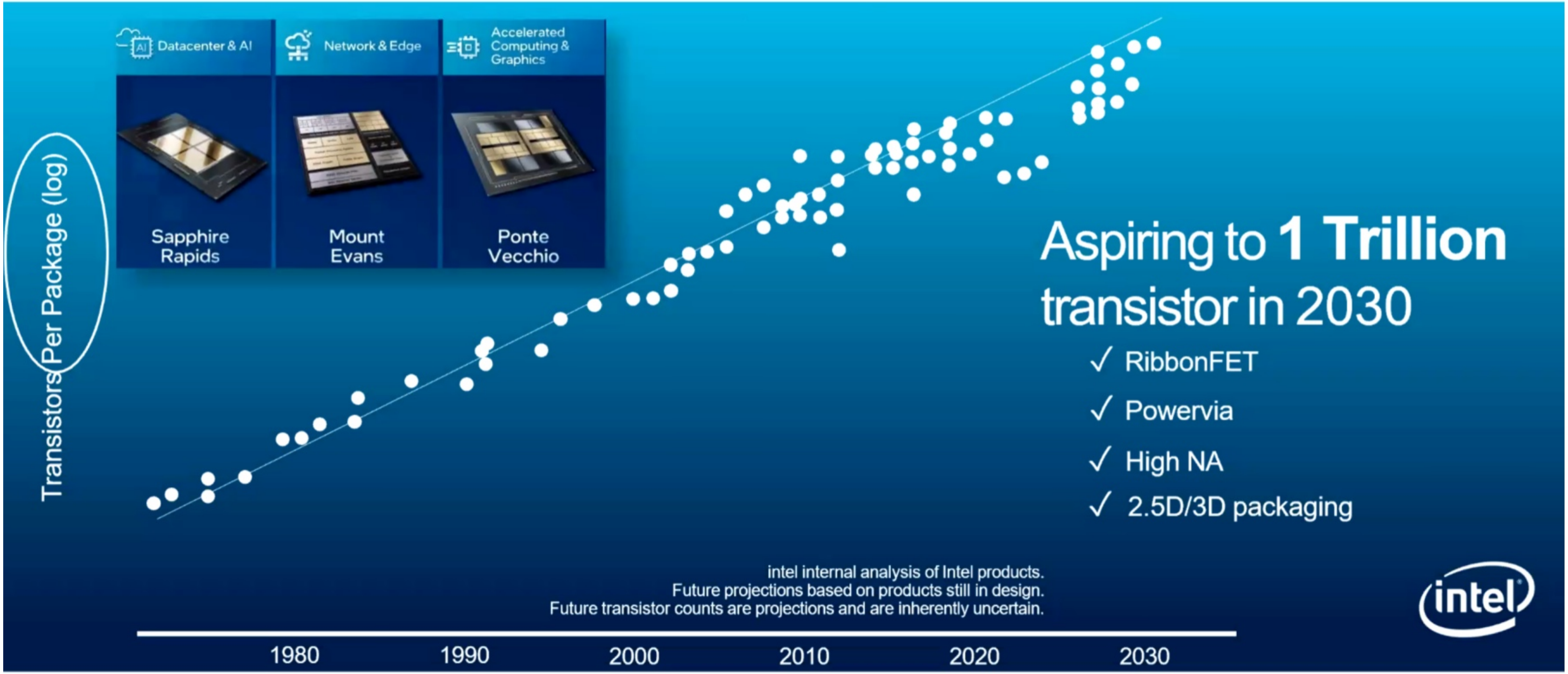
Data Set	H (bits)	Bin, Tree (/H)	Huffman(L0) (/H)	3-6-14 (/H)	
L0 central	4.69	1.24	1.01	1.10	12% missed opportunity
L3 outer ring	4.17	1.23	1.07	1.20	3% missed opportunity
L4 inner ring	4.29	1.23	1.05	1.17	5% missed opportunity

