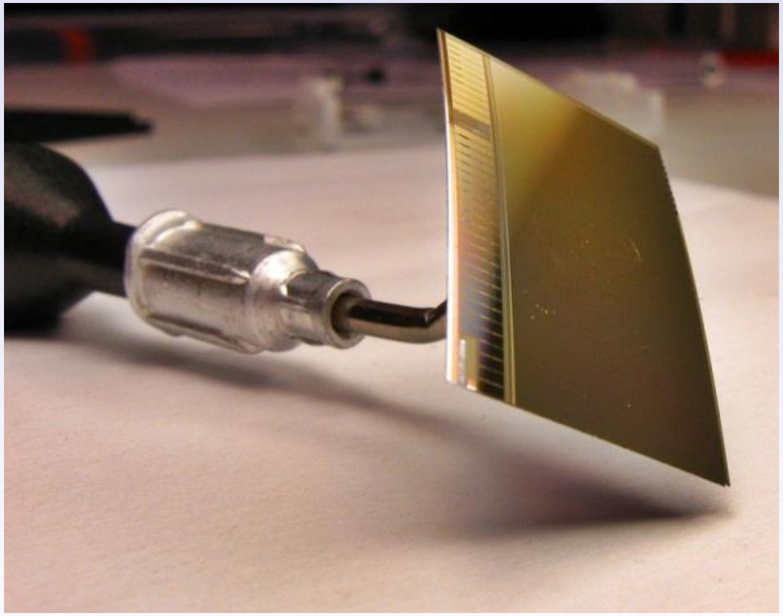
CMOS Monolithic Active Pixel Sensors

A tool to measure open charm particles

M. Deveaux
Goethe-Universität
Frankfurt/M



Sherlock Holmes and Mystery of the Soup

or

How to build a webcam based carrot detector

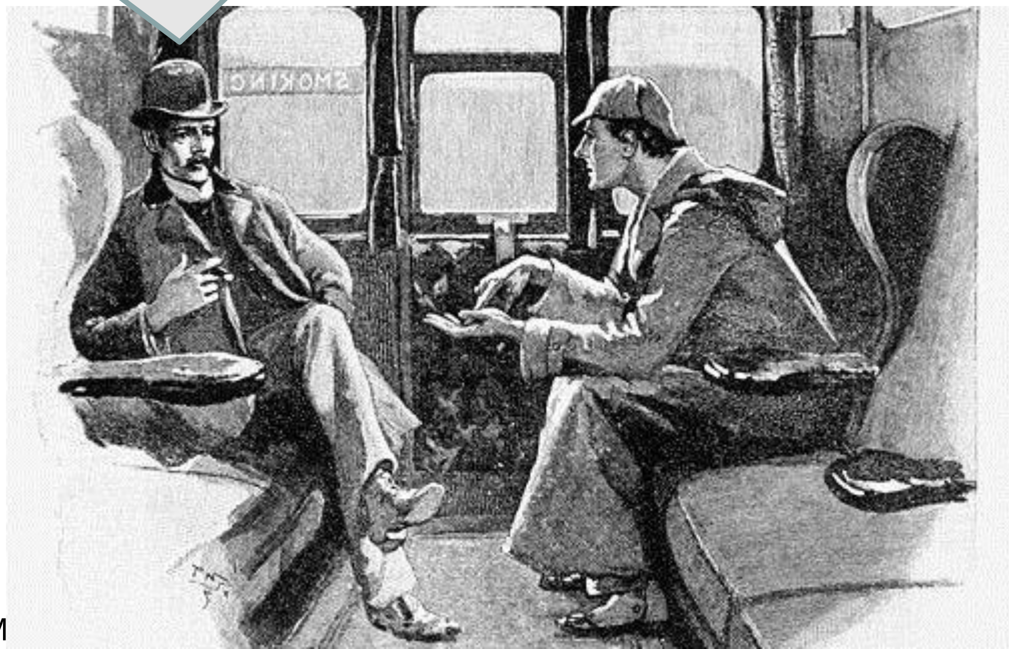
M. Deveaux
Goethe-Universität
Frankfurt/M

