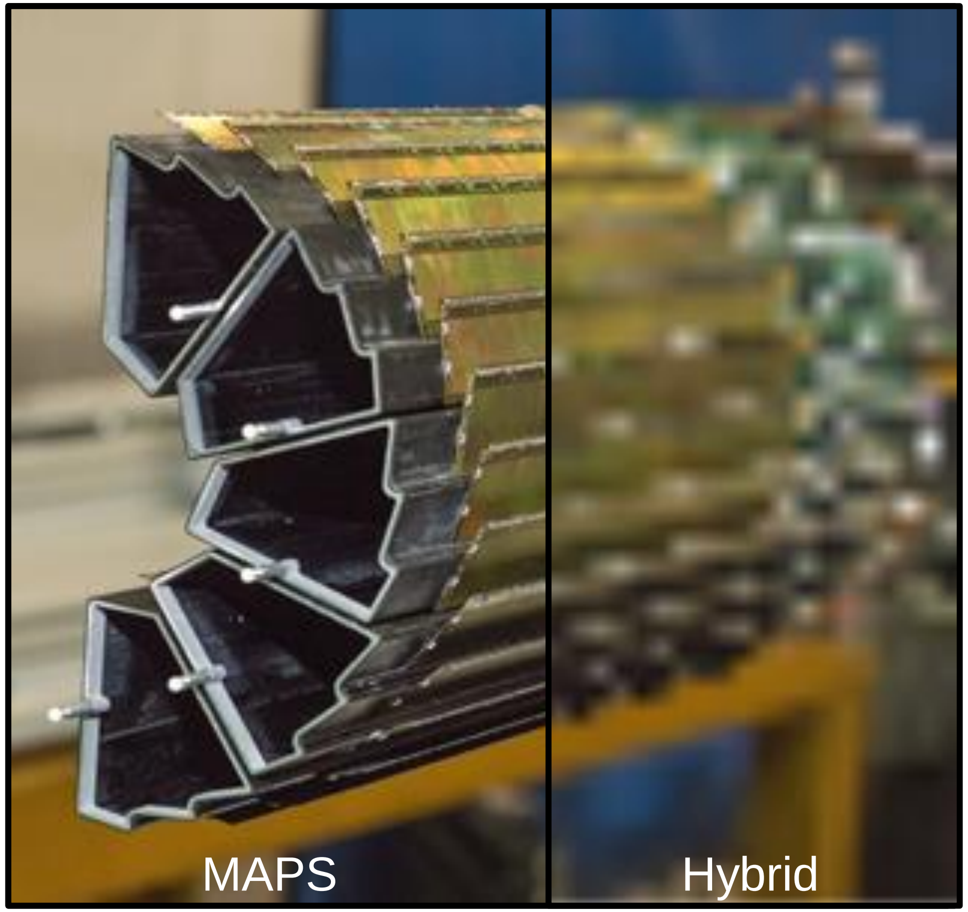
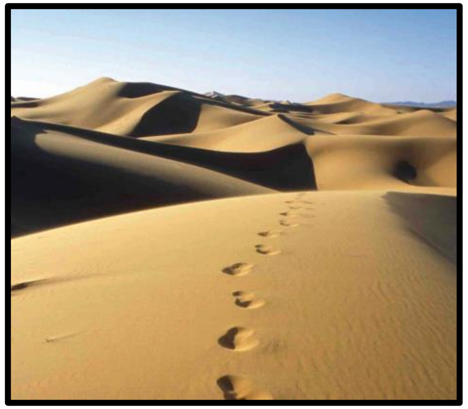
Silicon detectors IV

The rising of MAPS

M. Deveaux, GSI



Outline



+ ? =

1) Things you should know on silicon device production

2) CMOS Monolithic Active Pixel Sensors (MAPS)

   Why MAPS are cool.

   How not to collide the moon.

   The struggle for radiation tolerance.

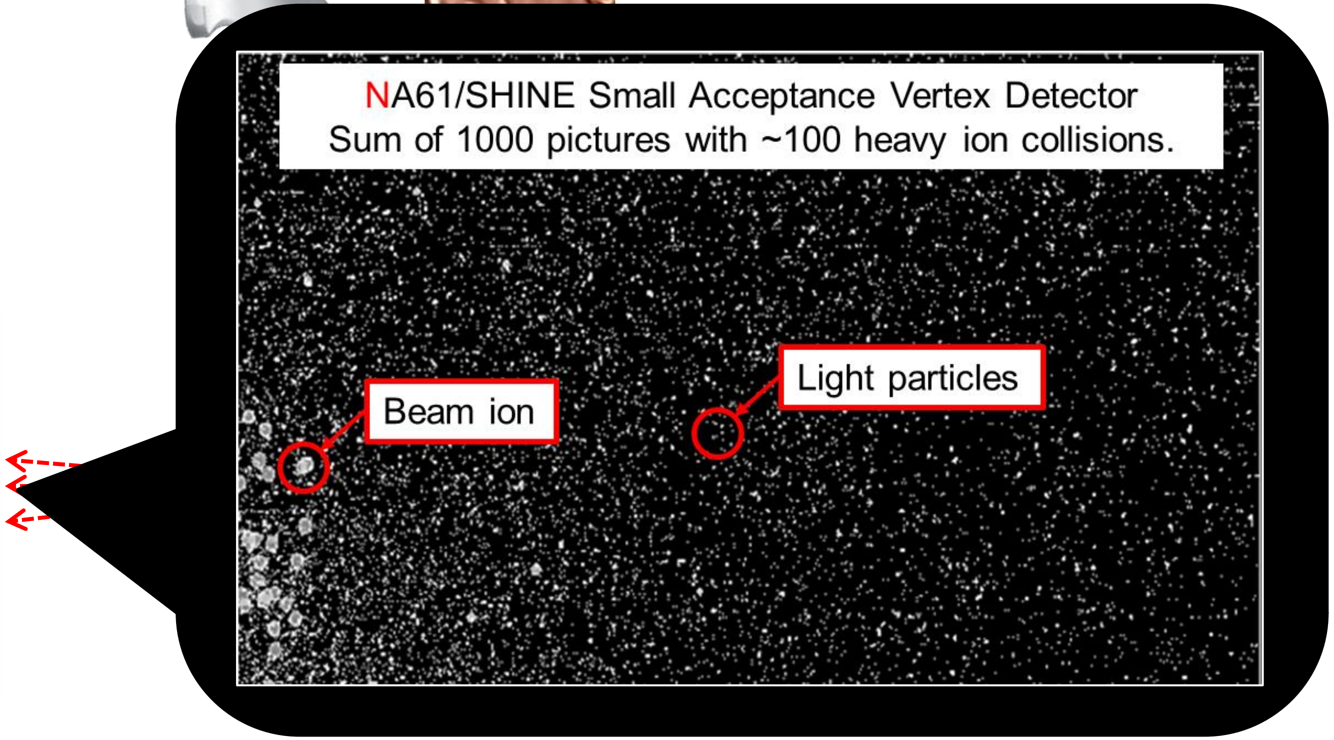
   One chip is not enough.

Reminder

What is required to build a particle detector?

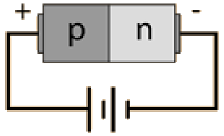
Mostly a hammer…

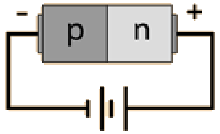
… a Webcam…



NA61/SHINE Small Acceptance Vertex Detector
Sum of 1000 pictures with ~100 heavy ion collisions.

Some equations





Width of the depleted zone:

$$w = \sqrt{\frac{2\epsilon_0\epsilon_r}{e}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)U_{ext}}$$

Break down voltage:

$$U_{max} = -\frac{1}{2}\frac{\epsilon_0\epsilon_r}{e}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)E^2_{max}$$

Capacity of the diode:

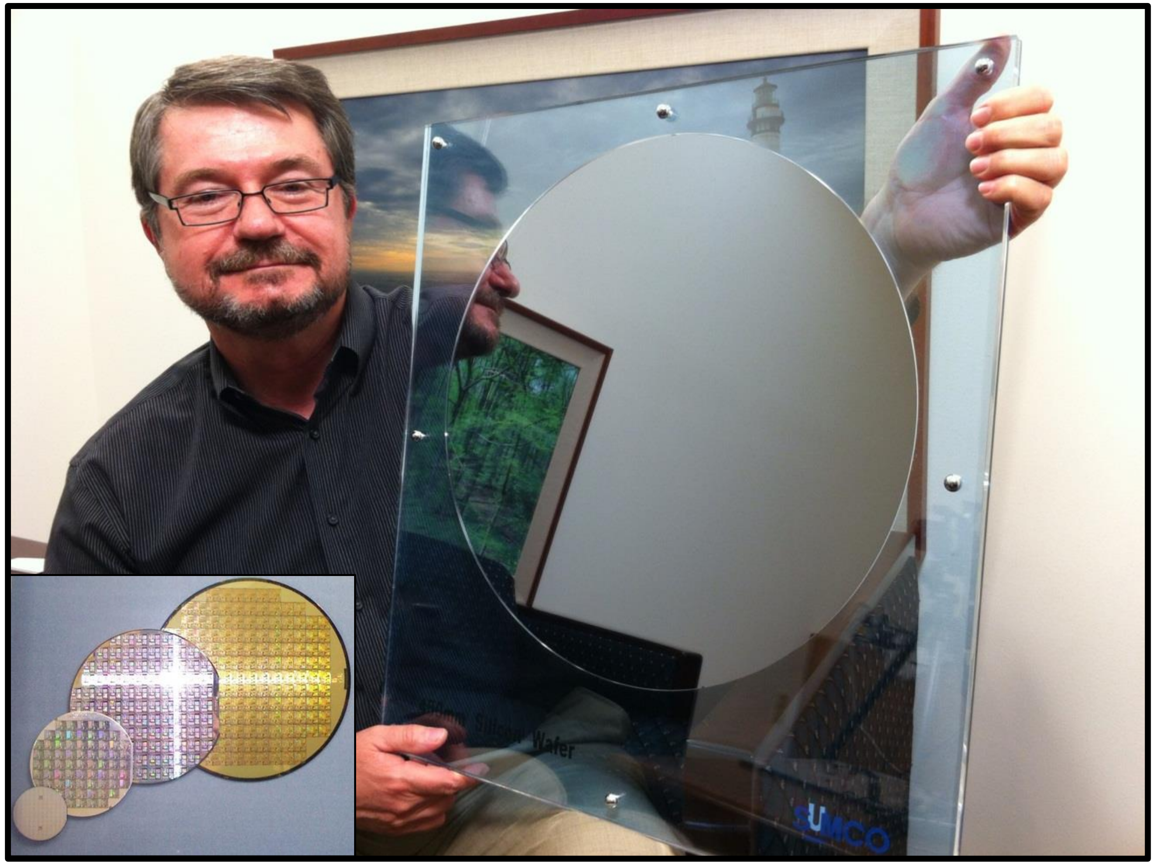
$$C = A \cdot \frac{\epsilon_0\epsilon_r}{w}$$

What doping do I use for cool detectors with cool integrated electronics?

Low doping: Cool detectors.
High doping: Cool electronics.

How to build silicon devices: Wafers

Black magic



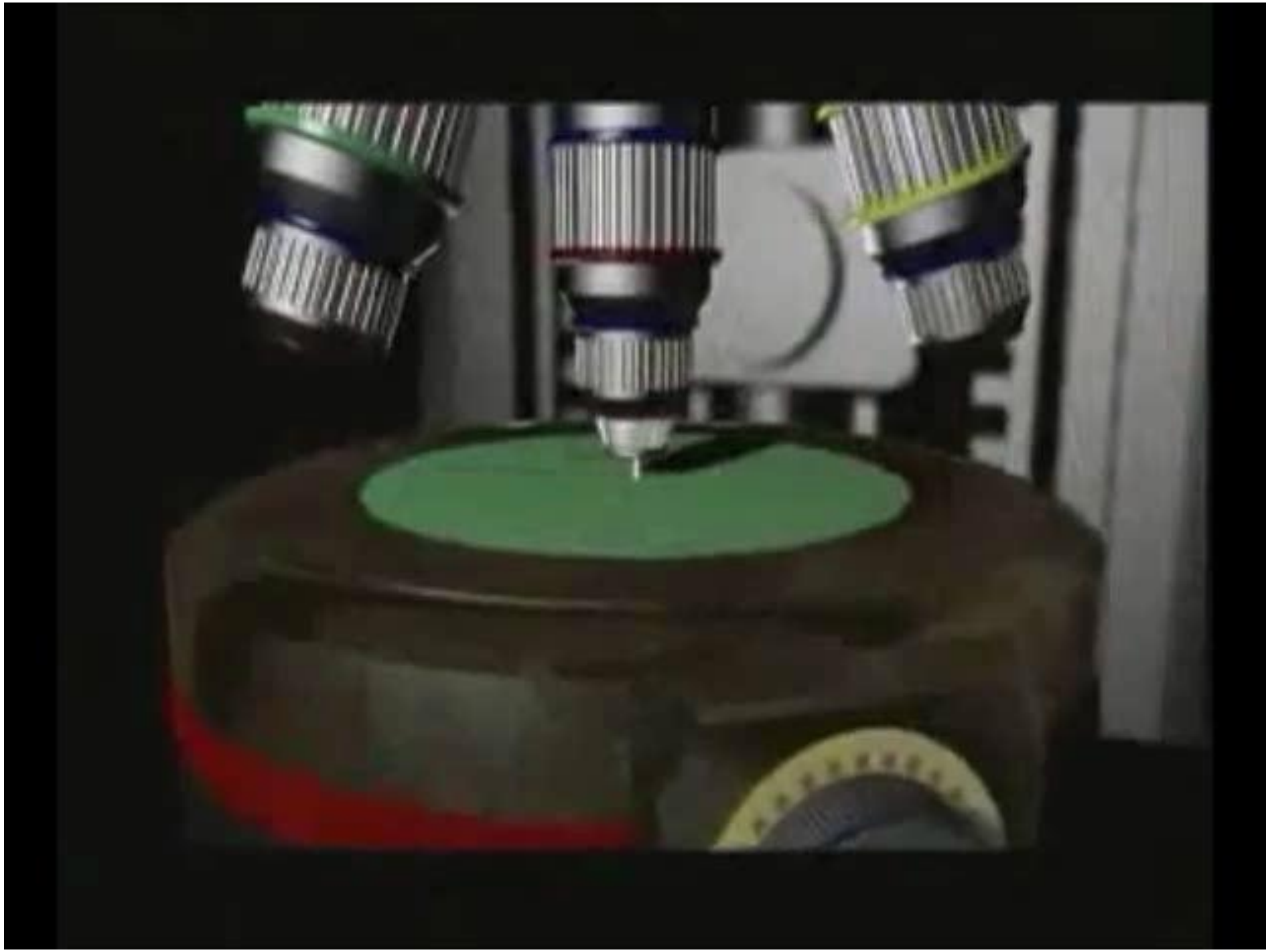
Silicon is melted into high purity mono-crystals.

- Purity = cost
- Remaining inpurities are controlled by doping.

⇒ All wafers are doped.
⇒ Low doing wafers are expensive.
⇒ Expensive stuff is rare industry (thus you don‘t get what you want).

Wafers exist in very different sizes, size matters.

Epitaxial layer



Words you should know

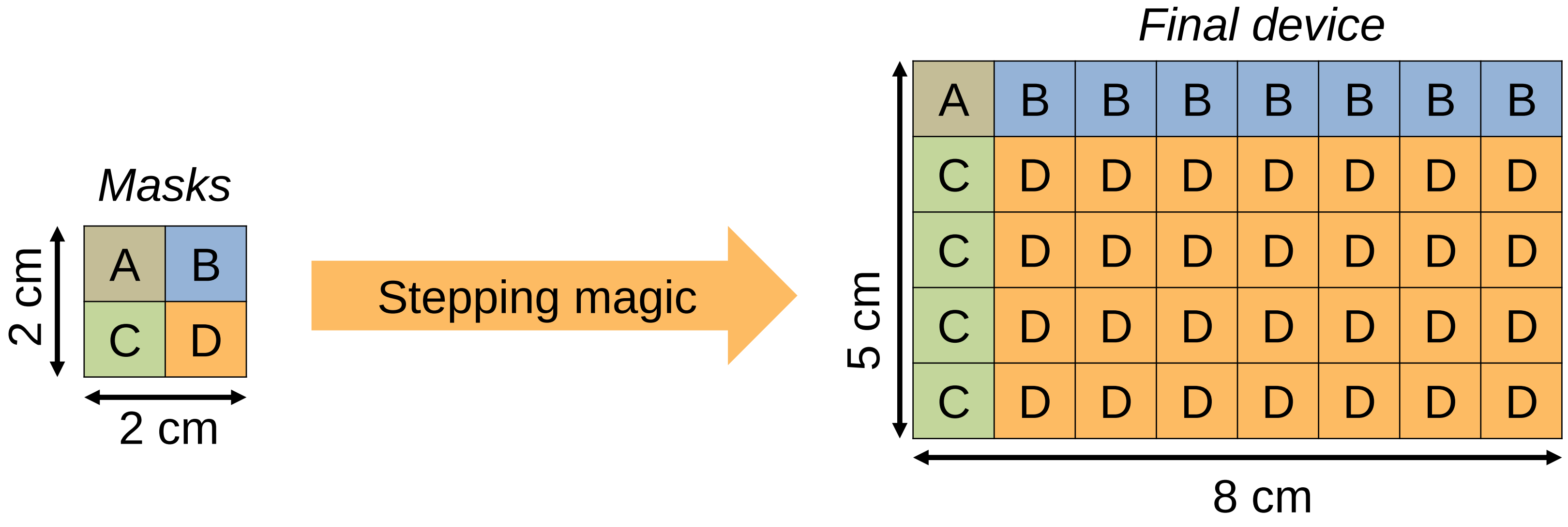
Minimum feature size (e.g. TJ 180 nm):

- Size of smallest structure on my realize with a process (typically transistor gate)
- Relevant sizes:
  - 5 nm (~50 atom layers) for modern digital electronics (e.g. smart phones).
  - 180 – 250 nm (detector electronics in production)
  - 28 – 65 nm (detector electronics under preparation)

Analog/radiation hard electronics:
A bit bigger is often better.

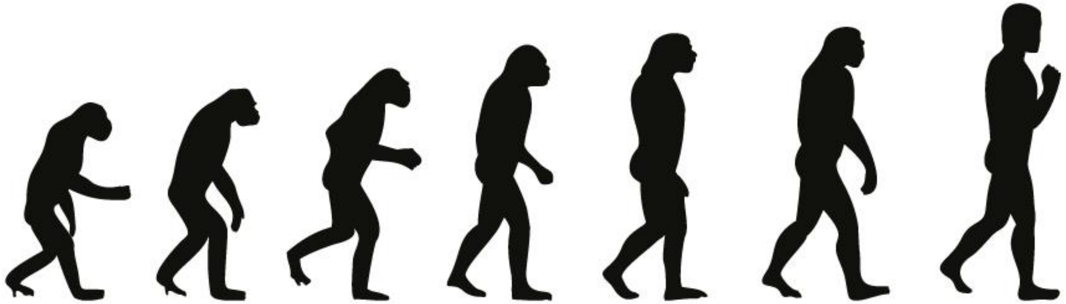
Reticle size: Biggest structure one can build with one lithography mask, typically ~3 x 2 cm².