Huffman(L0): Not compatible with RD53 data flow

3-6-14: Just change the values on the LUT, Nothing else

Extending Moore's Law

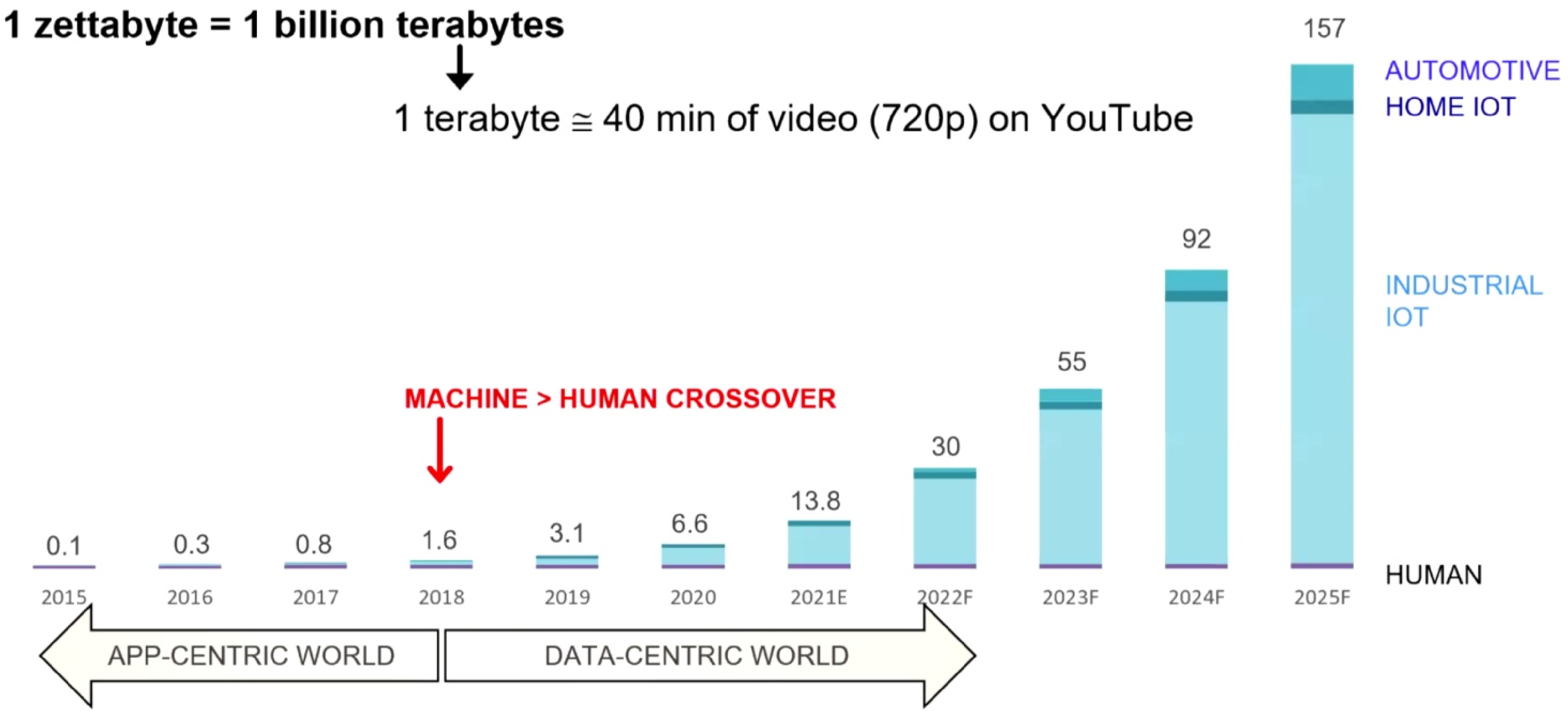
From 100 billion transistors today to 1 trillion transistors per package in 2030: 30% growth year on year