A Question to Sherlock Holmes

Prof. Dr. Johanna Wanka, Federal Minister of Research, Germany

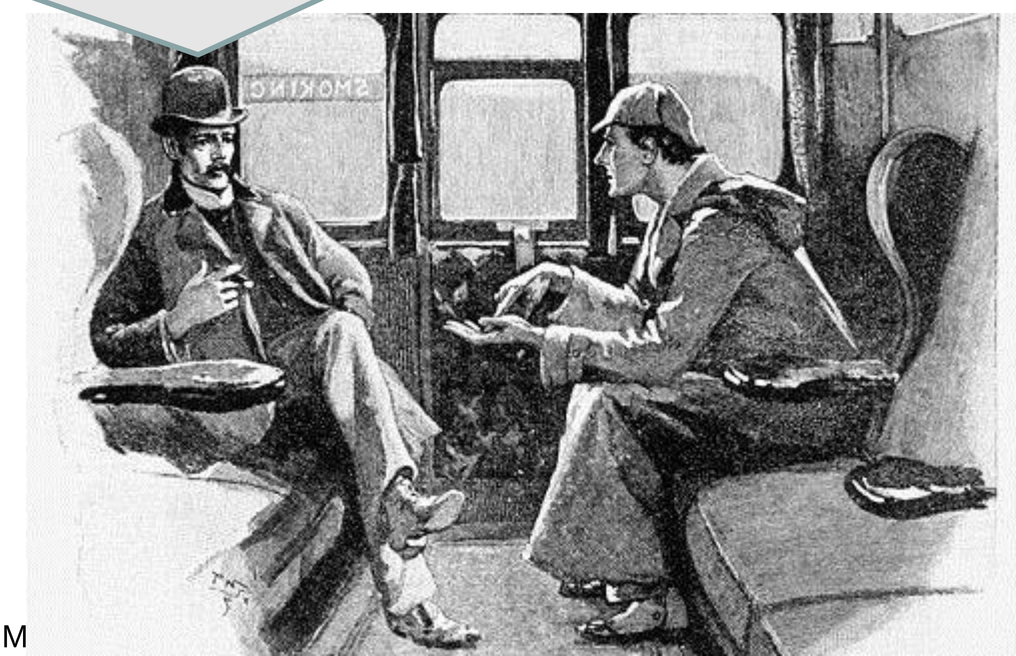
The soup

The cook



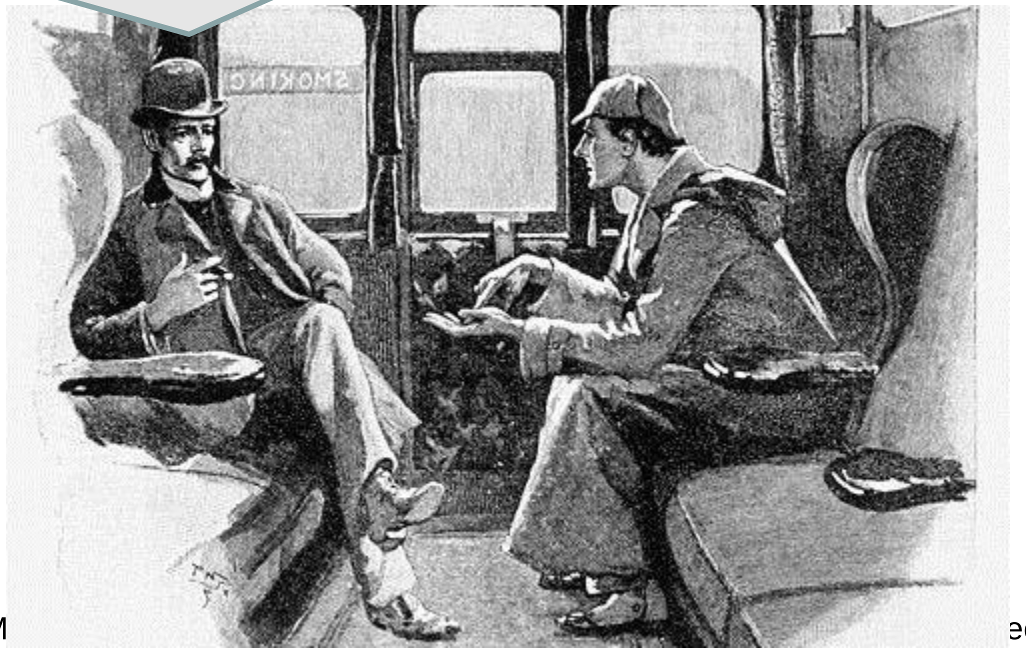
Sherlock Holmes Quest

How can one check that the soup has cooked?



Sherlock Holmes Quest

Sherlock Holmes Quest



Sherlock Holmes Quest

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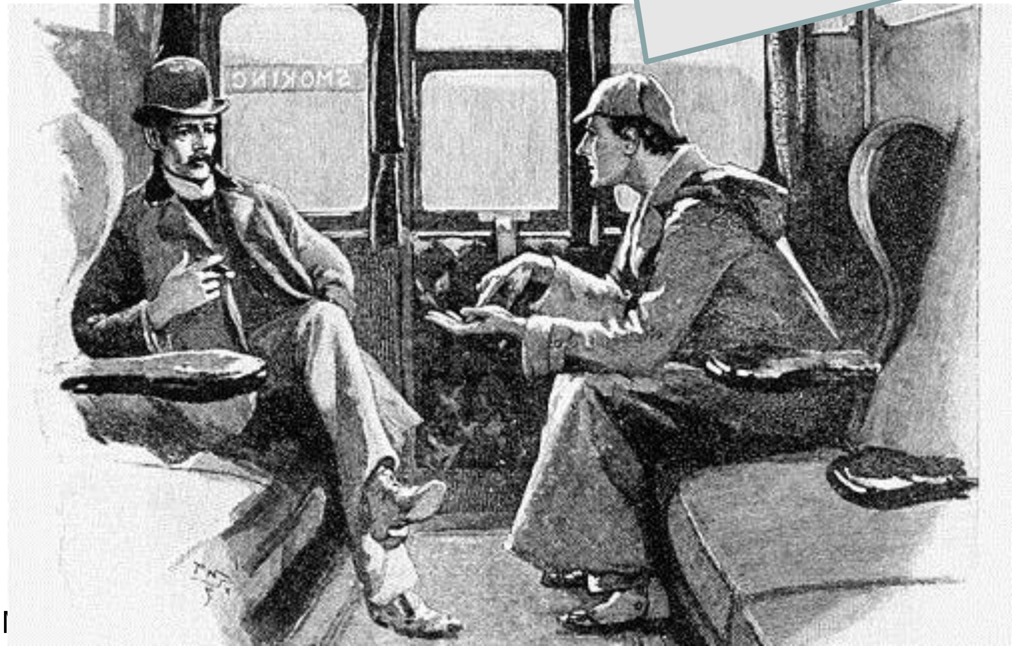
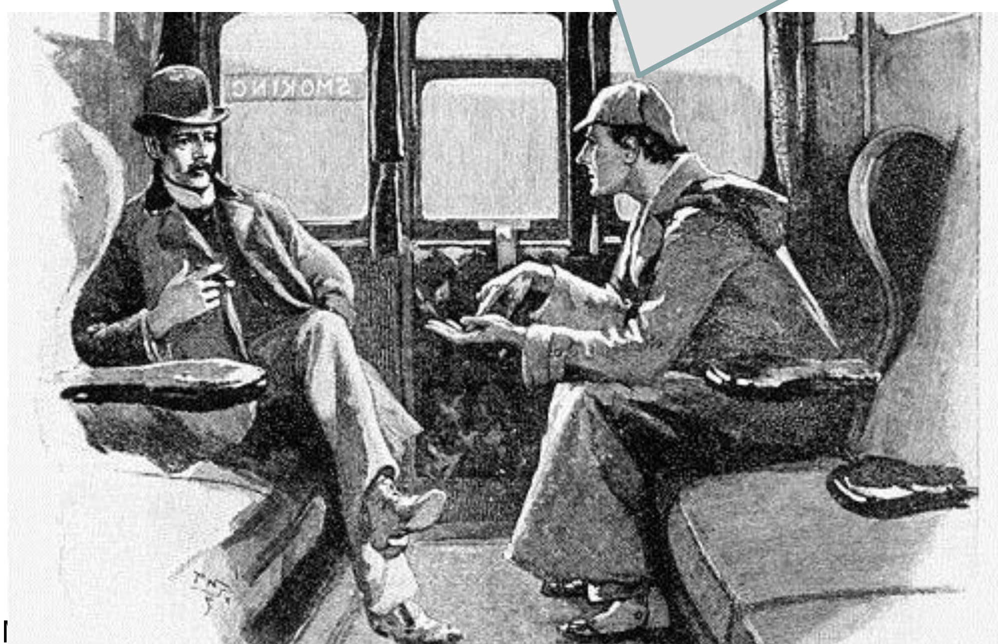