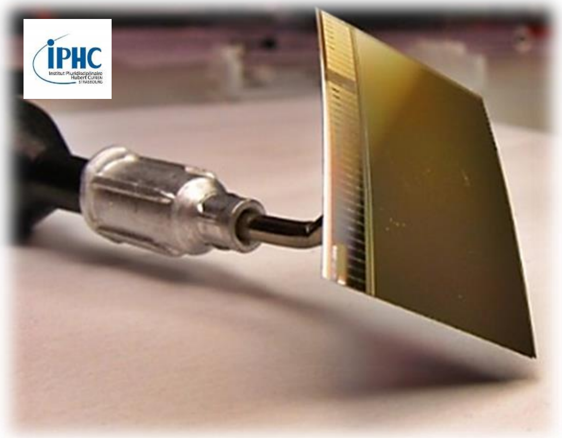
Stitching: Build > reticle size devices by using repetitive structures



The rising of MAPS

Geiger-counter (1932)

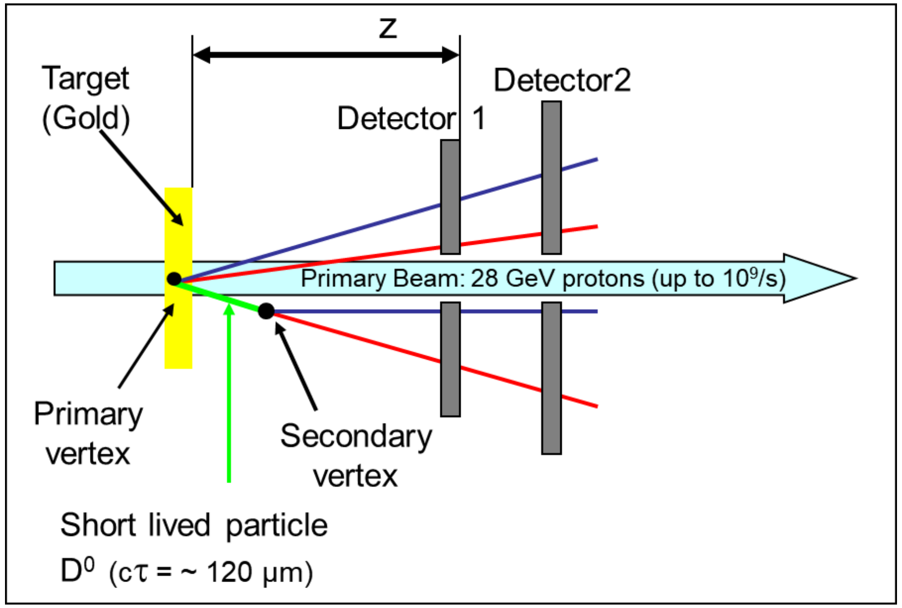




MAPS (nowadays)

How to find instable particles?

Works for "stable" particles reaching the detectors.
What about less stable particles?
Open strange: $c\tau \approx 10\ \mathrm{mm}$, Open bottom: $c\tau \approx 1\ \mathrm{mm}$, Open Charm: $c\tau \approx 0.1\ \mathrm{mm}$

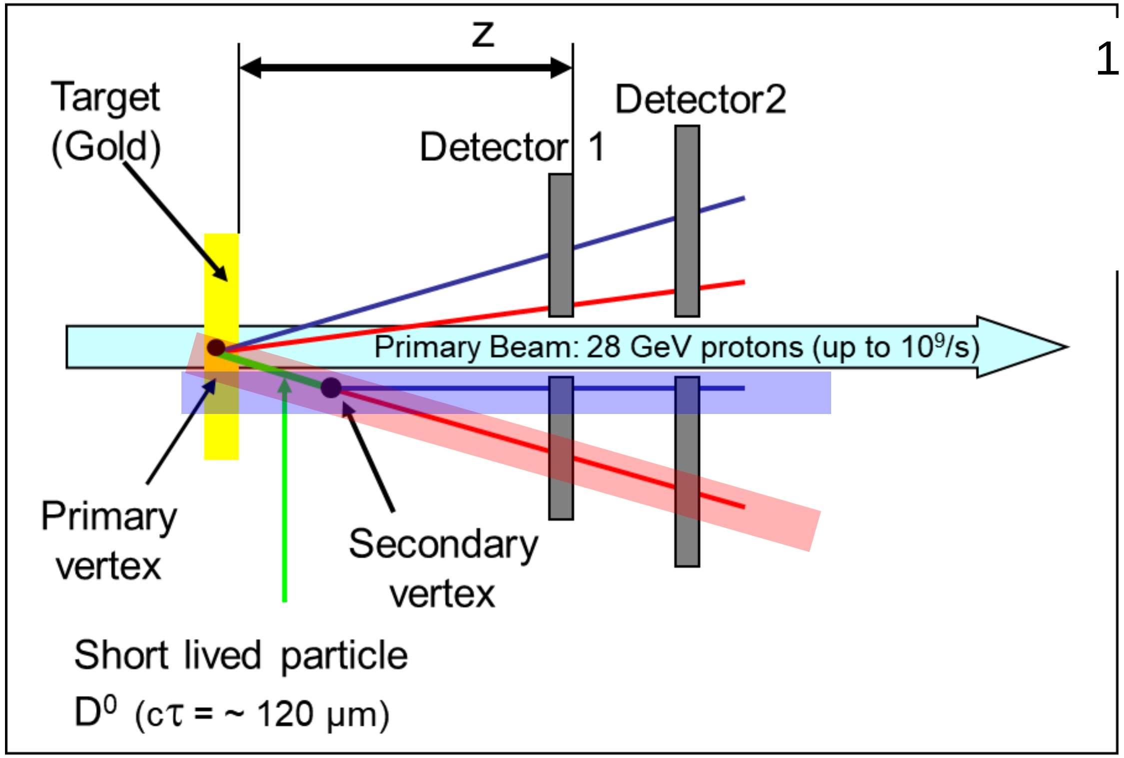


Prove existence of short lived particle by separating primary and secondary vertex.
Compute its properties by:

- Adding 4-vectors of daugters (invariant mass).
- "Add" quark content of daughters.

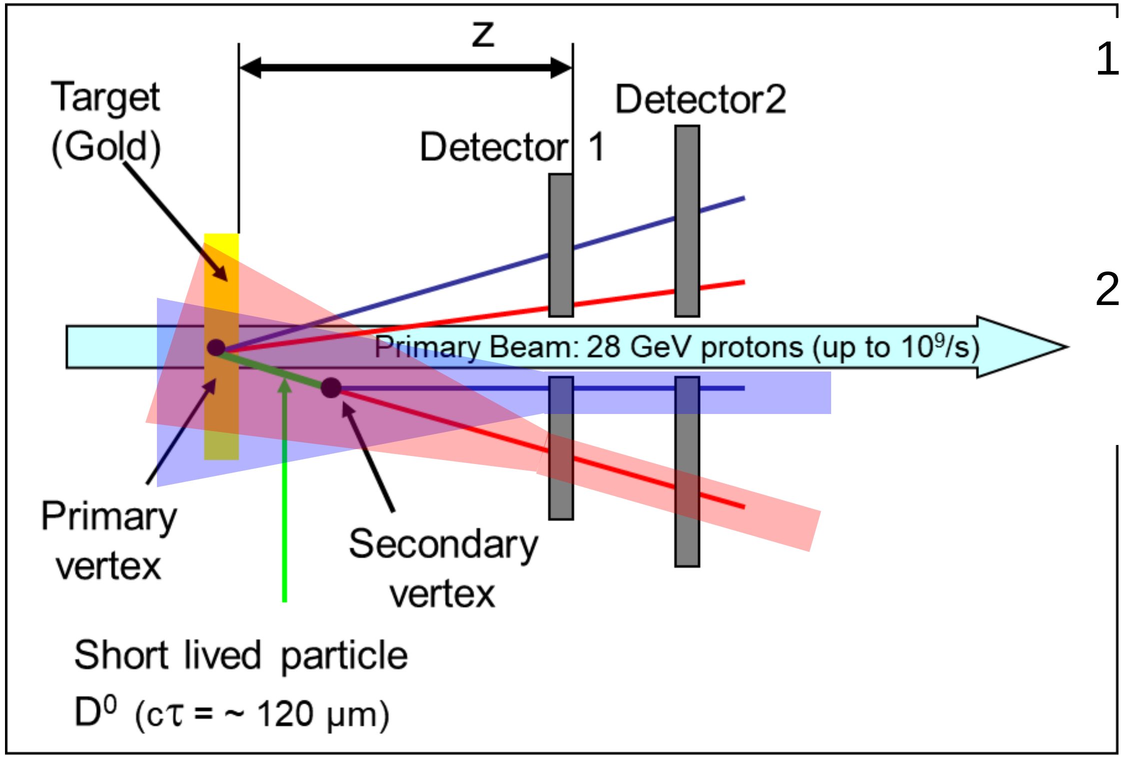
Sounds too easy, where is the challenge?

Where is the challenge?



1. Limited detector resolution spoils vertex resolution.
   - ➢ Needs <5µm.

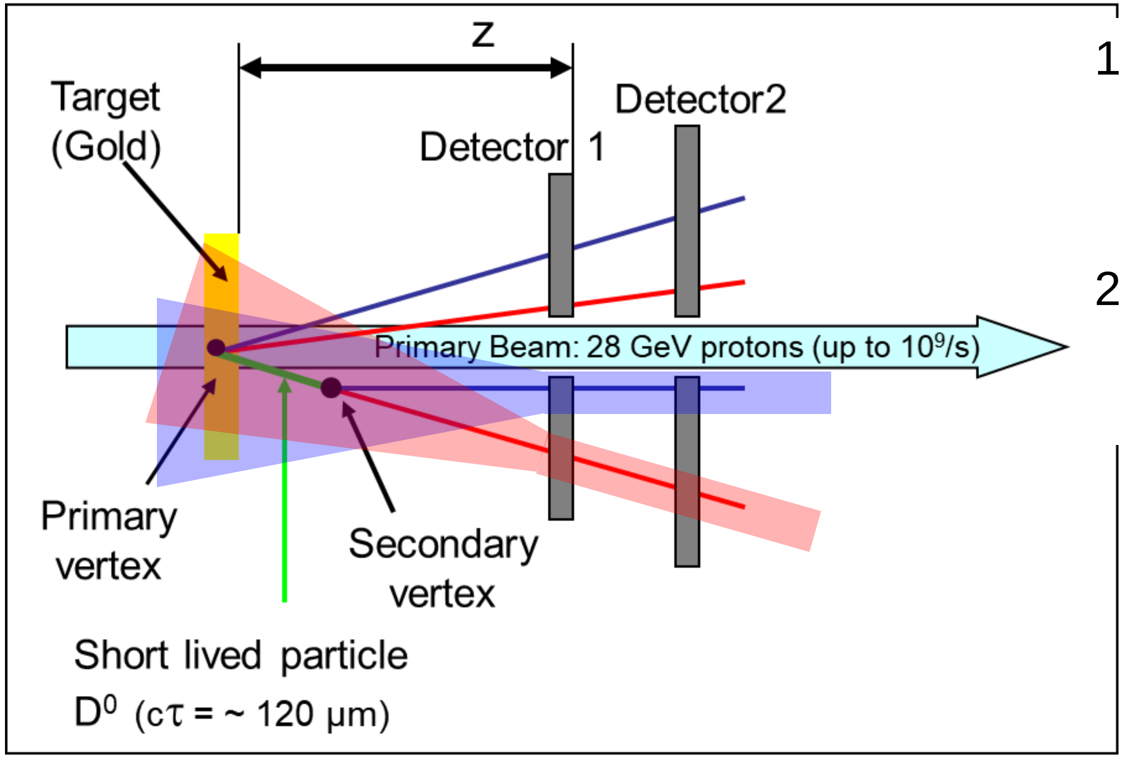
Where is the challenge?



1. Limited detector resolution spoils vertex resolution.
   - ➢ Needs <5µm.
2. Multiple coulomb scattering manipulated particle trajectory.
   - ➢ Needs x< 0.3% $X_{0.}$

Radiation length

Where is the challenge?



1. Limited detector resolution spoils vertex resolution.
   - ➢ Needs <5µm.
2. Multiple coulomb scattering manipulated particle trajectory.
   - ➢ Needs x< 0.3% X_0.

300µm Si

Radiation length

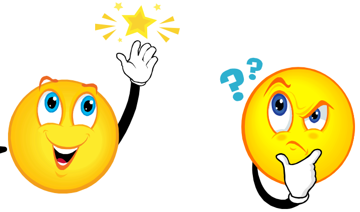
$\frac{x}{X_0}$ - Material budget.
$1\%\ X_0 \approx 1$ mm Si.
Data in PDG-booklet

Scattering angle

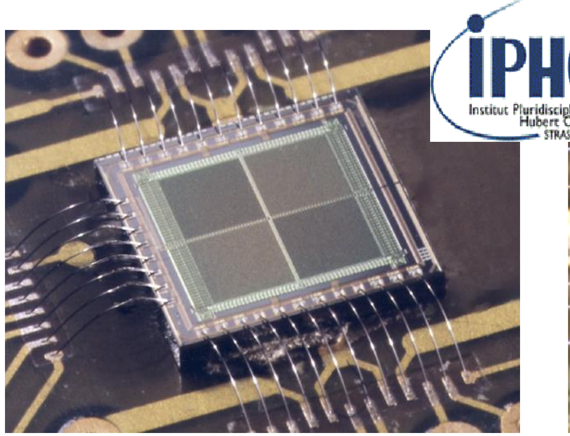
Relativistic particles with z=1

$$\Theta = \frac{13.6\ \mathrm{MeV}}{\beta\, c\, p} \cdot z \cdot \sqrt{\frac{x}{X_0}} \cdot \left[1 + 0.038 \log\left(\frac{x}{X_0}\right)\right]$$

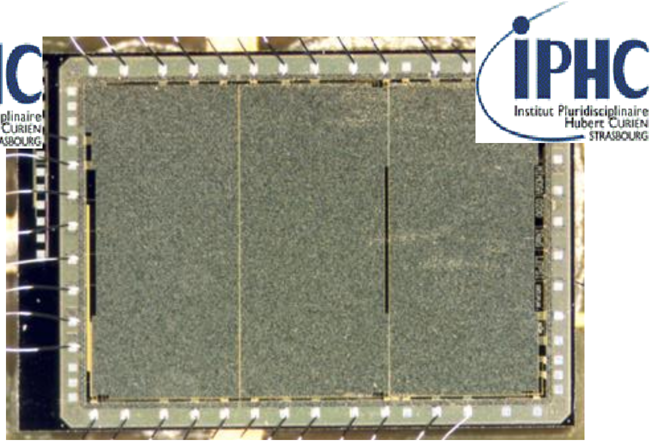
No challenge…
We just have to build mass-less detectors with infinitely good spatial resolution and perfect efficiency…



MAPS – the beginning

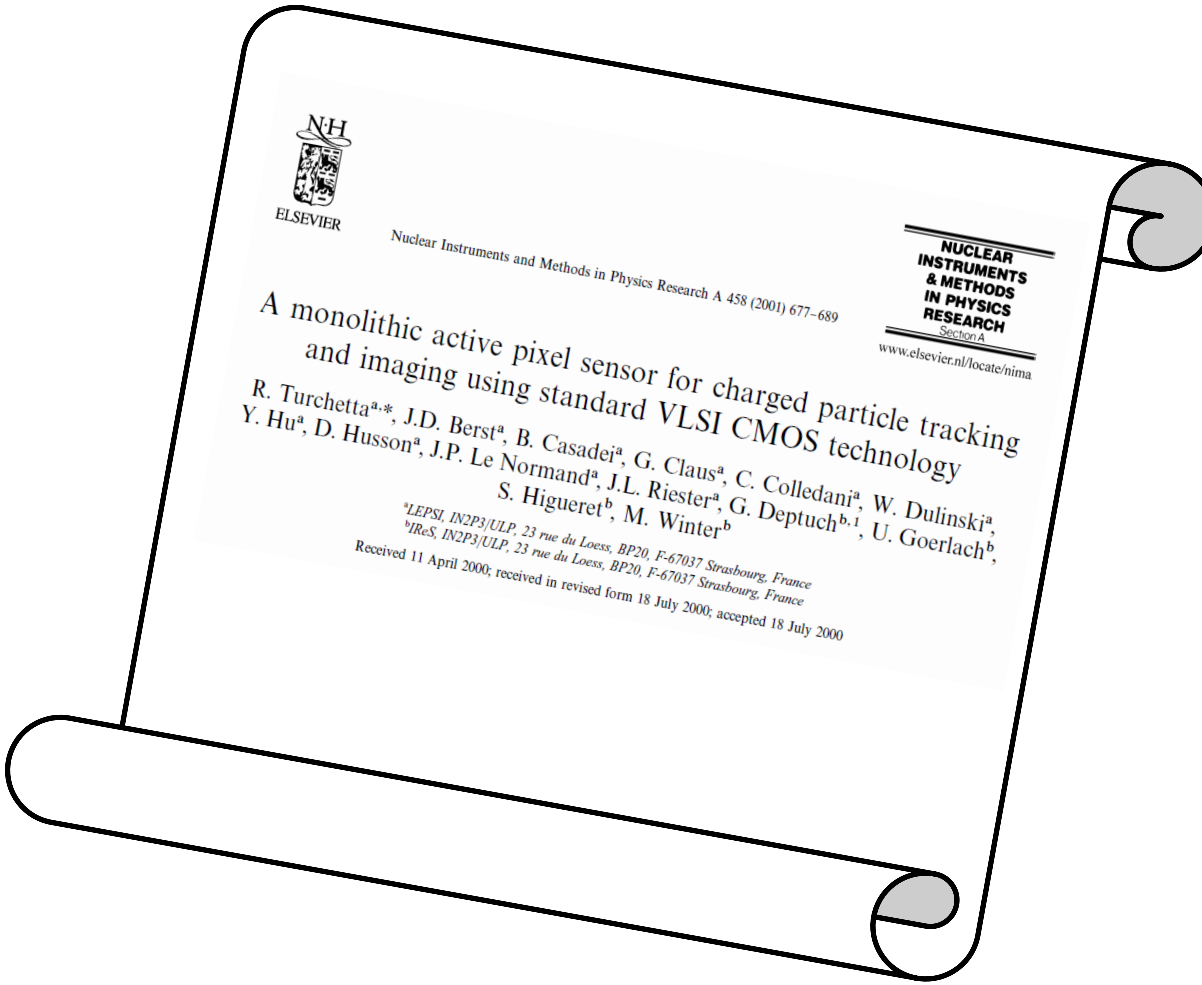


MIMOSA – 1 (1999)