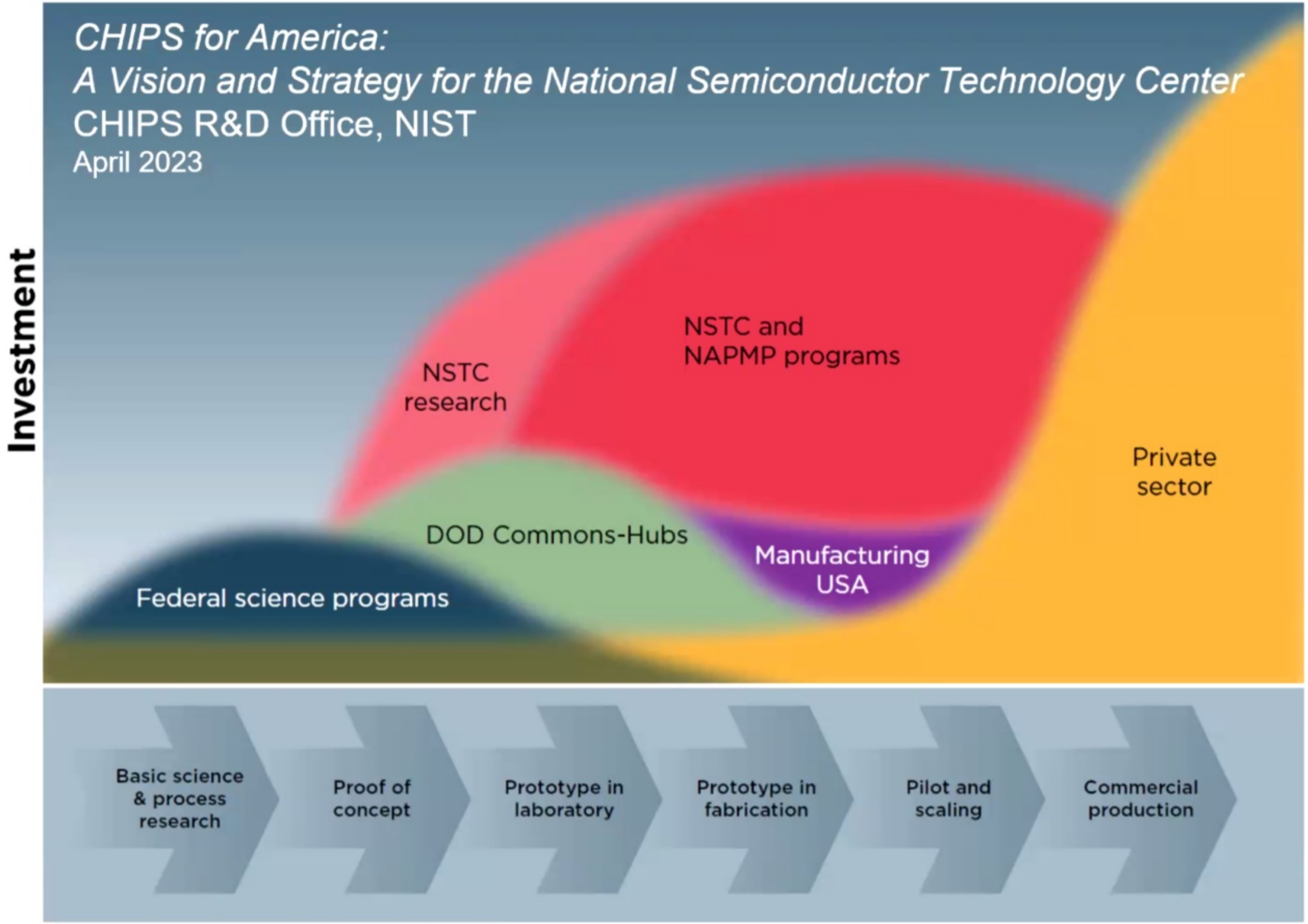
You haven't seen big data yet

Proliferation of Data (zettabytes)

Source: Om Nalamasu (Applied Materials), SEMI International Trade Partners Conference, November 2022



New tech development path

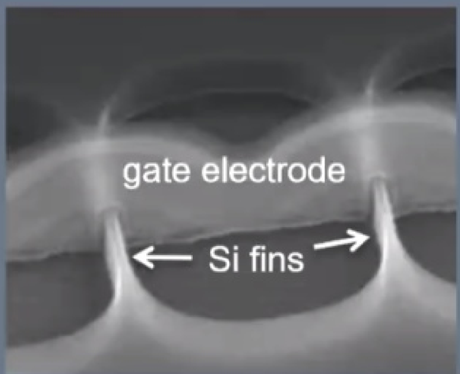


2022 State of the Art

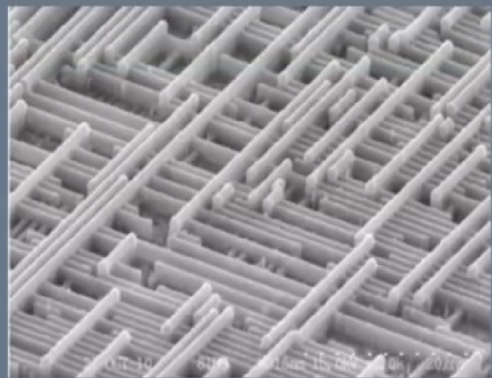
Semiconductor Manufacturing

Source: Om Nalamasu (Applied Materials), SEMI International Trade Partners Conference, November 2022

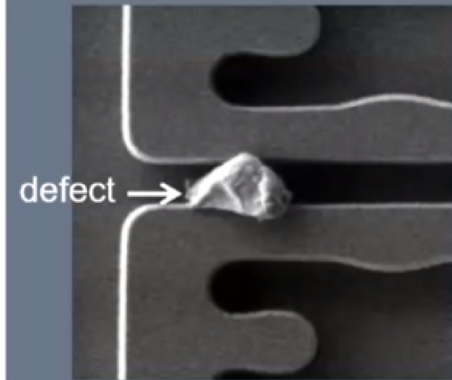
Manipulating materials with atomic precision on an industrial scale



Fin-shaped transistors with gate insulator layer formed by atomic layer deposition



20+ miles of nanoscale copper wiring in a little more than a half-inch square



Inspection equivalent to spotting a single ant from outer space, then identifying its species, in less than 1 sec

- **A leading-edge semiconductor fabrication plant (fab) costs ~$10B**
  - **300 mm wafers**
  - **>1000 process steps**
  - **100,000 wafers/month**