Sherlock Holmes Quest

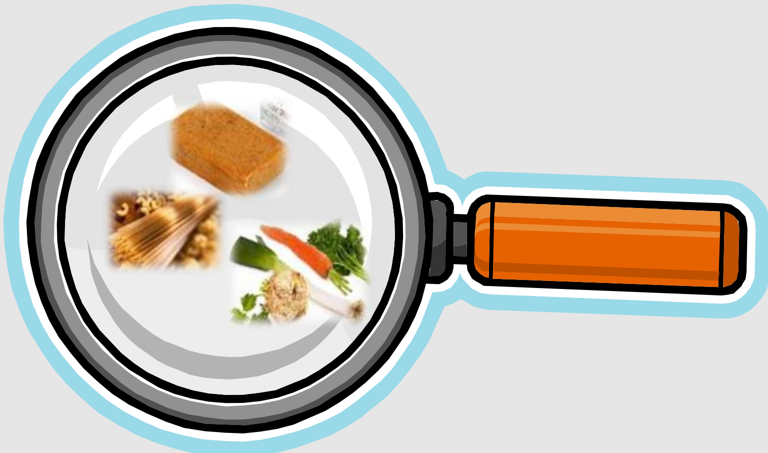
Dissolves fast

Gets quickly soft if cooked

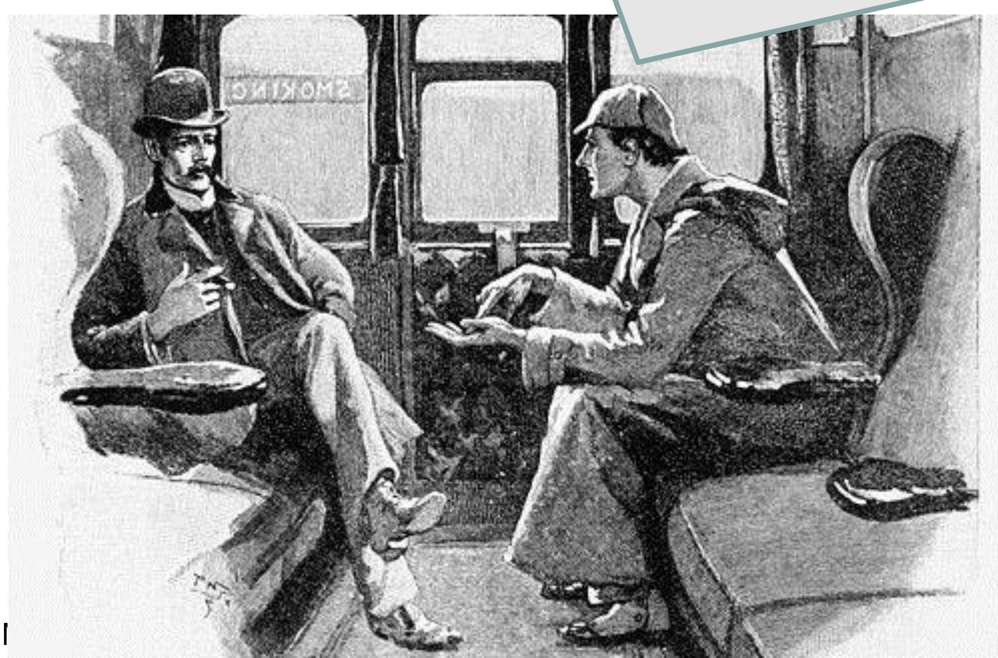
Gets slowly soft if cooked



Sherlock Holmes Quest



Lets test ingredients, which keep information on the cooking process.