MIMOSA – 1 (2000)

	Mi - 1
Pixel size [µm²]	20 x 20
Pixel number	N x 64 x 64
Readout	Analog
Frame time [µs]	~10^4
Dead time	> 50%



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Nuclear Instruments and Methods in Physics Research A 458 (2001) 677–689

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

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A monolithic active pixel sensor for charged particle tracking and imaging using standard VLSI CMOS technology

R. Turchetta[a,*], J.D. Berst[a], B. Casadei[a], G. Claus[a], C. Colledani[a], W. Dulinski[a], Y. Hu[a], D. Husson[a], J.P. Le Normand[a], J.L. Riester[a], G. Deptuch[b,1], U. Goerlach[b], S. Higueret[b], M. Winter[b]

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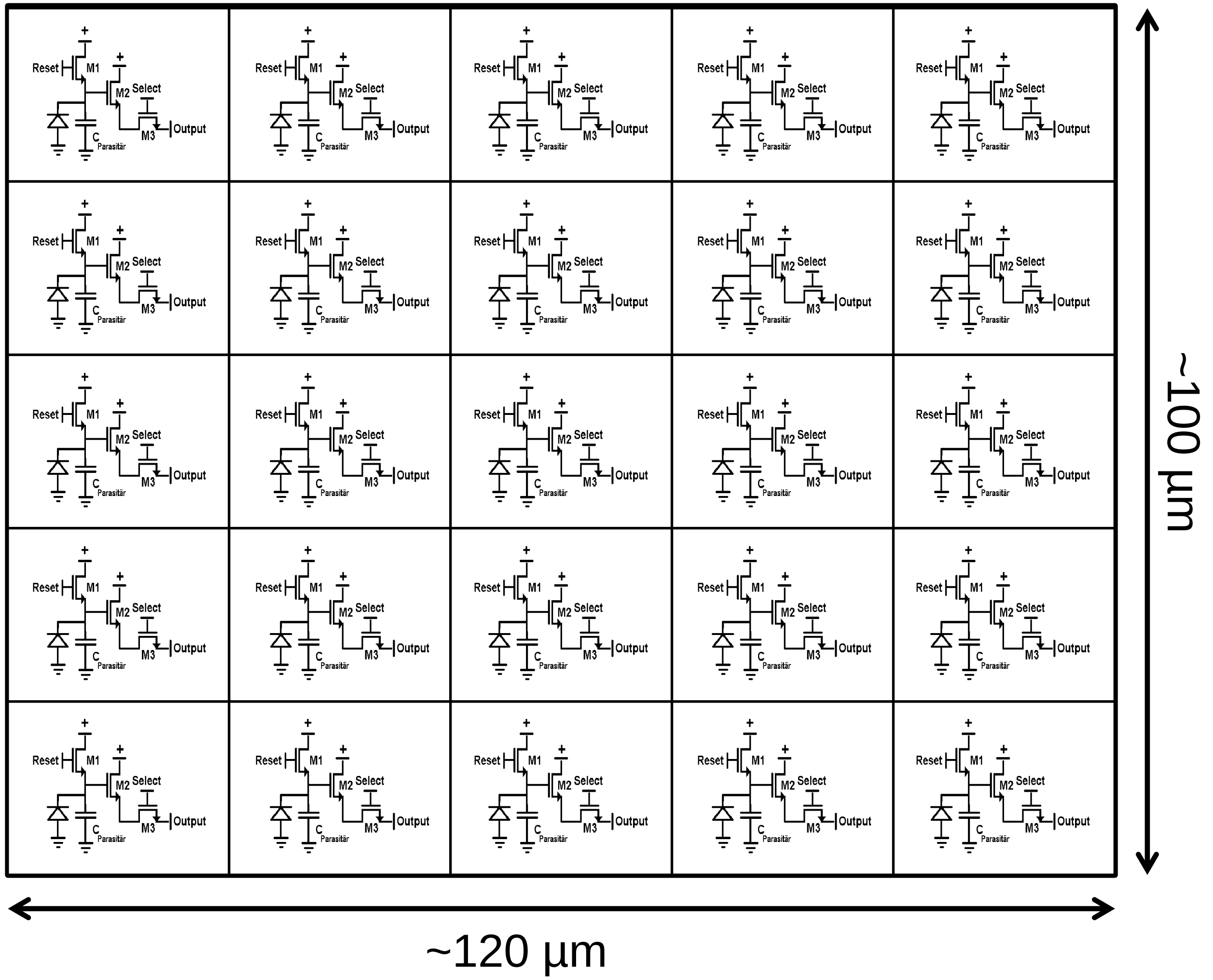
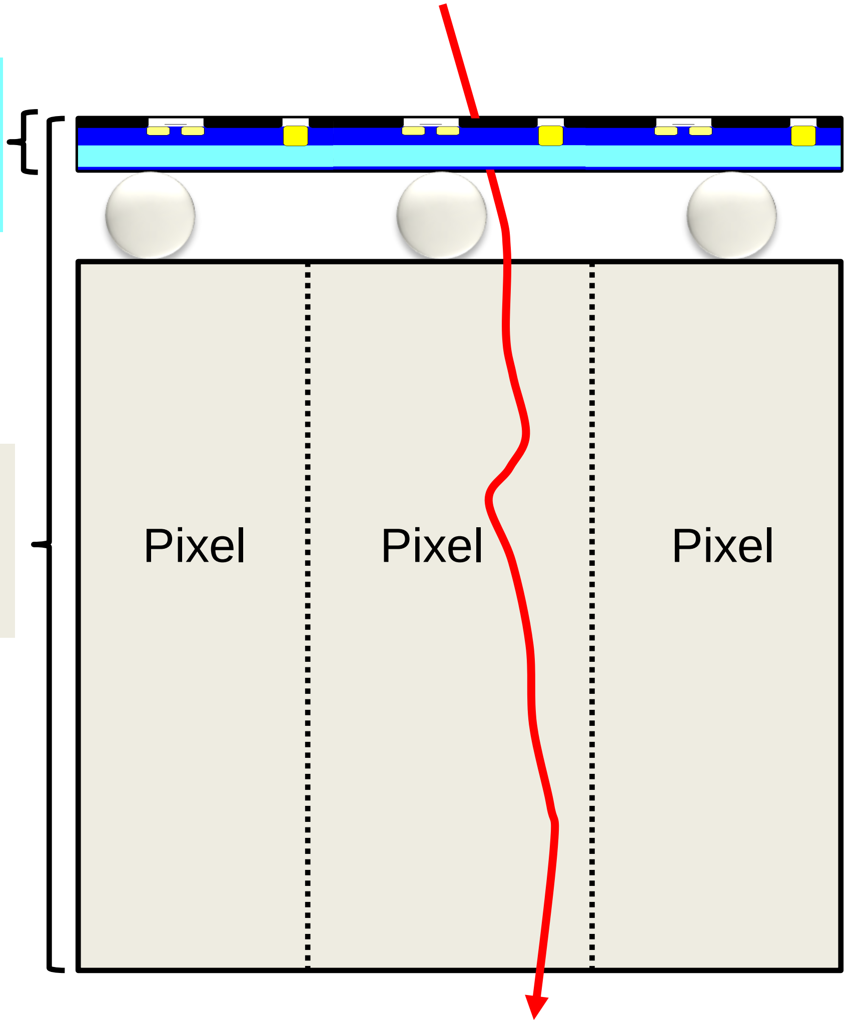
MAPS vs. Hybrid pixels

CMS @ LHC – Hybrid Pixel



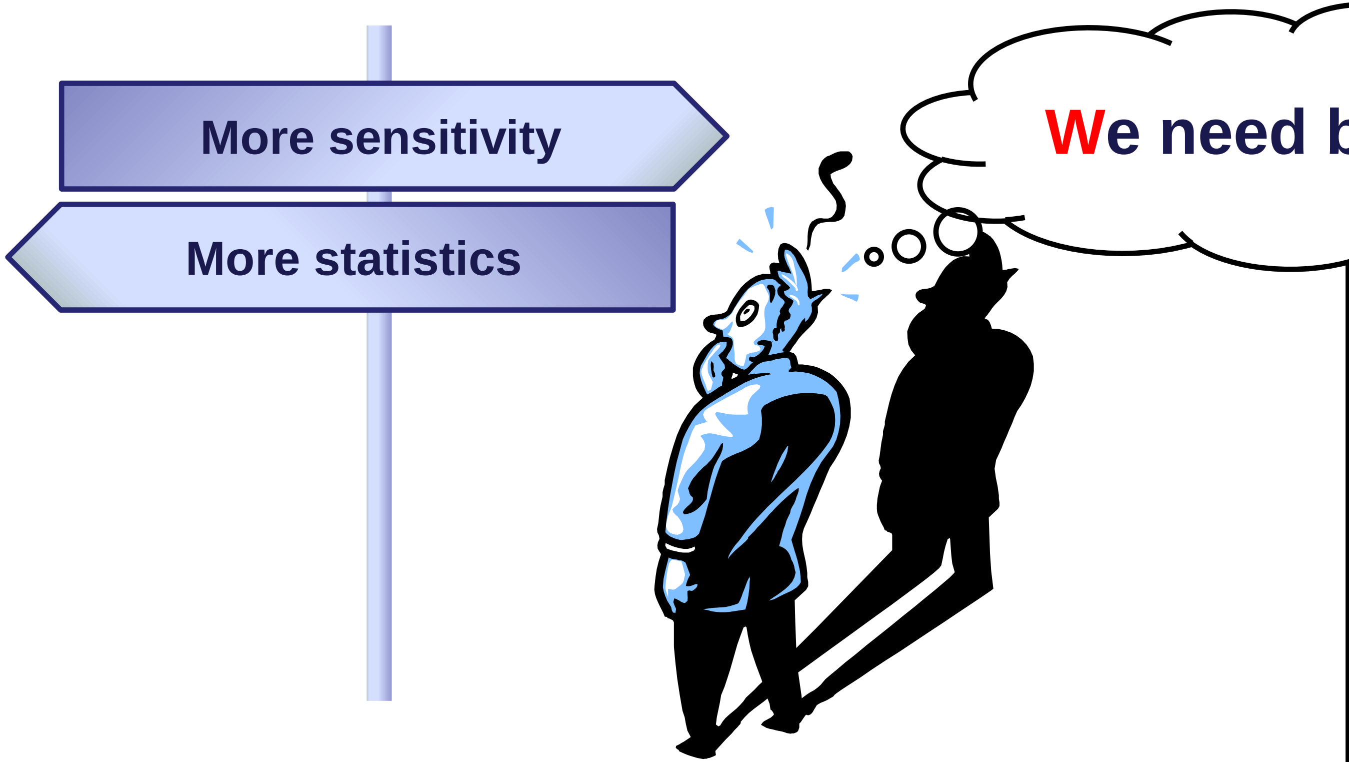
MAPS:
~0.05 µm
Si equivalent

Hybrid:
0.5mm Si
equivalent

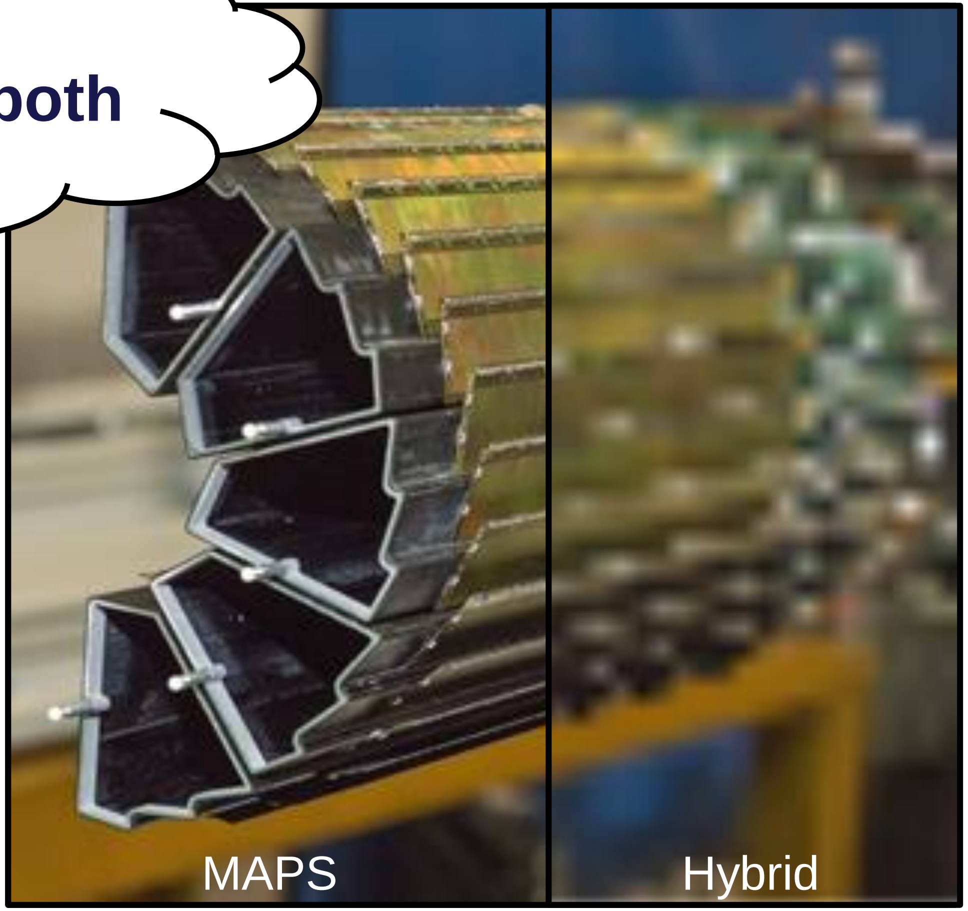


Multiple coulomb scattering:
Particle trajectory is manipulated by detector.
Angle scales with $\sqrt{\text{thickness}}\,/\,p$

MAPS – the hope and limitations

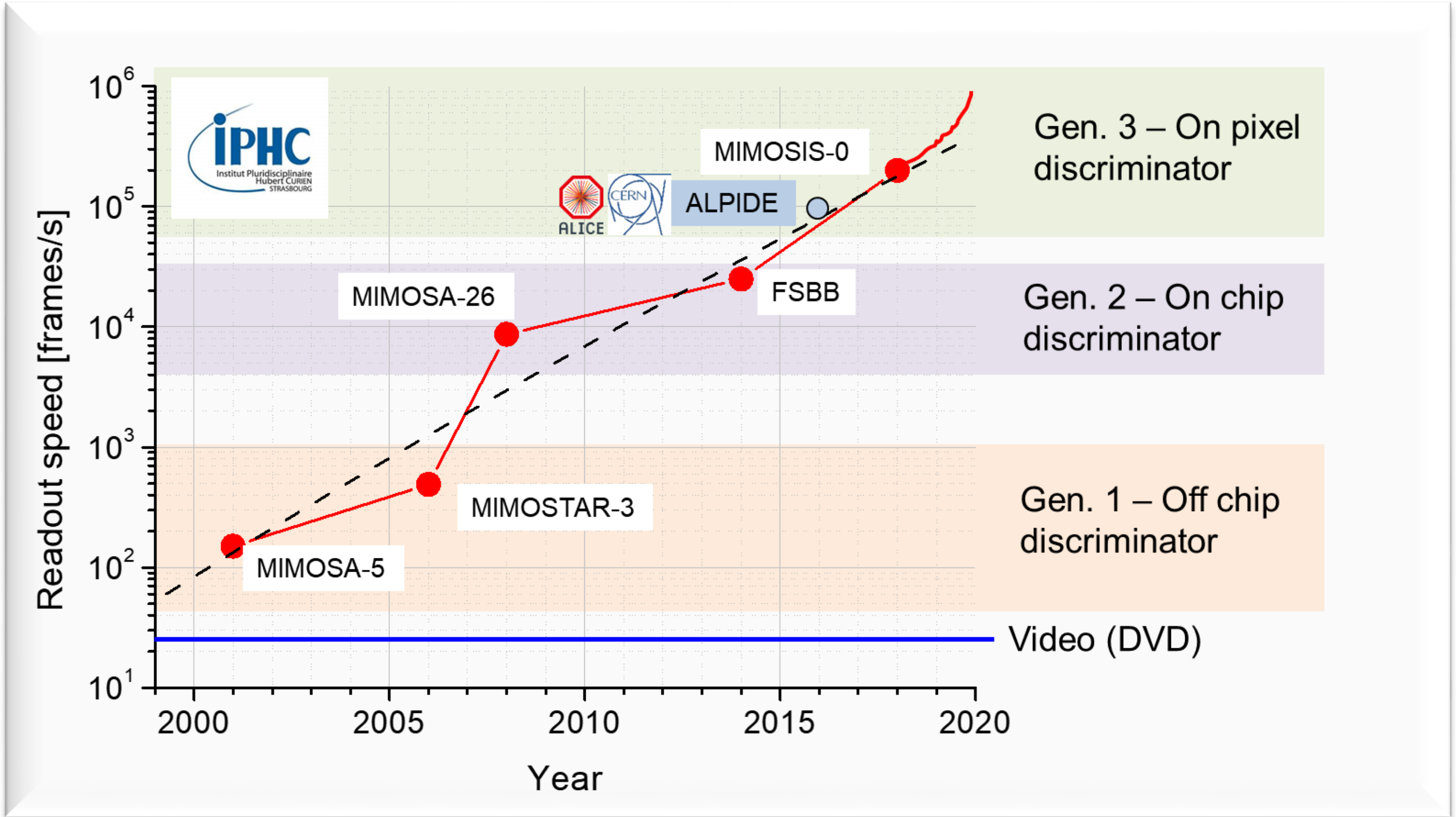


	Hybrid pixels (2001)	MAPS (2001)
Single point resolution	~ 30 µm	~2 µm
Material budget	~ 500 µm Si	~ 50 µm Si