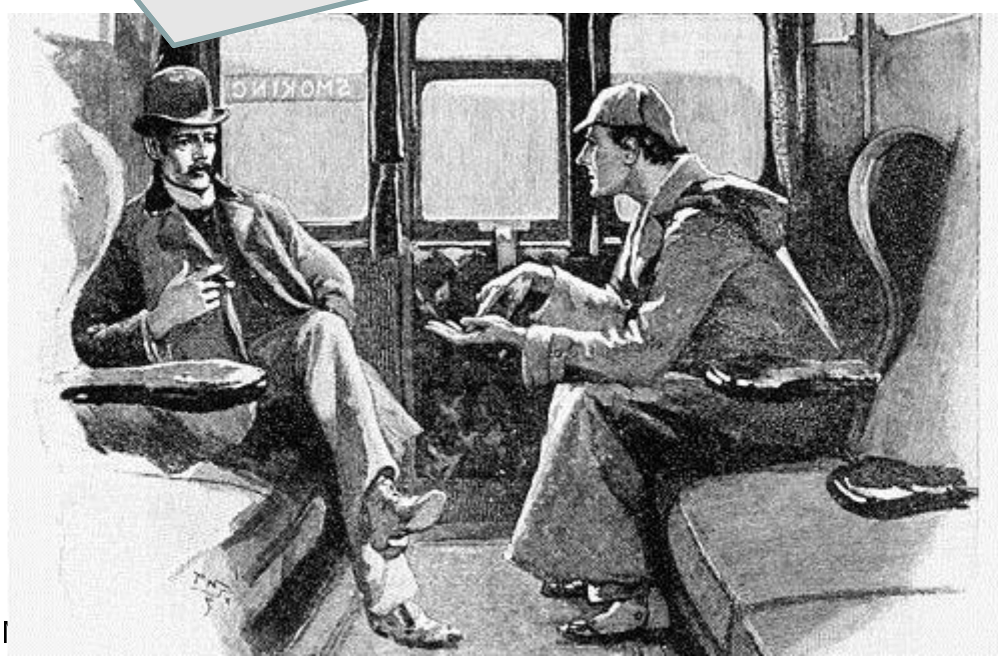


Sherlock Holmes Quest

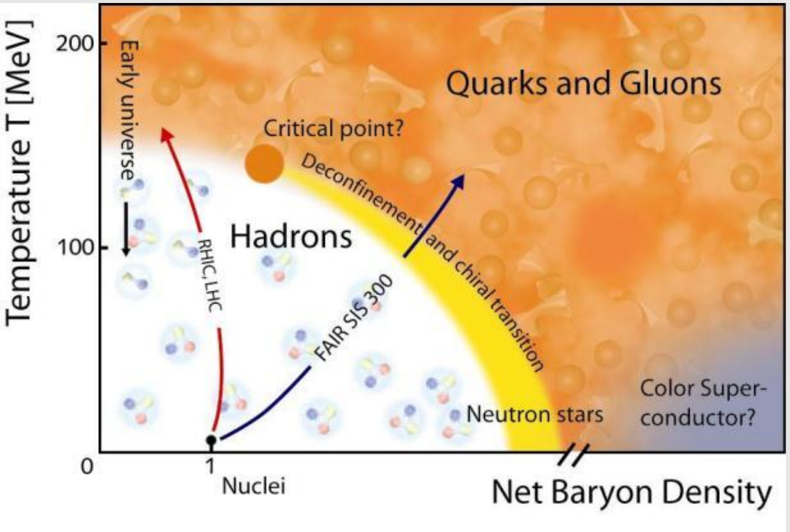
Dissolves also at room temperature

Keeps softening after cooking

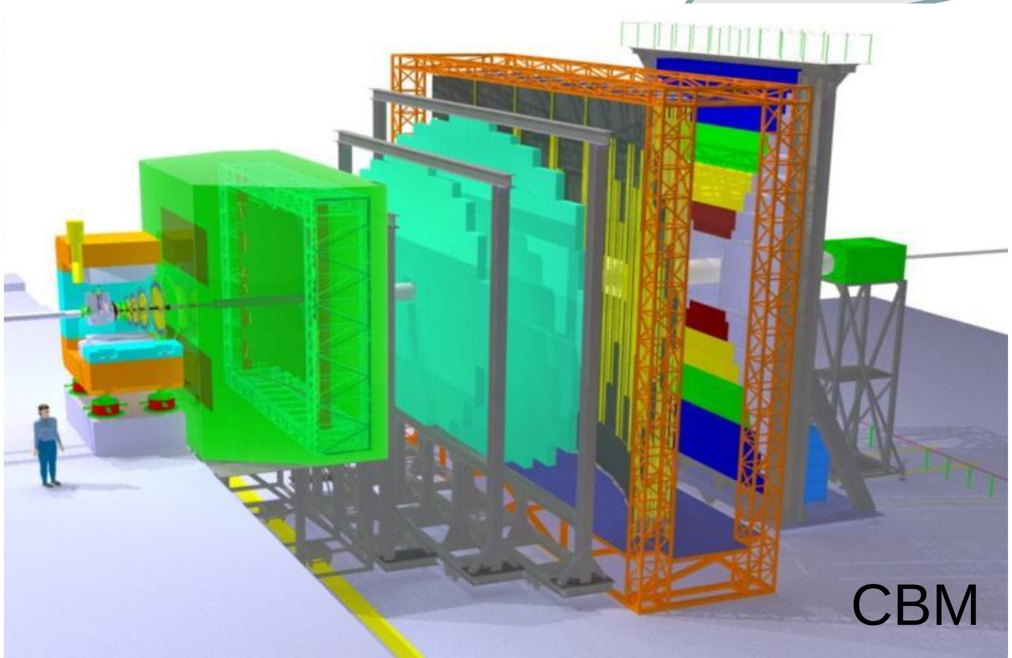