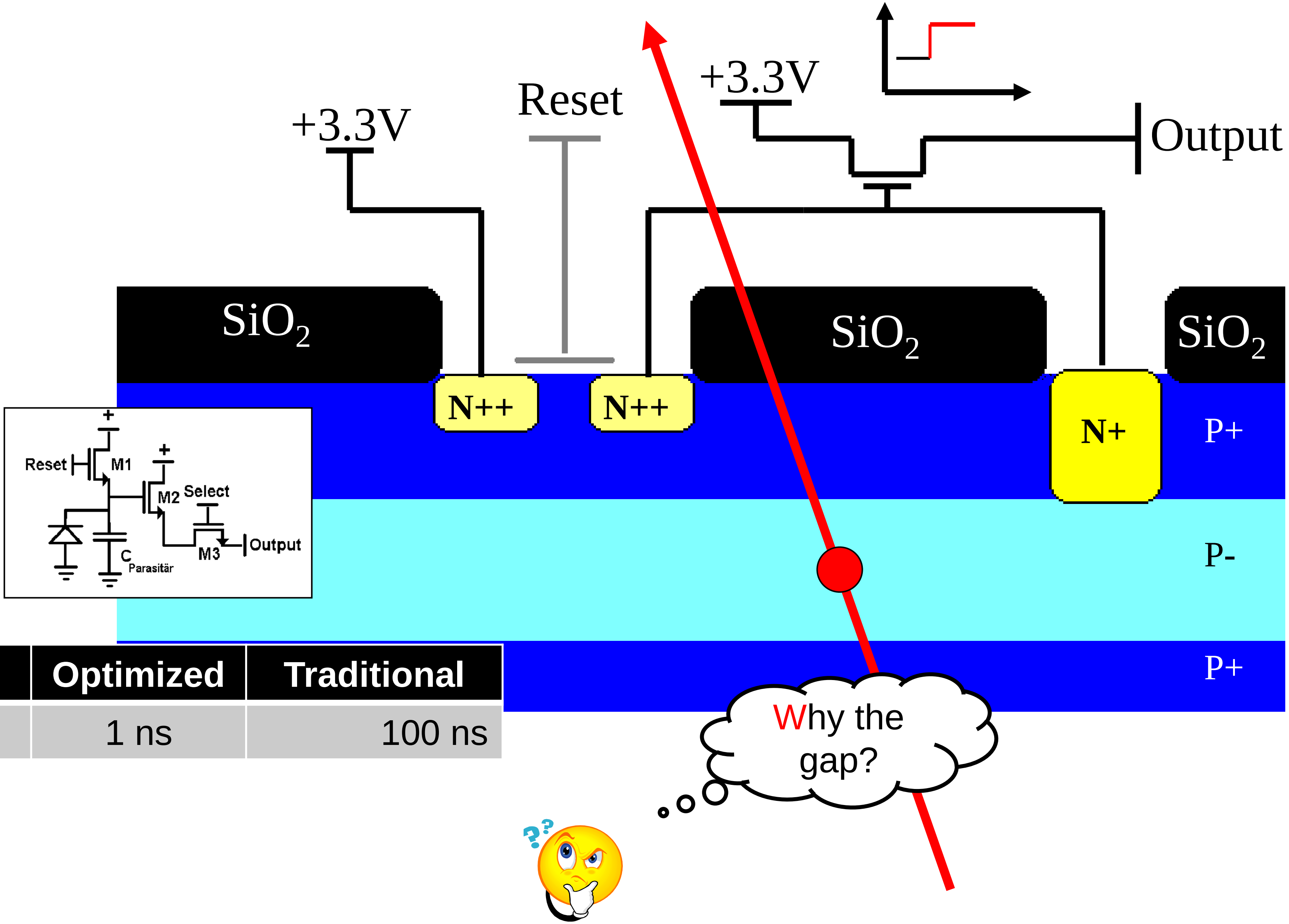
MAPS show charge sharing:
$\sigma \approx p/10$ (analog readout)
$\sigma \approx p/10$ (digital readout)

The need for speed



Time resolution?
Particle rate?
Data bandwidth?

Speed of MAPS: Limiting factors

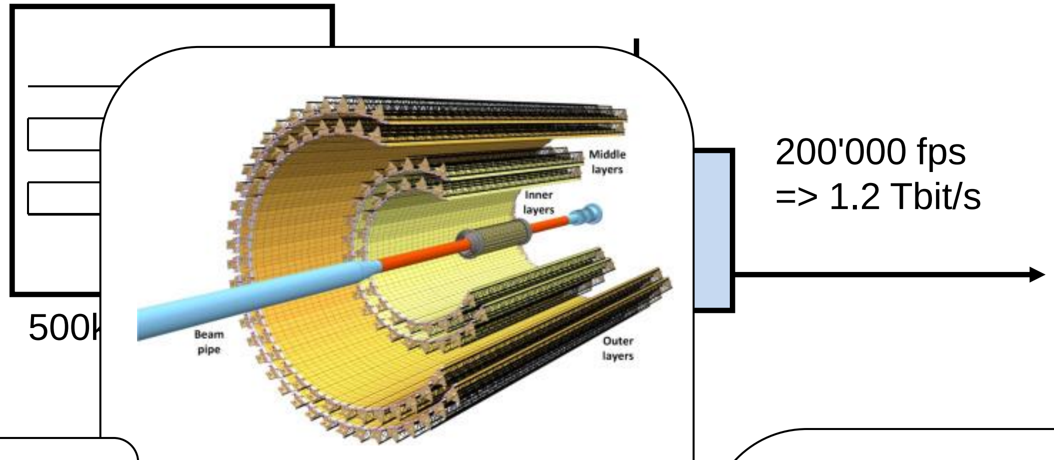


	Optimized	Traditional
Charge collection time	1 ns	100 ns

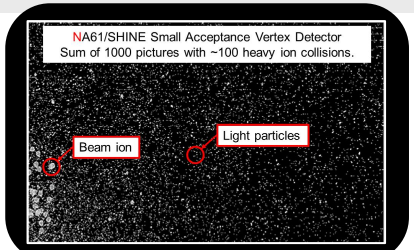
Block diagram of Gen. 1 MAPS

Sensor

External ADC



200'000 fps
=> 1.2 Tbit/s



How much data would you get from a 10m² detector?

Maybe ~3 PB/s.

Should we start a new pile once per hour?

600m/s

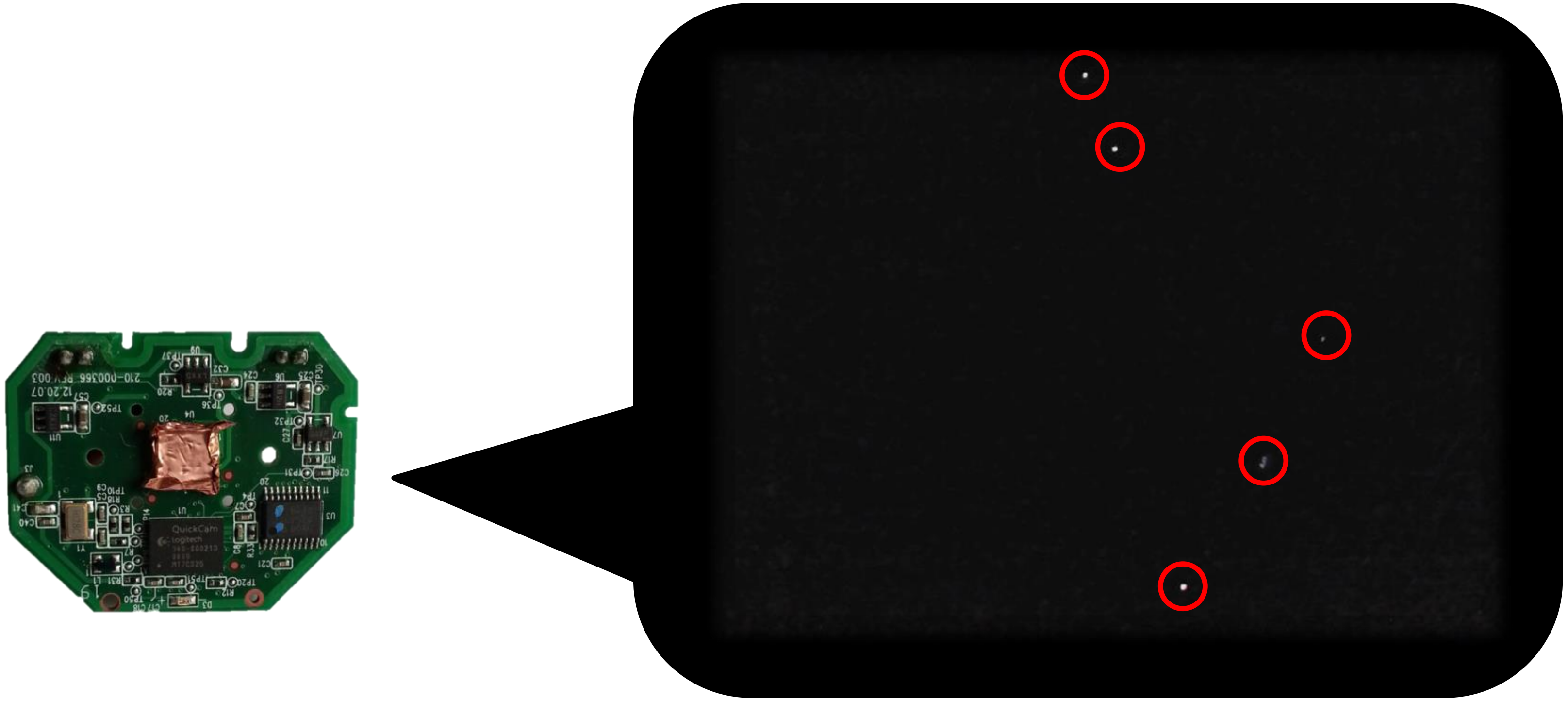
8000m/s

3PB/s = 30000m/s
3.5h to moon.

?

What about data compression?

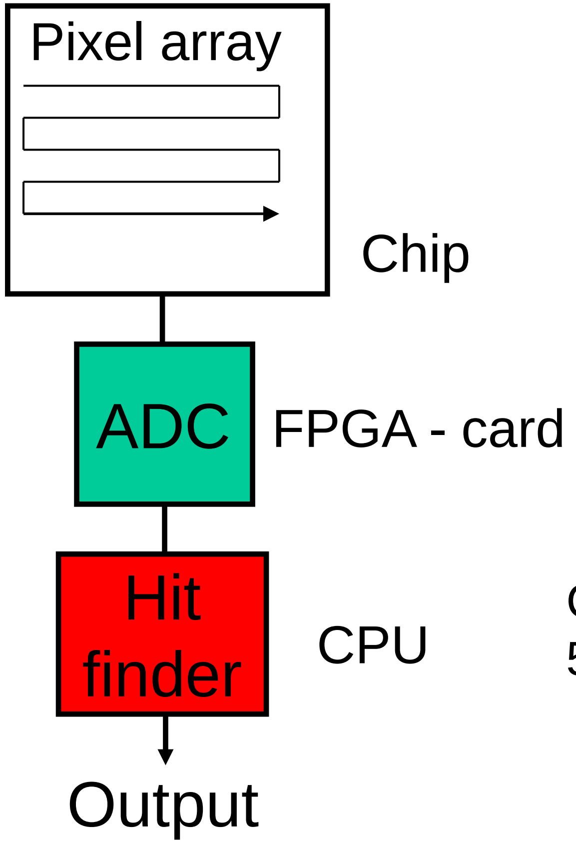
How do to data compression

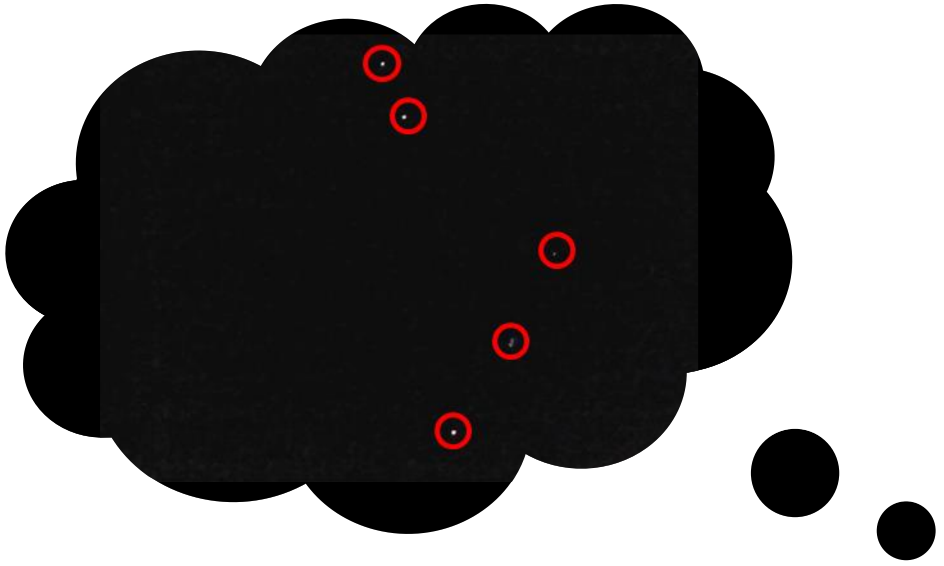


Most pixels in the frame (>99.5%) show black.
Only few pixels show white.

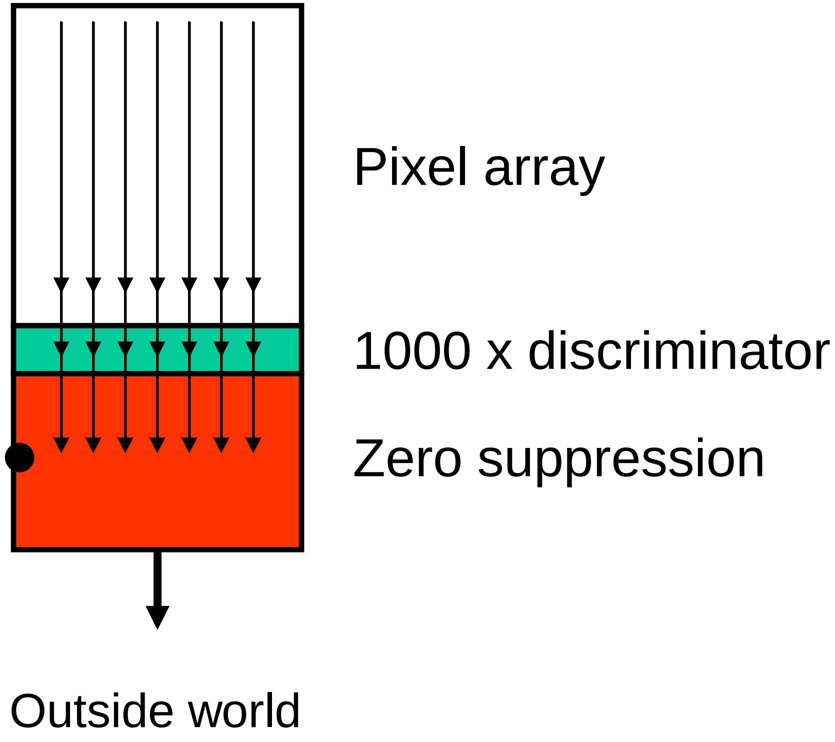
Idea: Ignore all black pixels.

How to readout the pixels?





Compress by ignoring dark pixels:
5000 Mbps => 200 Mbps (x25 reduction)



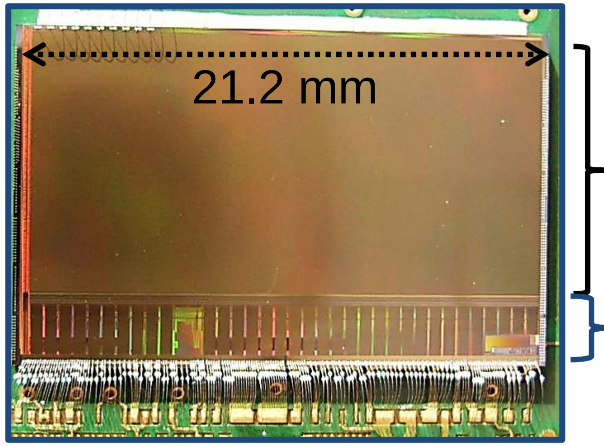
Rolling shutter readout:
Read pixels sequentially.

Frame time: $t_{int} = \frac{N}{f} \approx \frac{10^5}{10^7\,\mathrm{Hz}} \approx 10\ \mathrm{ms}$

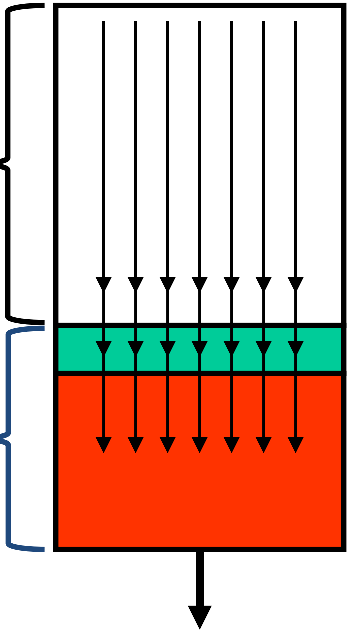
Column parallel rolling shutter readout:
Read pixels of one column sequentially.

Frame time: $t_{int} = \frac{N}{f} \approx \frac{10^3}{10^7\,\mathrm{Hz}} \approx 0.1\ \mathrm{ms}$

Generation 2 Sensors



MIMOSA-26
Known from the EU-DET telescope

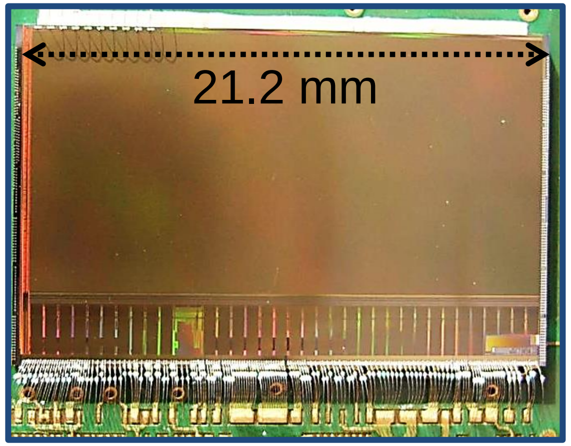


ULTIMATE (STAR-PXL detector)

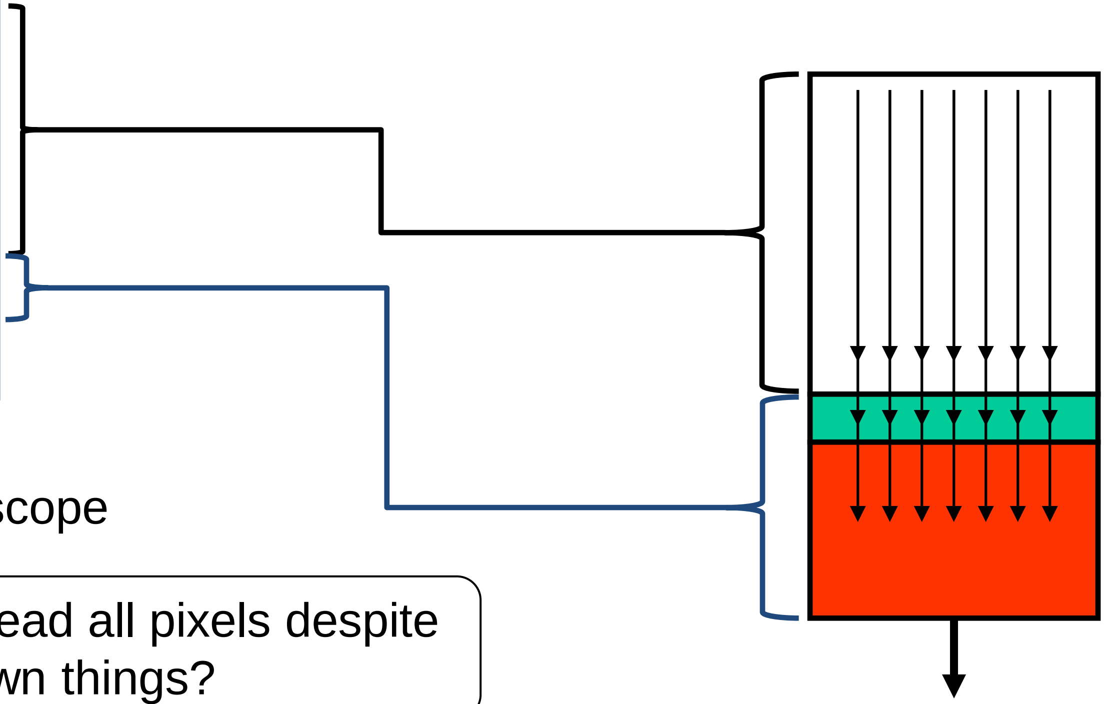
Column parallel rolling shutter readout:
Read pixels of one column sequentially.

Frame time: $t_{int} = \frac{N}{f} \approx \frac{10^3}{10^7\,\mathrm{Hz}} \approx 0.1\ \mathrm{ms}$

Generation 2 sensors



MIMOSA-26
Known from the EU-DET telescope



Pixel array

1000 x discriminator

Zero suppression

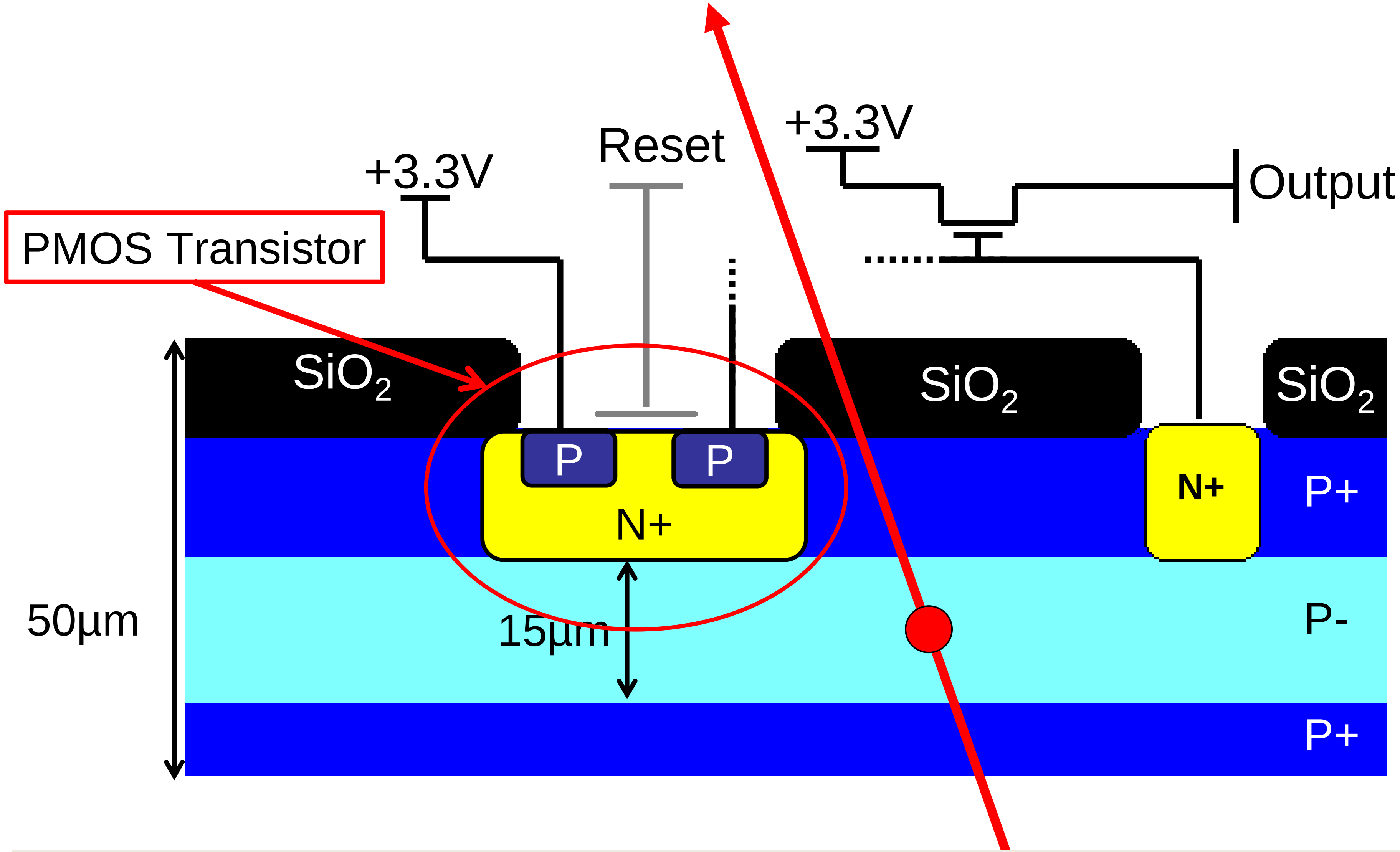
Outside world

Why do you read all pixels despite this slows down things?

Because it needs in-pixel discriminators. That's not easy.

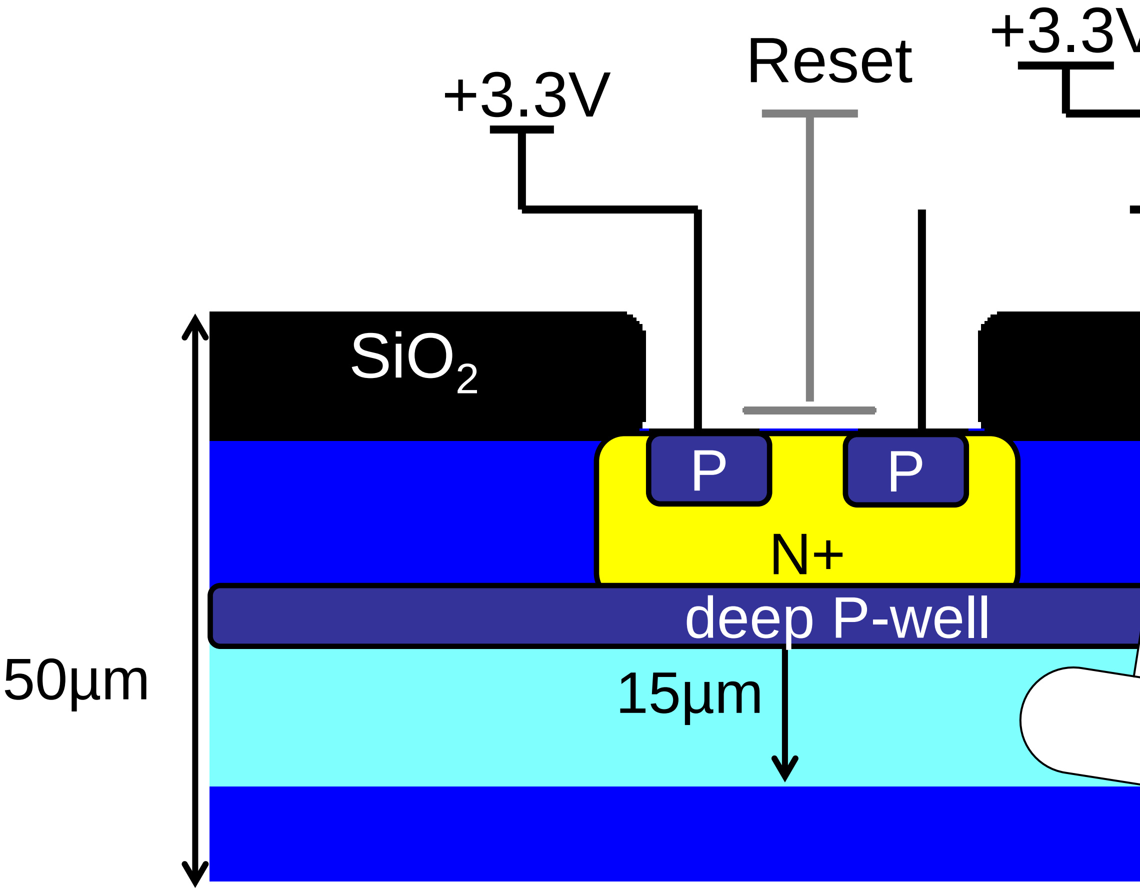
Column parallel rolling shutter readout:
Read pixels of one column sequentially.

Frame time: $t_{int} = \frac{N}{f} \approx \frac{10^3}{10^7\,\mathrm{Hz}} \approx 0.1\ \mathrm{ms}$



In standard CMOS sensors, no PMOS transistors are possible in pixel
=> No high level functions like discriminators … => “slow”

Quad – Well process

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Article

Monolithic Active Pixel Sensors (MAPS) in a Quadruple Well Technology for Nearly 100% Fill Factor and Full CMOS Pixels

Jamie Alexander Ballin [2], Jamie Phillip Crooks [1], Paul Dominic Dauncey [2], Anne-Marie Magnan [2], Yoshinari Mikami [3,], Owen Daniel Miller [1,3], Matthew Noy [2], Vladimir Rajovic [3,***], Marcel Stanitzki [1], Konstantin Stefanov [1], Renato Turchetta [1,*], Mike Tyndel [1], Enrico Giulio Villani [1], Nigel Keith Watson [3], John Allan Wilson [3]**

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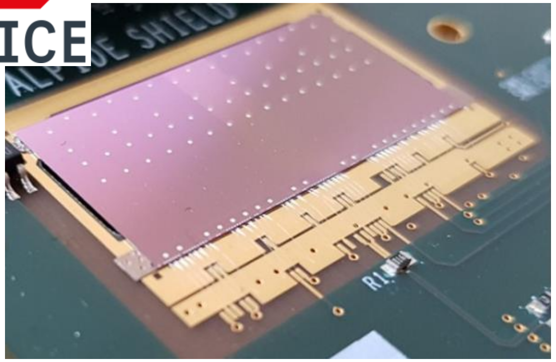
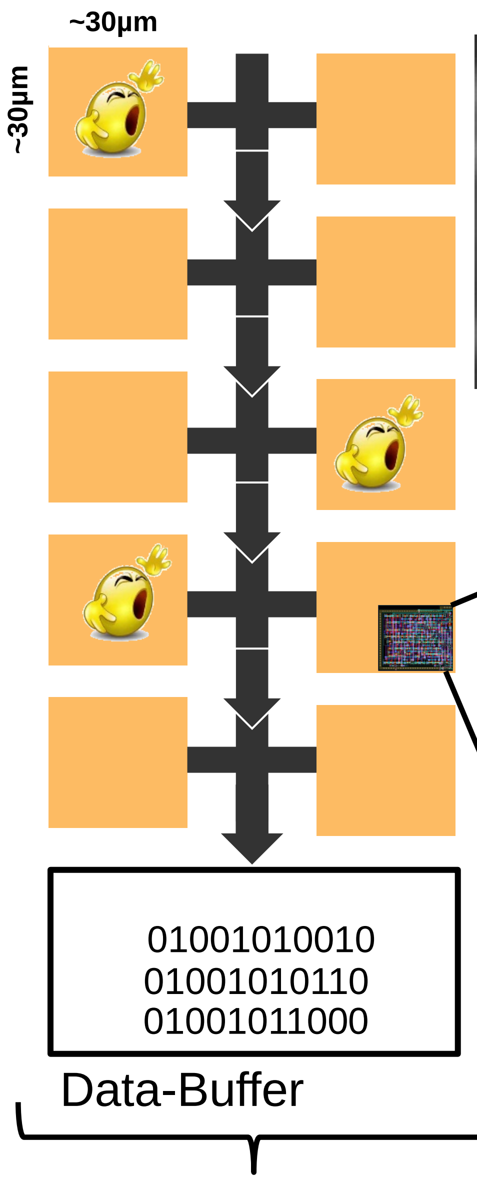
[3] School of Physics and Astronomy, University of Birmingham, Birmingham, B15 2TT, U.K

Progress was reached with Quad-well CMOS as provided by the manufacturer TowerJazz (180 nm).

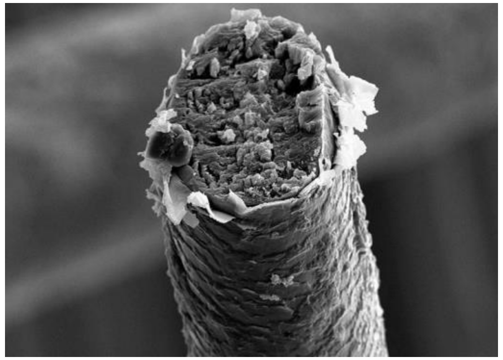
How to get the data out?



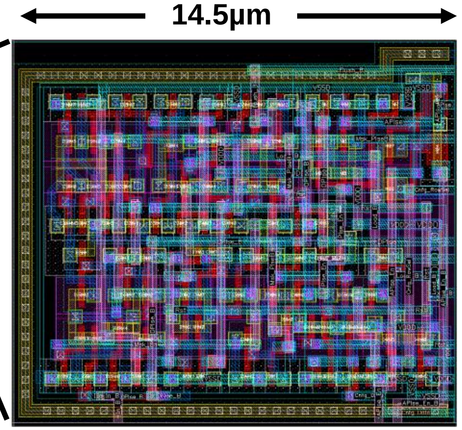
ALPIDE Sensor.
~ 50 mW/cm²



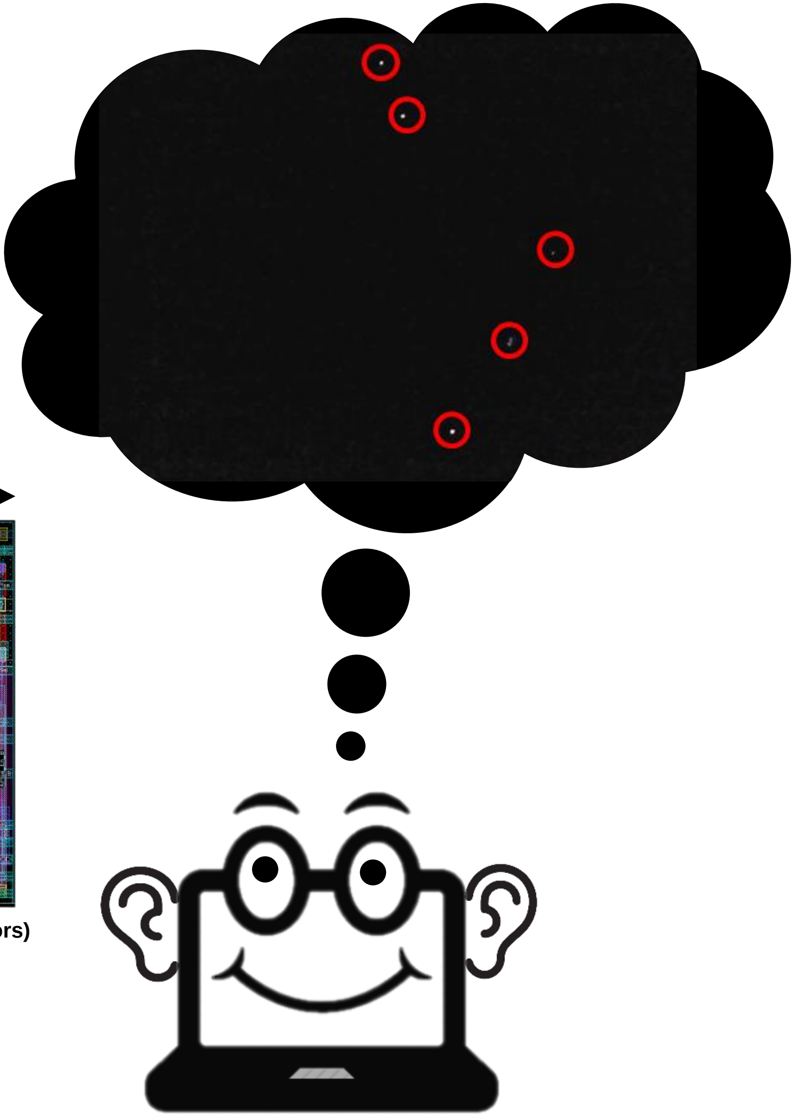
On-chip



Human hair (to scale)



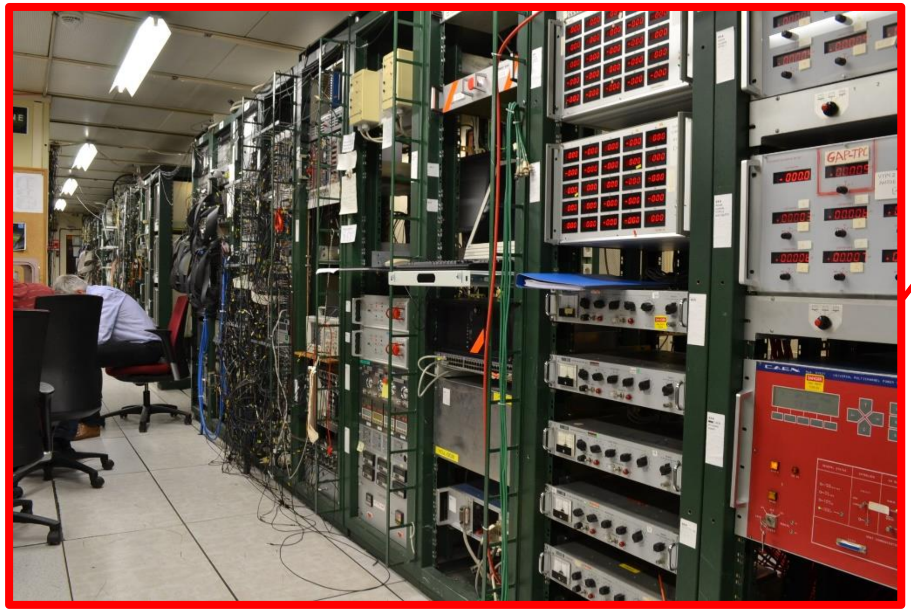
Mimosis Pixel Logic Layout (106 Transistors)

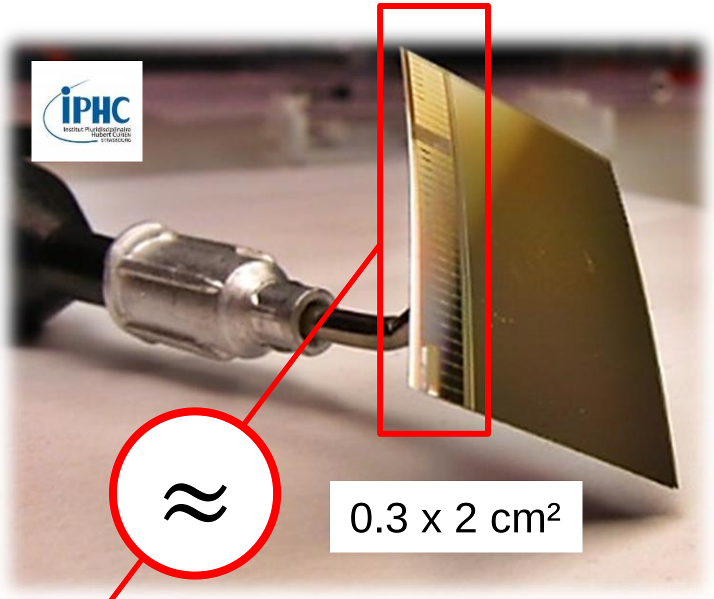


Off-chip

Side band contains:
- Data buffers.
- Voltage regulators, trim DACs.
- Slow control interface.
- Temperature sensors.