Reacts slowly, might overlook cooking



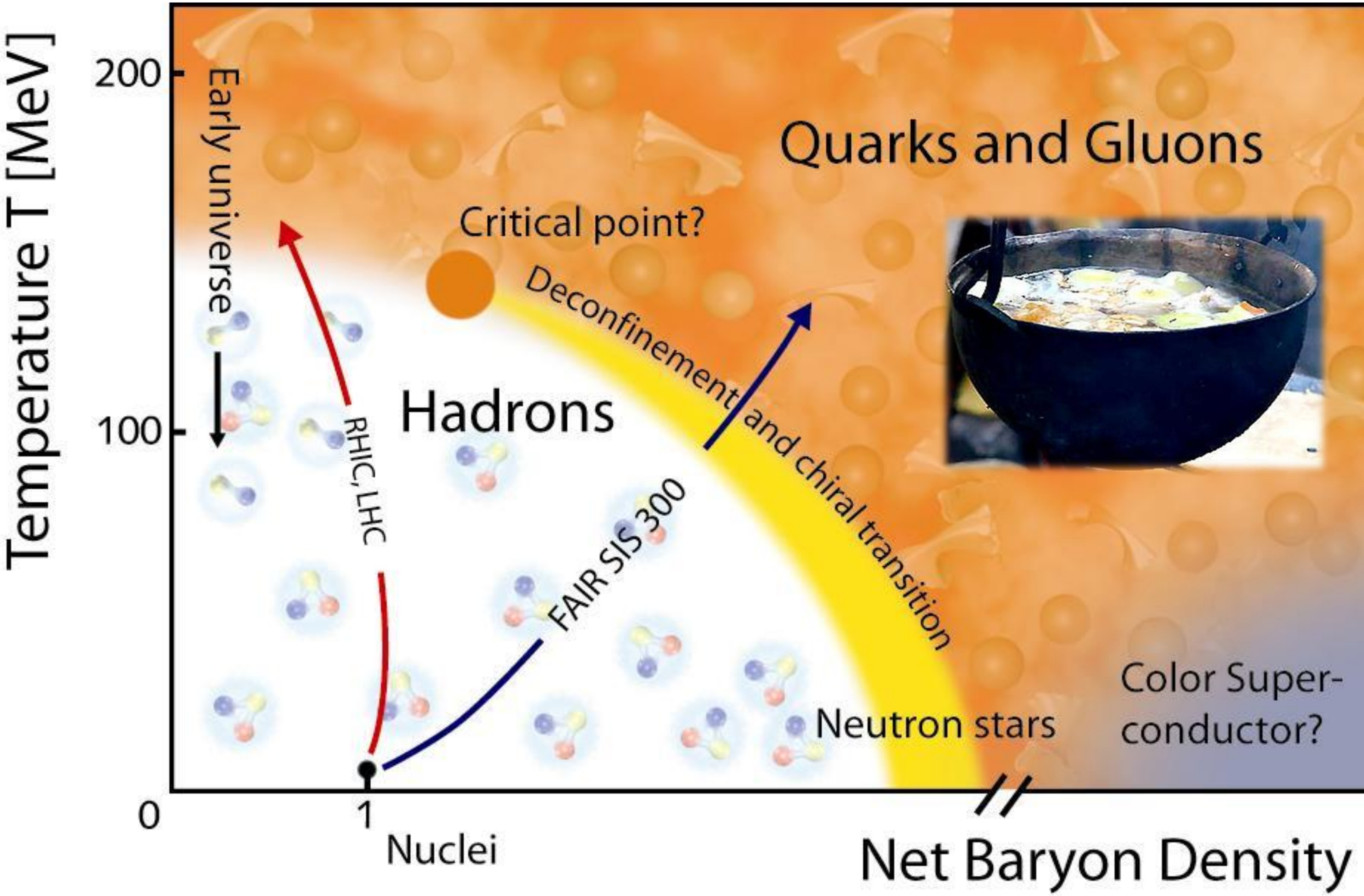
The Quest of modern heavy ion experiments



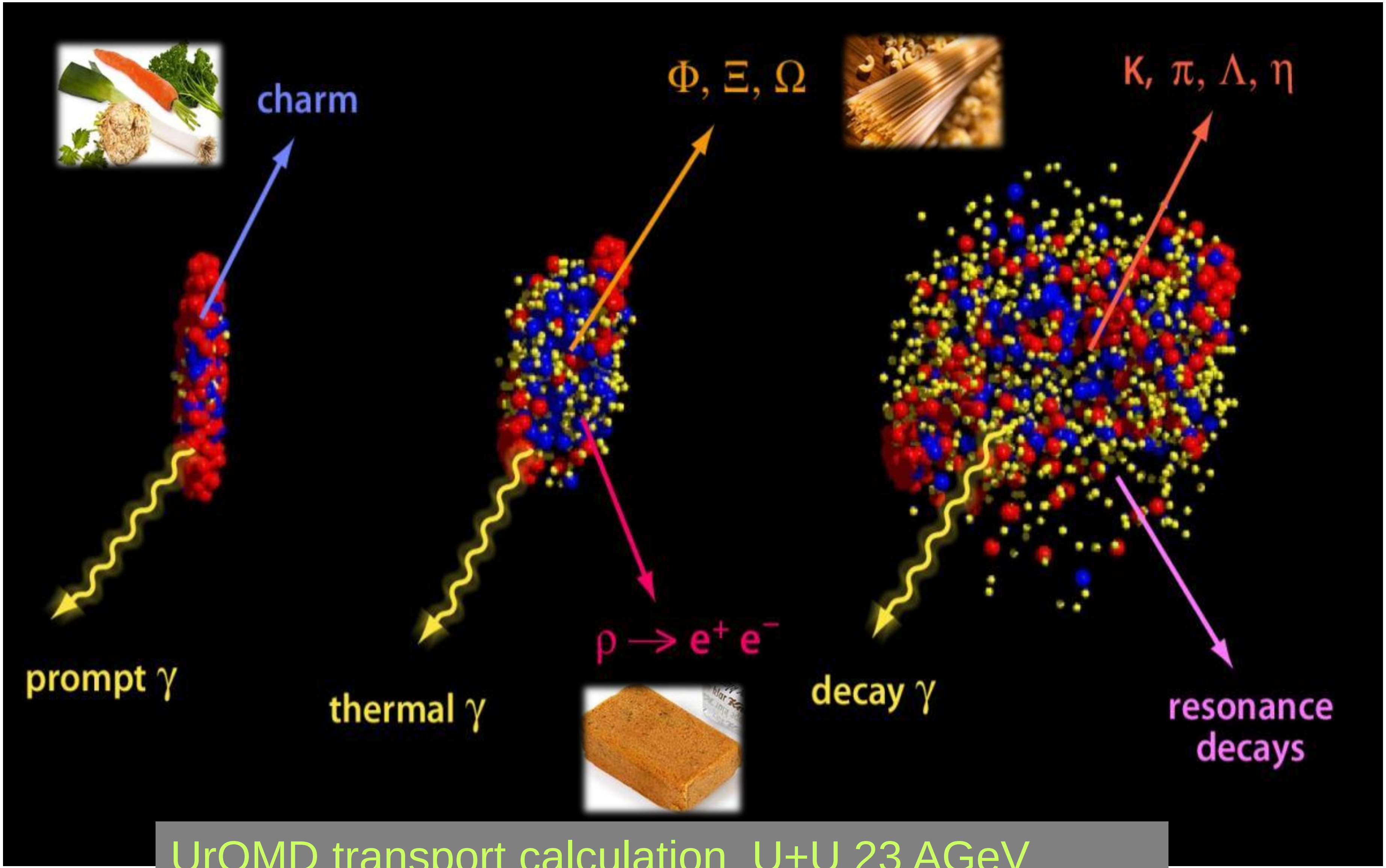
We will have to test as many ingredients as possible to obtain a conclusive answer.