…





CMOS technology integrates:
- Sensors.
- Analog electronics.
- Digital data processing.

Data compression - Efficiency

No data compression

600m/s

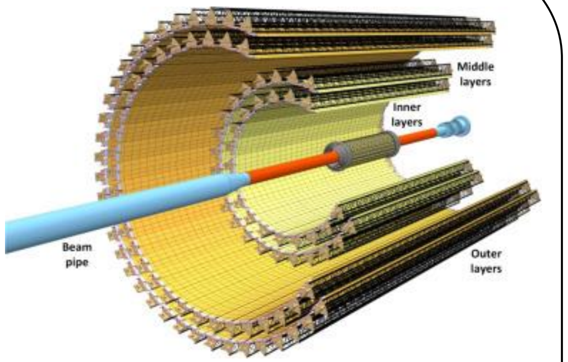
8000m/s

3PB/s = 30000m/s
3.5h to moon.

?

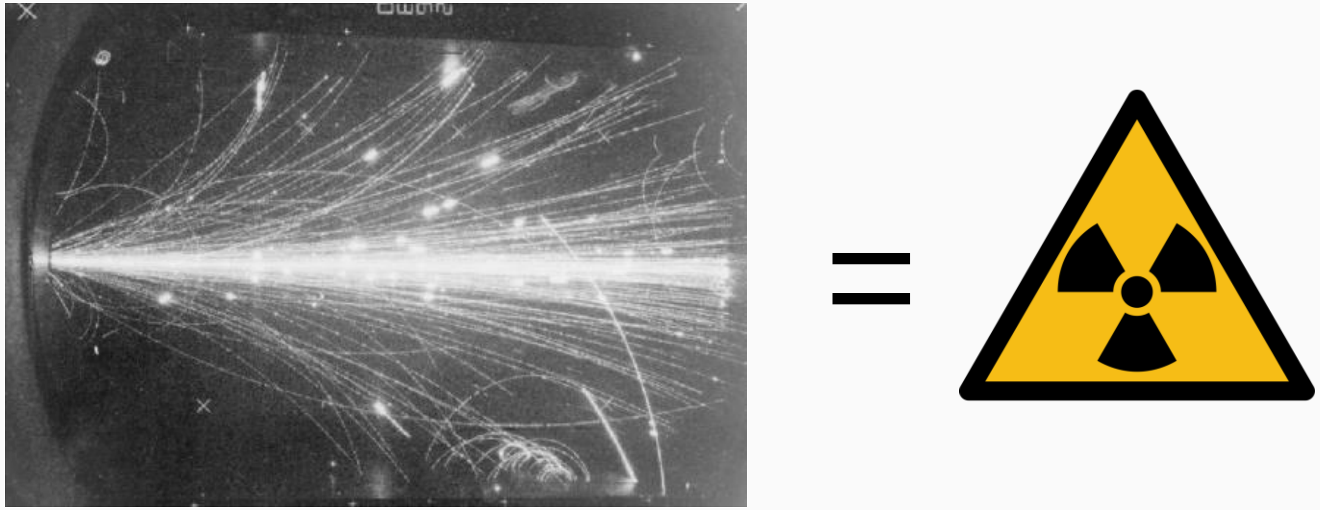
With data compression

~30GB/s = 0.5 m/s

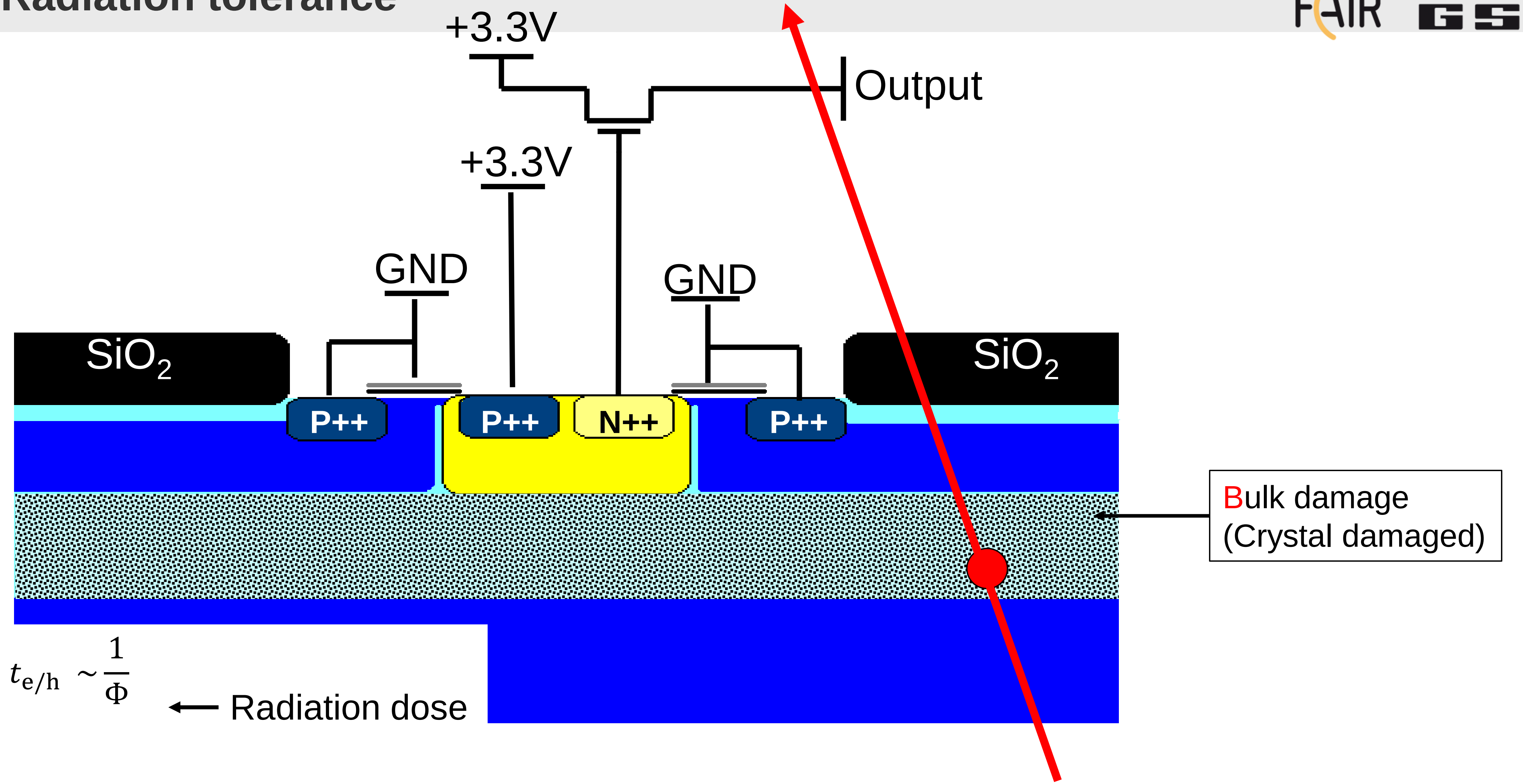


How much data would you get from a 10m² detector?

Radiation tolerance



Radiation tolerance



$$t_{e/h} \sim \frac{1}{\Phi}$$

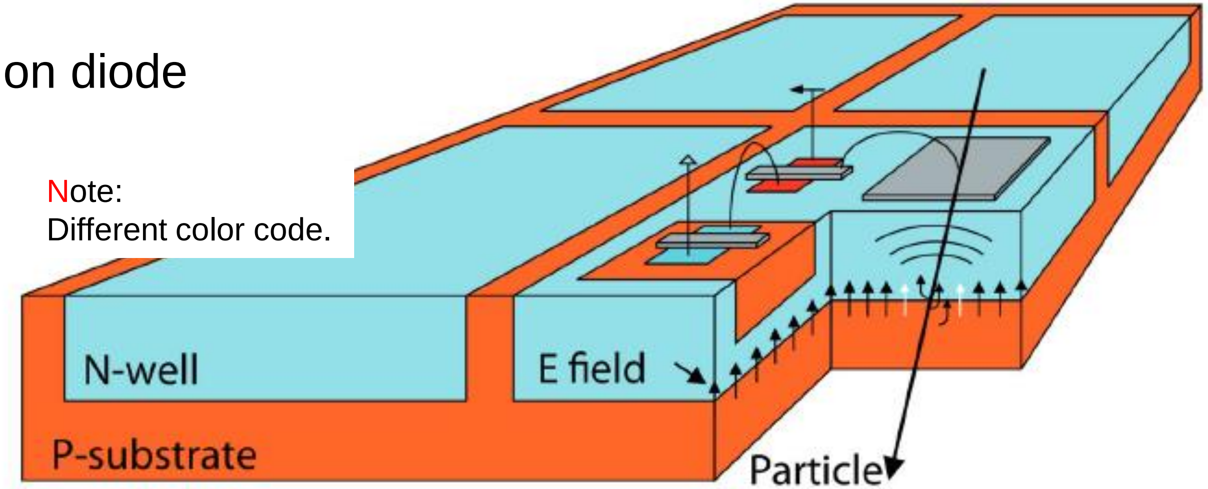
Inititially: Charge collection by diffusion=> slow => Radiation tolerance: 10^{12} n_{eq}/cm^2

Idea: Apply electric fields => Speed up

High Voltage (HV)-MAPS

Idea:
Use "High Voltage" CMOS Process.
Embed all electronics into the collection diode
⇒ Allows for fast readout.
⇒ Allows to apply >50 V.

Note:
Different color code.



I.Peric, P. Fischer et al., NIM A 582 (2007) 87

Pro:
- Worked with HV – triple well process (best option at the time).
- Very fast time resolution (<10 ns) for individual hits.
- Very radiation hard due to big diodes and high voltage. →

$$W = \sqrt{\frac{2\,\varepsilon_S\,(U_{bi} - U)}{e\,N_A}}$$

Limits:
- Rather sizeable pixels (e.g. 80x80µm²).
- High capacitive noise.
- Relatively high power consumption.

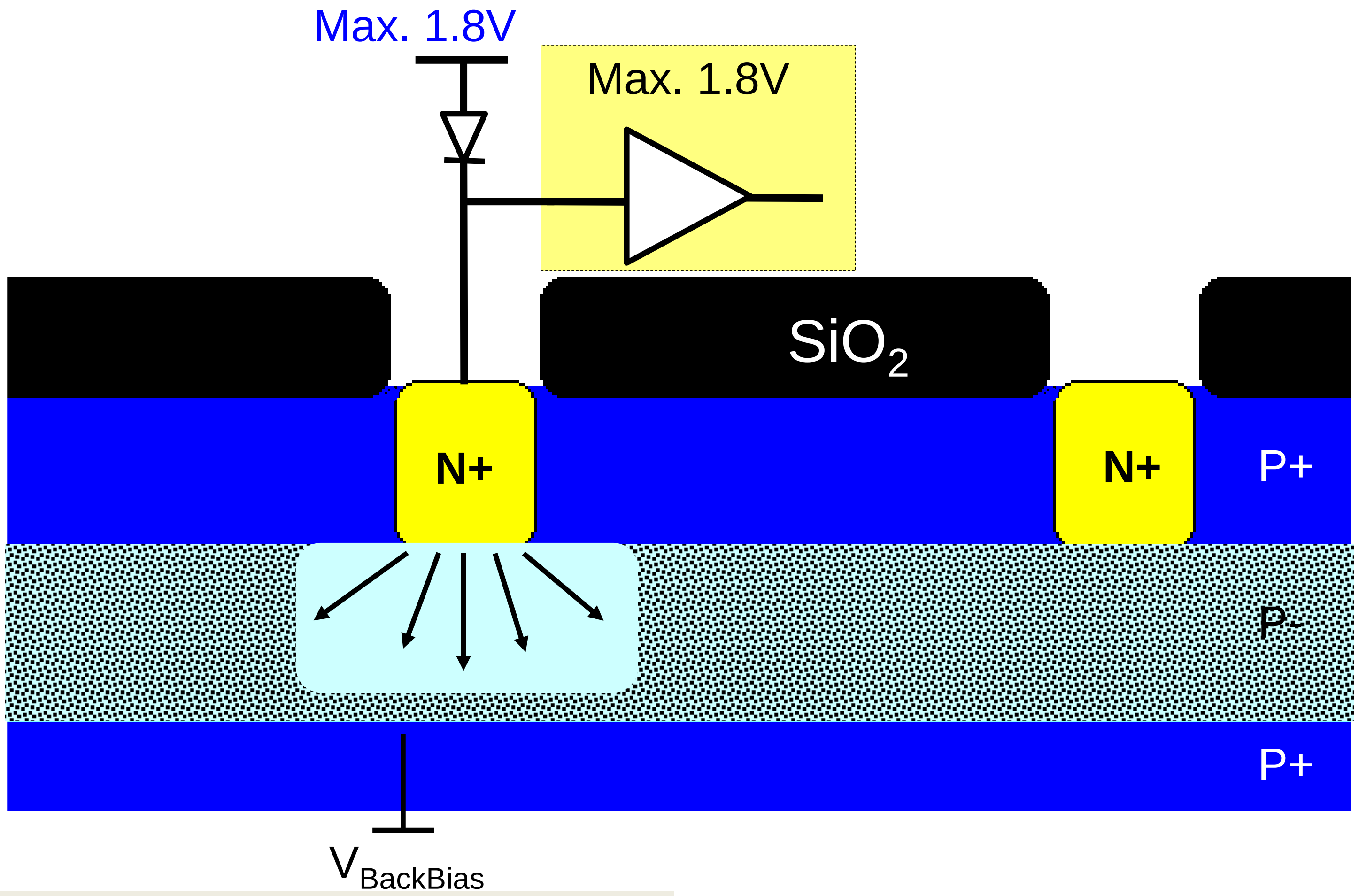
Radiation tolerance: D-MAPS

Flat diodes:

$$W = 2\sqrt{\frac{2\,\varepsilon_S\,(U_{bi} - \boldsymbol{U})}{e\,N_A}}$$

Point diodes:

$$W = 6^{(?)}\sqrt{\frac{2\,\varepsilon_S\,(U_{bi} - \boldsymbol{U})}{e\,N_A}}$$



Improvements
- Reduce doping, add back bias, e.g. ALPIDE (hard for >6V).

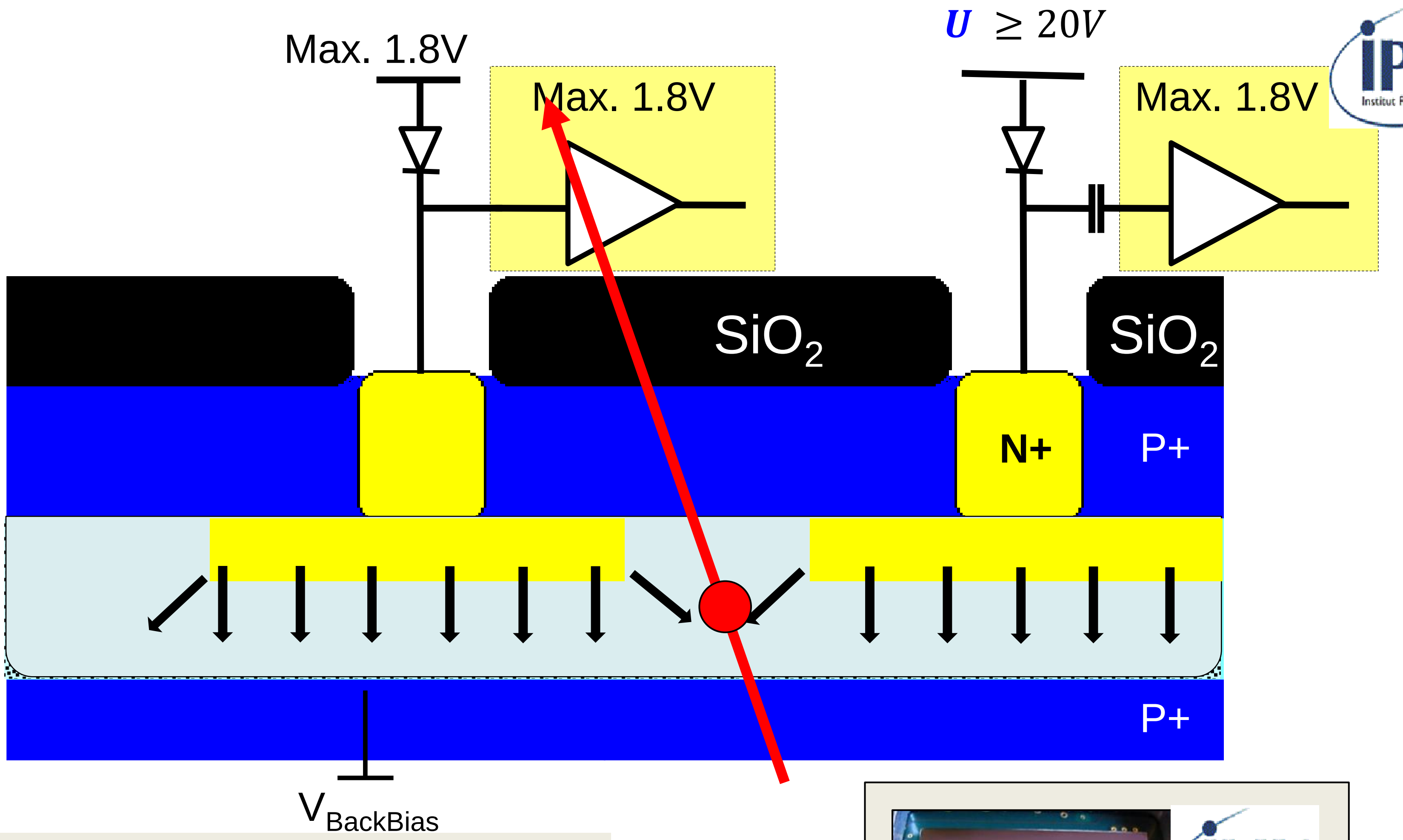
Radiation tolerance: D-MAPS

Flat diodes:

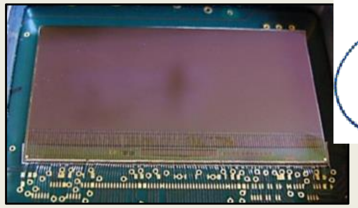
$$W = \sqrt[2]{\frac{2\,\varepsilon_S\,(U_{bi} - U)}{e\,N_A}}$$

Point diodes:

$$W = \sqrt[6^{(?)}]{\frac{2\,\varepsilon_S\,(U_{bi} - U)}{e\,N_A}}$$



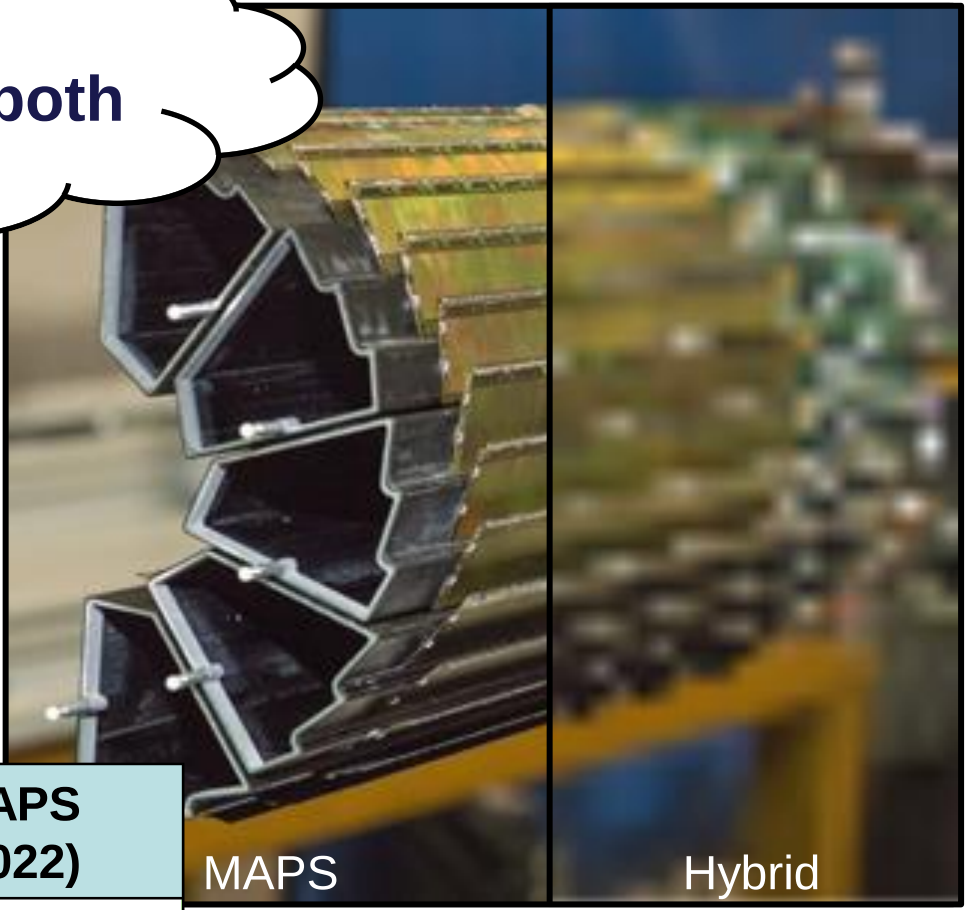
Improvements
- Reduce doping, add back bias, e.g. ALPIDE (hard for >6V).
- Extend diodes (H. Pernegger et al., 2017 JINST 12 P06008)
- Add AC-Pixel (MIMOSIS-1)



MIMOSIS-1

MAPS – the hope and limitations

We need both



	Hybrid pixels (2000)	MAPS (2000)	MAPS (2022)
Single point resolution	~ 30 µm	~2 µm	
Material budget	~ 500 µm Si	~ 50 µm Si	
Time resolution	25 ns	~10 ms	
Radiation hardness	~10^{15} n_{eq}/cm²	10^{12} n_{eq}/cm²	

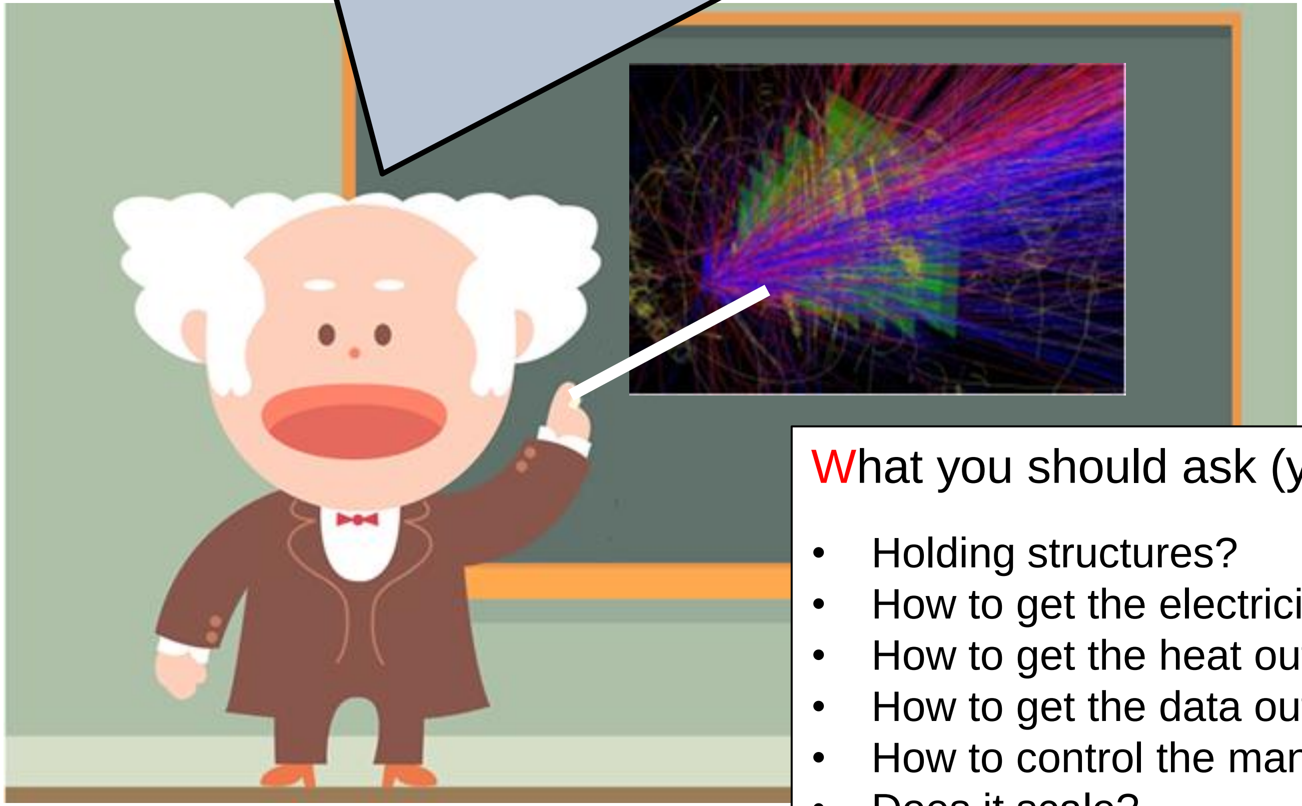
→ ~10 ns (65 nm technology)

And Moore's law goes on…

Detector integration

Again, this structure will be fixed with

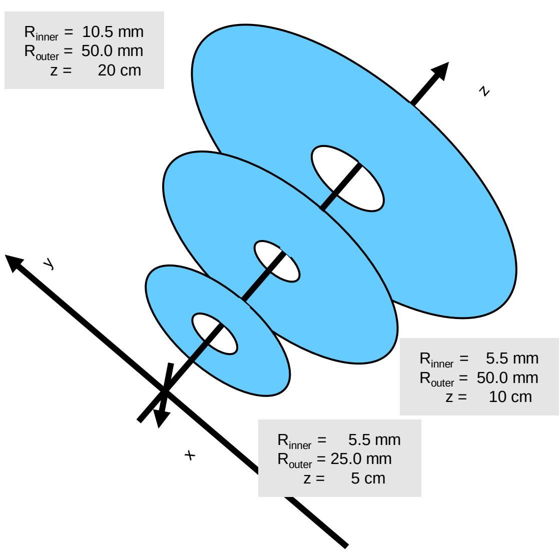
the novel ***Anti Gravitation Glue™***.

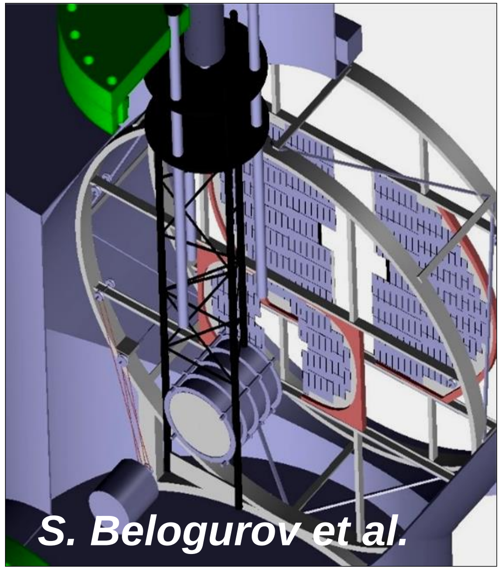


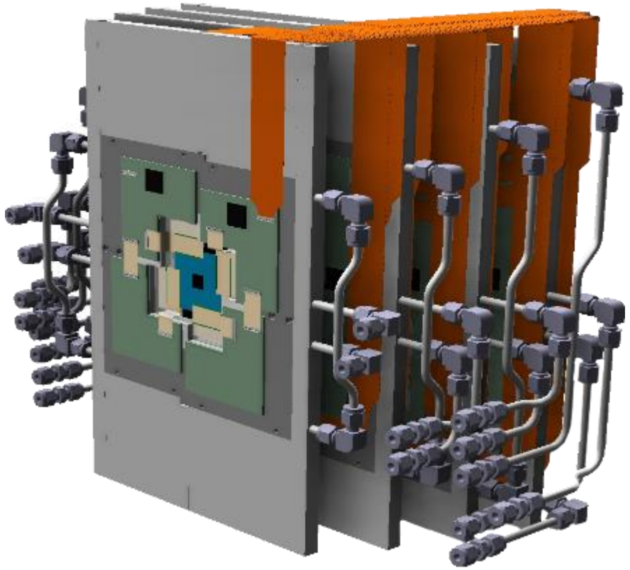
What you should ask (yourself):

- Holding structures?
- How to get the electricity in?
- How to get the heat out?
- How to get the data out (mind finite data bandwidth of cables)?
- How to control the many sensors?
- Does it scale?
- Will it tolerate radiation (no standard ICs)?

Pictures of a detector project (CBM-MVD)




S. Belogurov et al.



2004

- Flying disks.
- Technology unknown.
- No material estimate.

2007 (painting)

- Rough guess on technology.
- Rough guess on material.
- 2/4 stations missing.
- Simple digitizer model.

2015

- Material gets realistic.
- Sensor models.
- 2 stations added to help tracking.

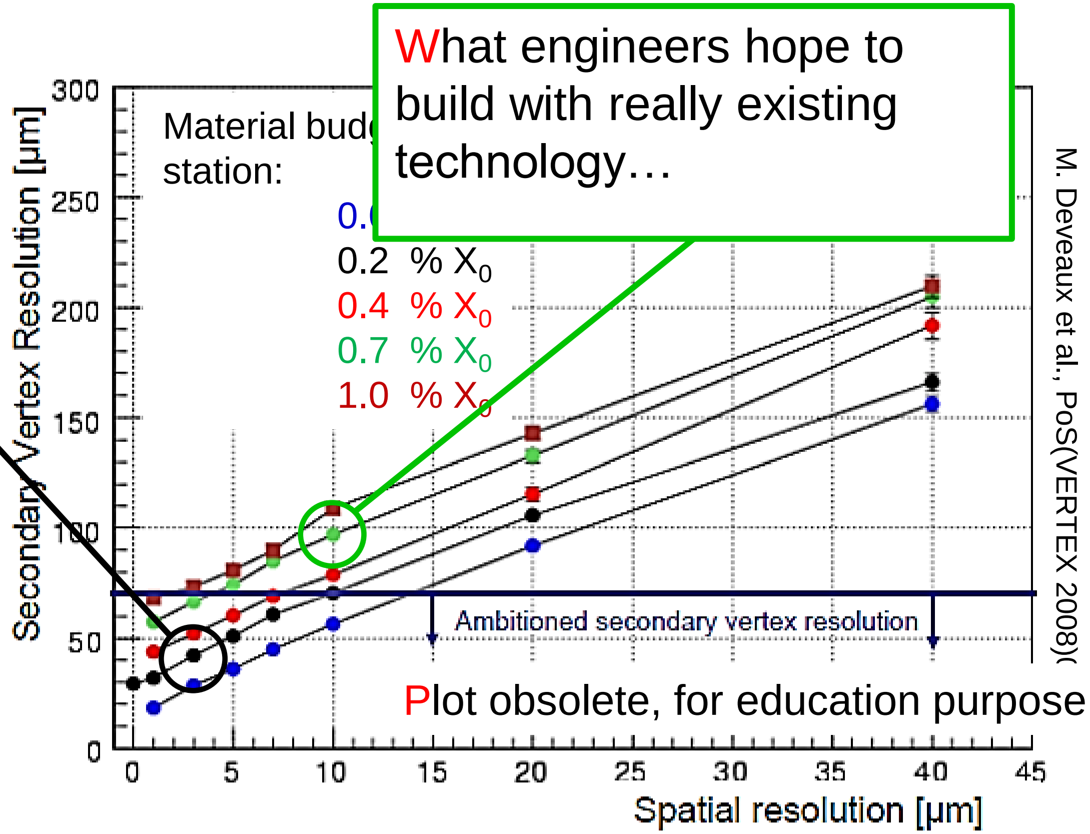
Used for many feasibility studies of CBM physics.

Inaccurate material may cause substantial uncertainties.

Simulation vs. engineering

CBM - MVD – secondary vertex resolution

What physicists simulated because „we didn‘t know the specs of the cables yet“…



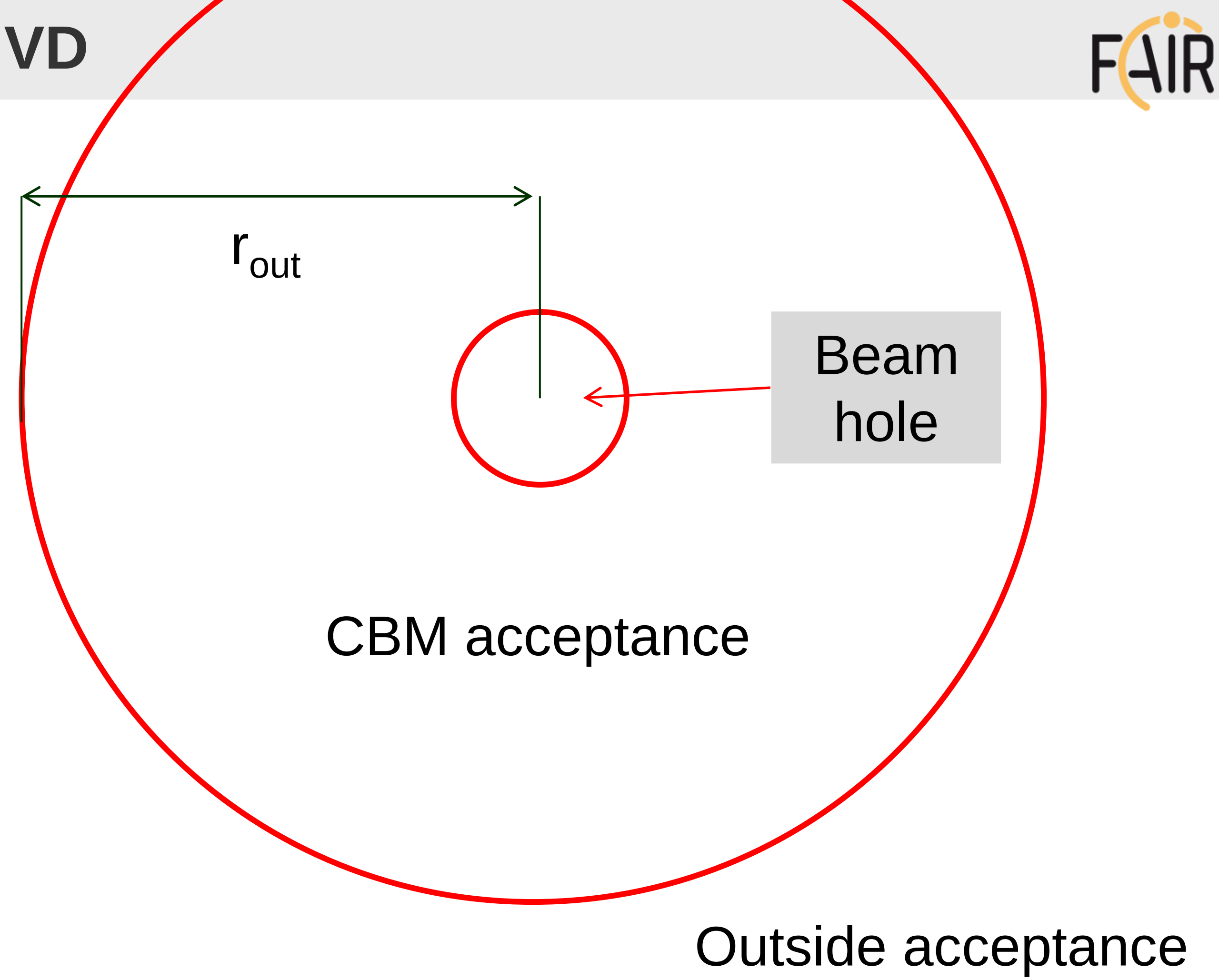
What engineers hope to build with really existing technology…

M. Deveaux et al., PoS(VERTEX 2008)(

Plot obsolete, for education purpose only.