What means soup: Hadronic Matter



What means carrot: Observables



UrQMD transport calculation U+U 23 AGeV

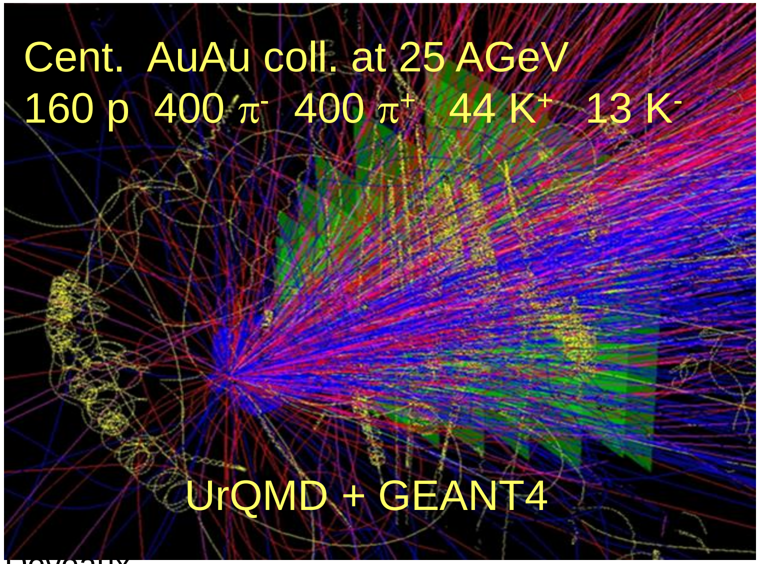
My topic today

How can

this technology help to…

find this…

in this!

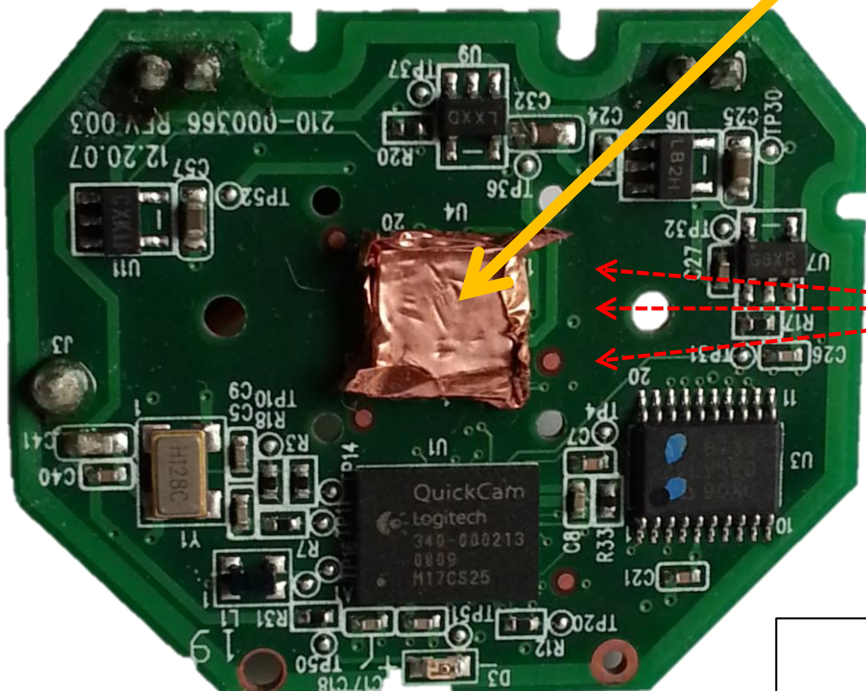


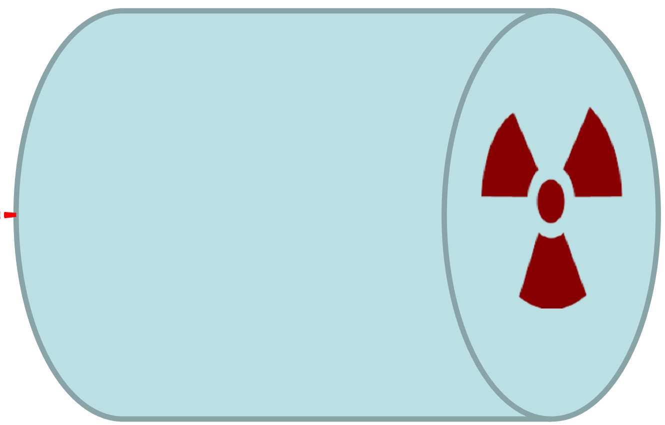
I. Vassiliev, C. Dritsa

Why webcams?