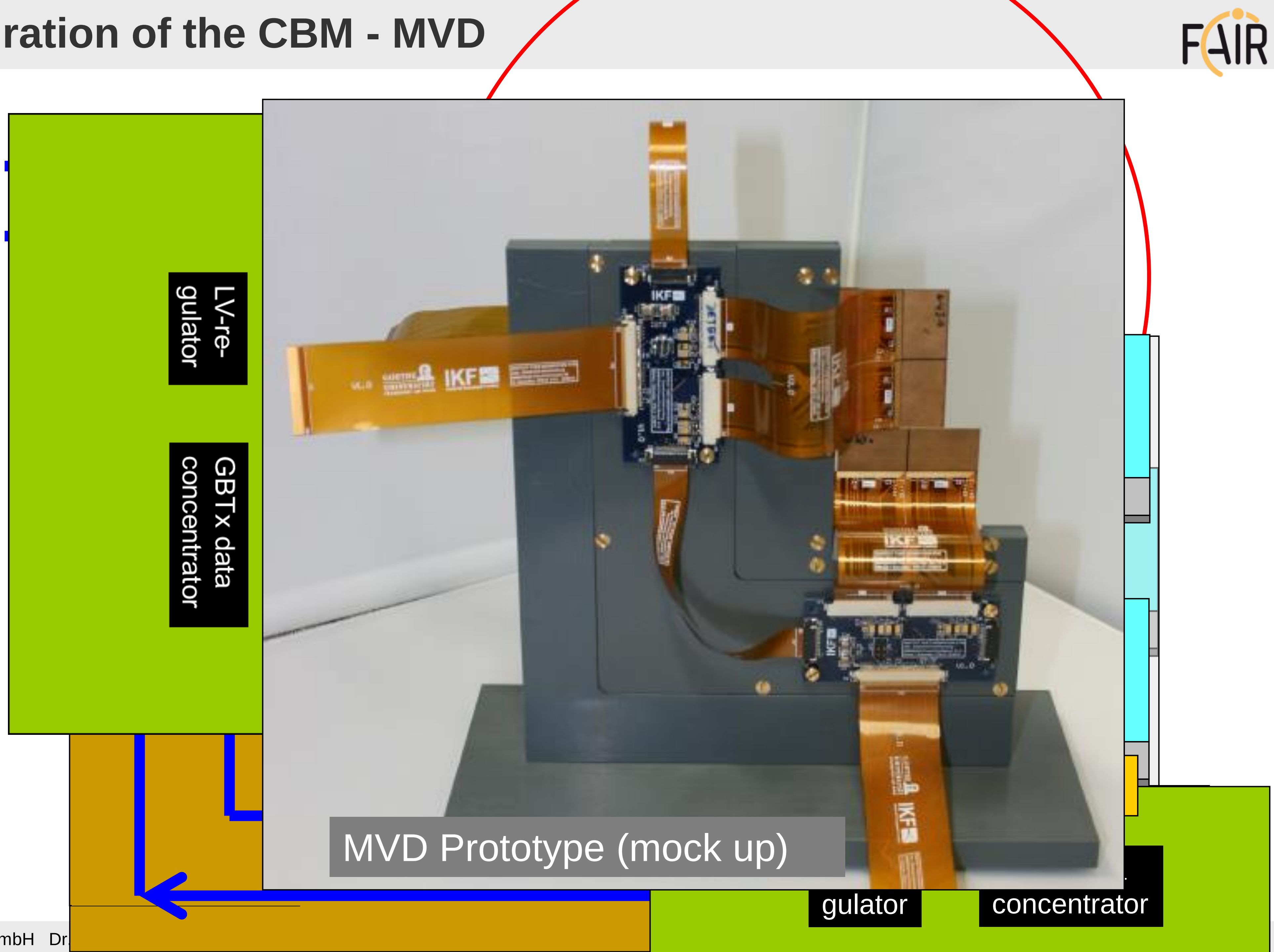
Detector material budget is dominated by the infrastructure.
Missing information turns often into too optimist physics simulations.
Remain cautions, conservative: You see what you put.

Integration of the CBM - MVD



Vacuum operation requires actively cooled device.
- Use cooling support from diamond to move heat out of acceptance
- Put heat sink and FEE outside acceptance

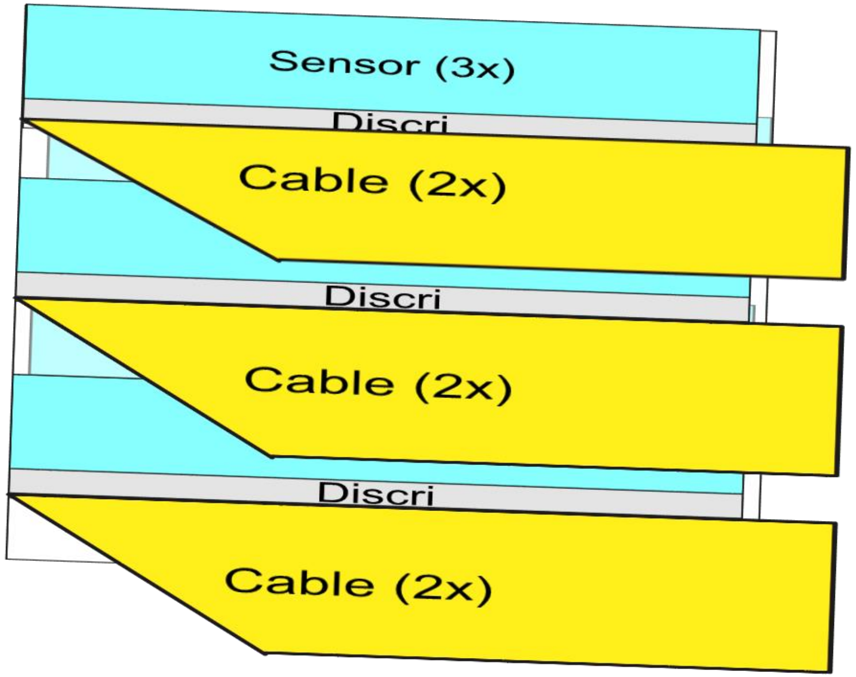
Integration of the CBM - MVD



MVD Prototype (mock up)

Check for scaling and real world performance

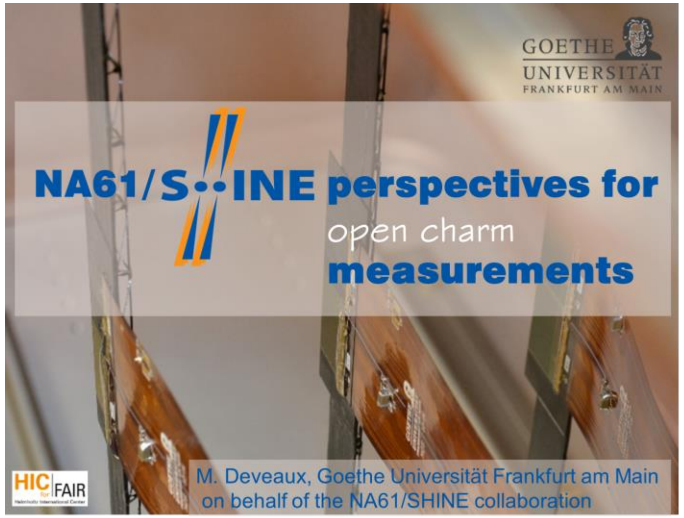
PRESTO:
Prototype of a quarter station incl. sensors (MIMOSA-26), cables, support etc.



Integration completed. Test:

- Vacuum compatibility
- Temperature cycling
- …

(More than) A spin-off:



GOETHE UNIVERSITÄT FRANKFURT AM MAIN

NA61/SHINE perspectives for open charm measurements

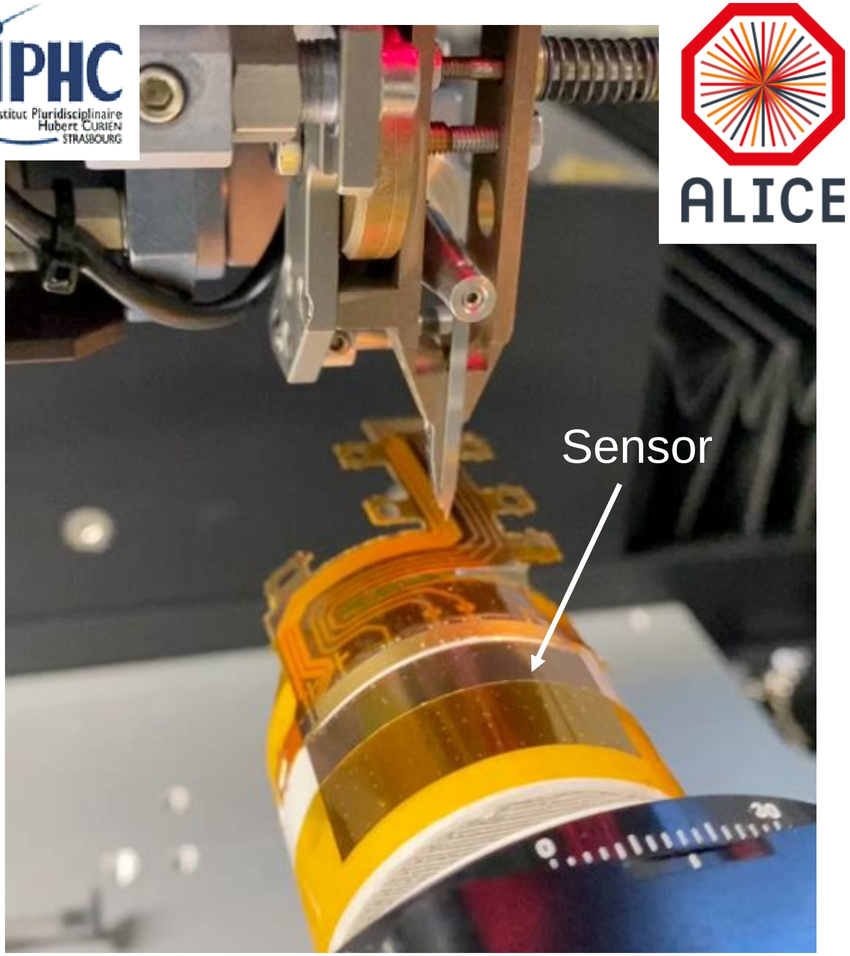
M. Deveaux, Goethe Universität Frankfurt am Main
on behalf of the NA61/SHINE collaboration

HIC for FAIR

M. Deveaux for NA61/SHINE,
SQM2017, Utrecht, Netherlands

The NA61/SHINE vertex detector uses (and tests) MVD prototype/PRESTO electronics

Outlook: The ALICE-ITS3 vision.



ALICE ITS-3 program:
Curved – Wafer detectors

Summary and conclusion

CMOS Monolithic Active Pixel Sensors

- Show lowest material budget together with highest granulartity.
- Integrate pixels and electronics on one system-on-a-chip.
- Can be mass produced with industrial CMOS processes at low cost.

- Are the coolest detectors ever made (my biased personal opinion).

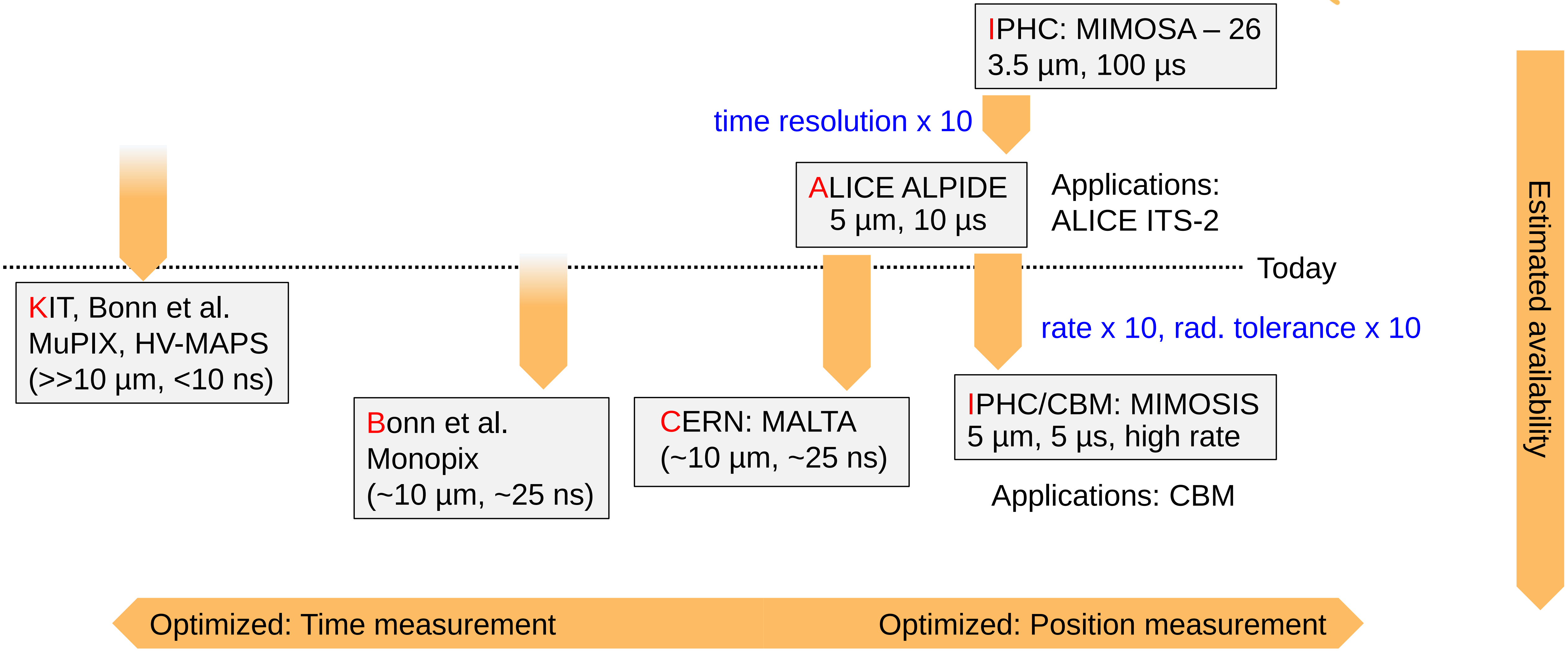
When building detectors, consider that:

- the material budget and performance of detectors is determined by infrastructure.
  ⇒ Optimizing sensors wins the battle, optimizing cables and cooling wins the war.

- Being too optimist in simulations is mostly self-cheating.
  ⇒ Try to be conservative if you are missing detailed knowledge.

The performance of MAPS was improved by a factor 1000 during the past 20 years…
… and the story has just started.

MAPS – Outlook: R&D streams



IPHC: MIMOSA – 26
3.5 µm, 100 µs

time resolution x 10

ALICE ALPIDE
5 µm, 10 µs

Applications:
ALICE ITS-2

Today

KIT, Bonn et al.
MuPIX, HV-MAPS
(>>10 µm, <10 ns)

Bonn et al.
Monopix
(~10 µm, ~25 ns)

CERN: MALTA
(~10 µm, ~25 ns)

rate x 10, rad. tolerance x 10

IPHC/CBM: MIMOSIS
5 µm, 5 µs, high rate

Applications: CBM

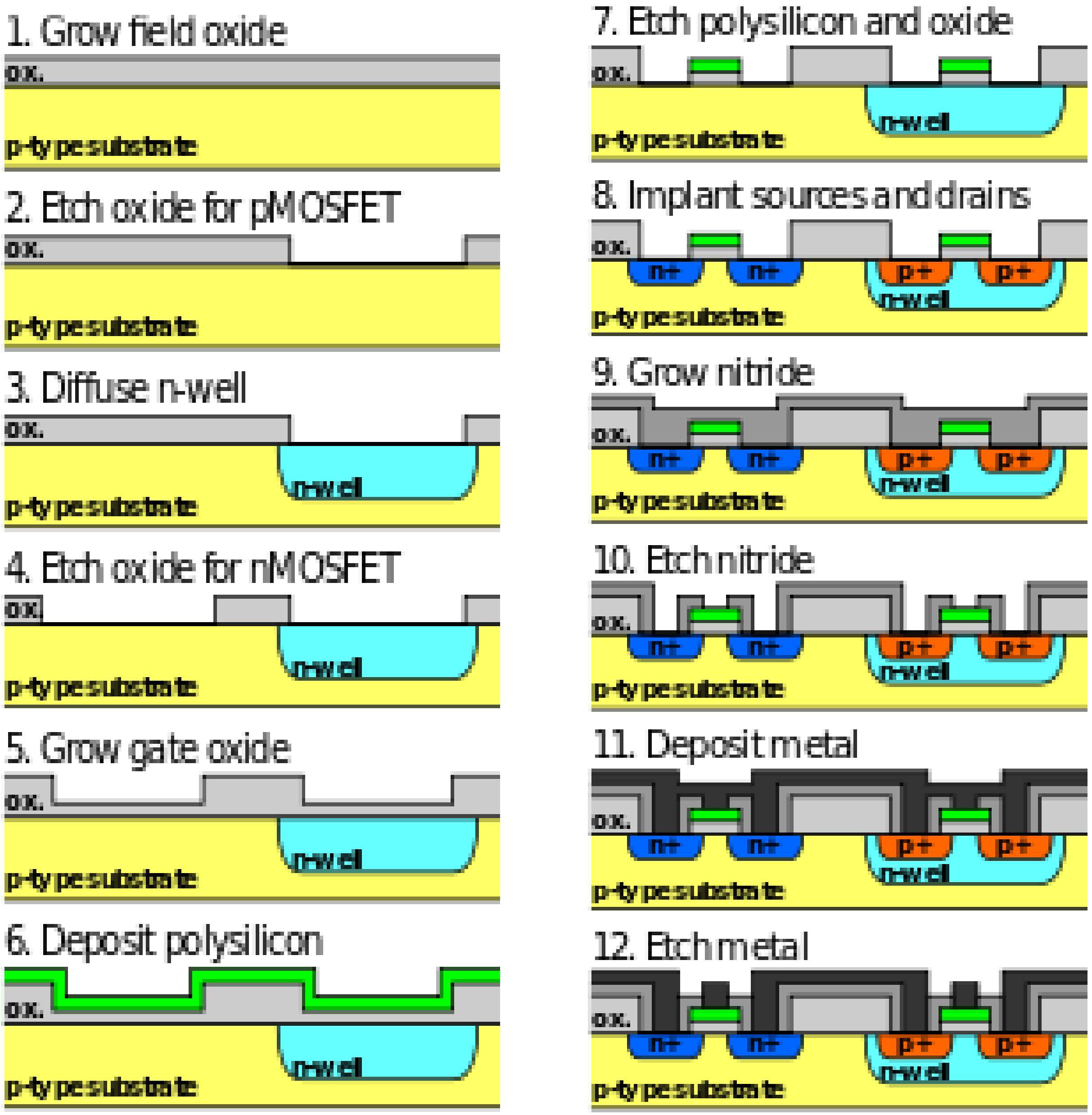
Estimated availability

Optimized: Time measurement

Optimized: Position measurement

Toward new frontiers:
Tower/Jazz 65 nm CIS technology (CERN, DESY, IPHC…)

Once again in slow…



CMOS production:

- Is highly complex (special companies needed).
- Works with lithography.
- Needs ~ 20 – 30 masks for modern processes.