Why webcams

Add metall foil to deflect light

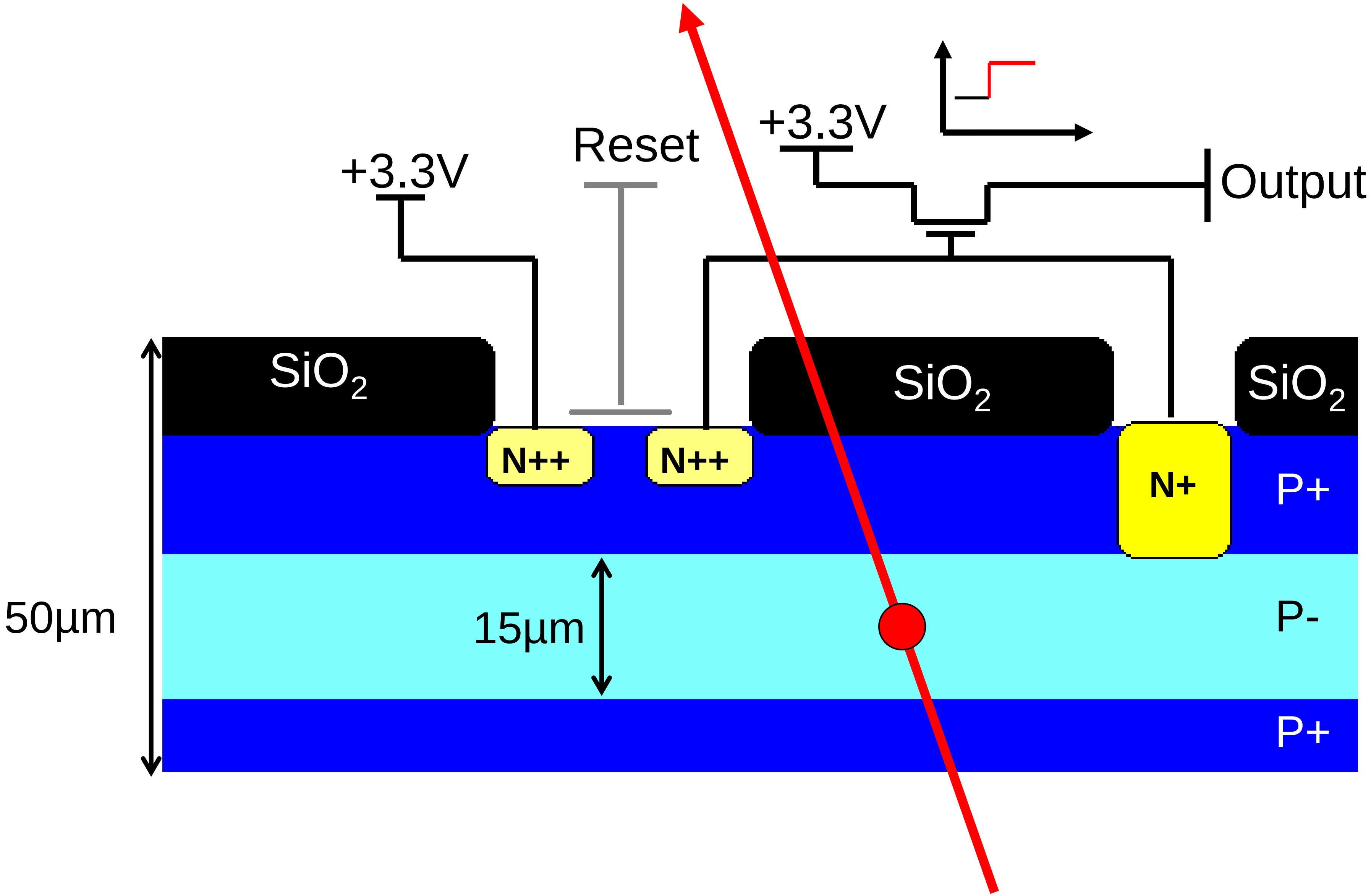




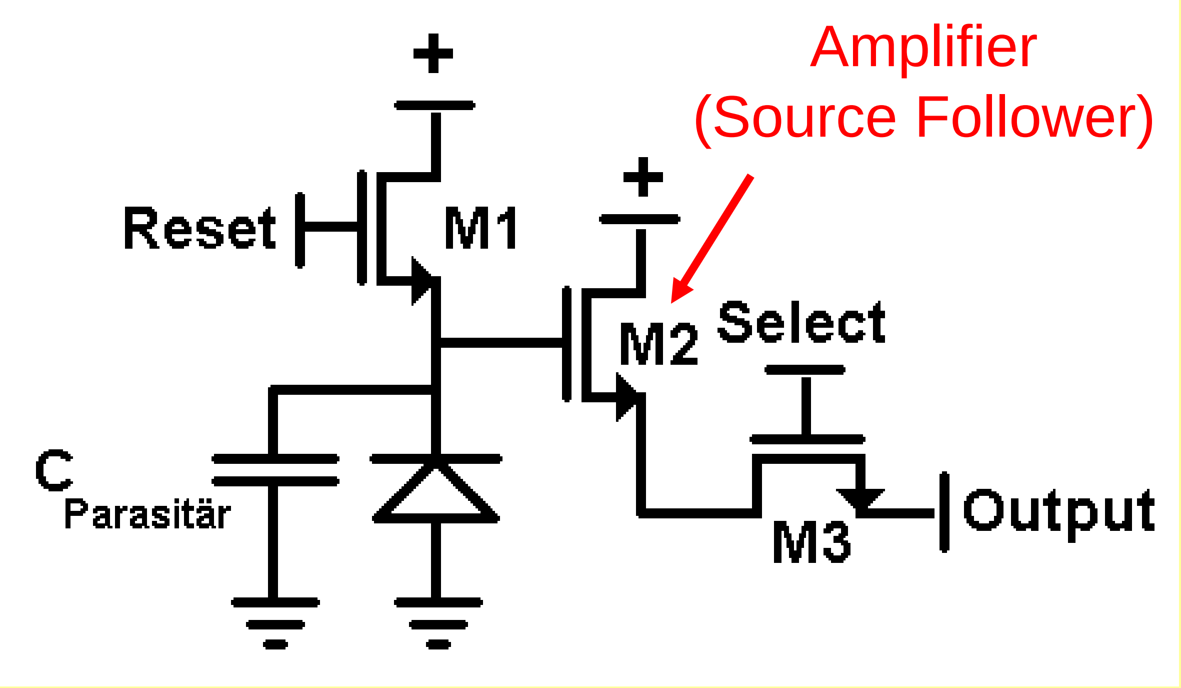
A little radioactivity
(Am-241, 60 keV photons work fine)

Why webcams?

How does a webcam work?

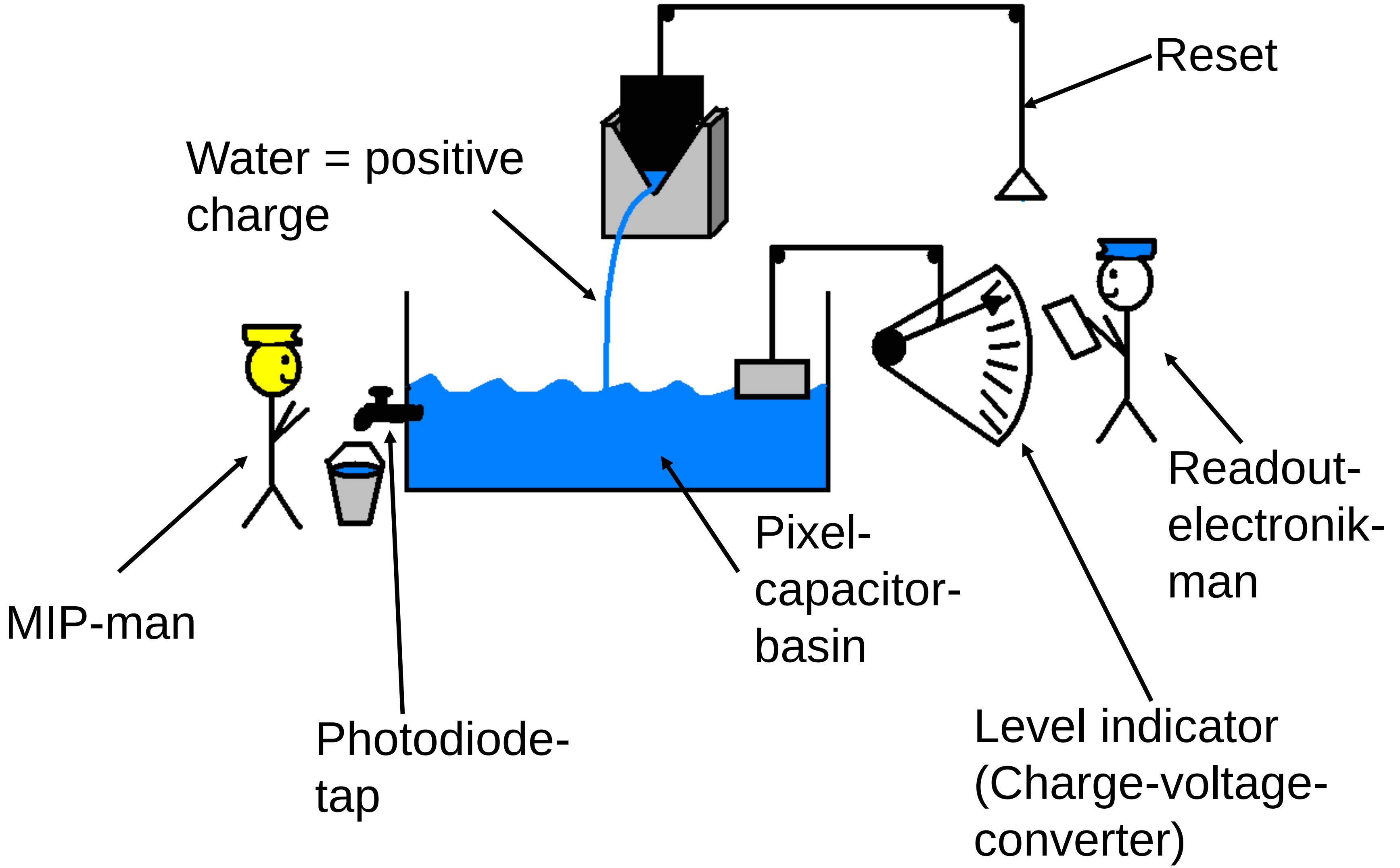


The pre-amplifyer



Layout of a classical Active Pixel
(simplified)

Operation principle of the pre-amplifyer

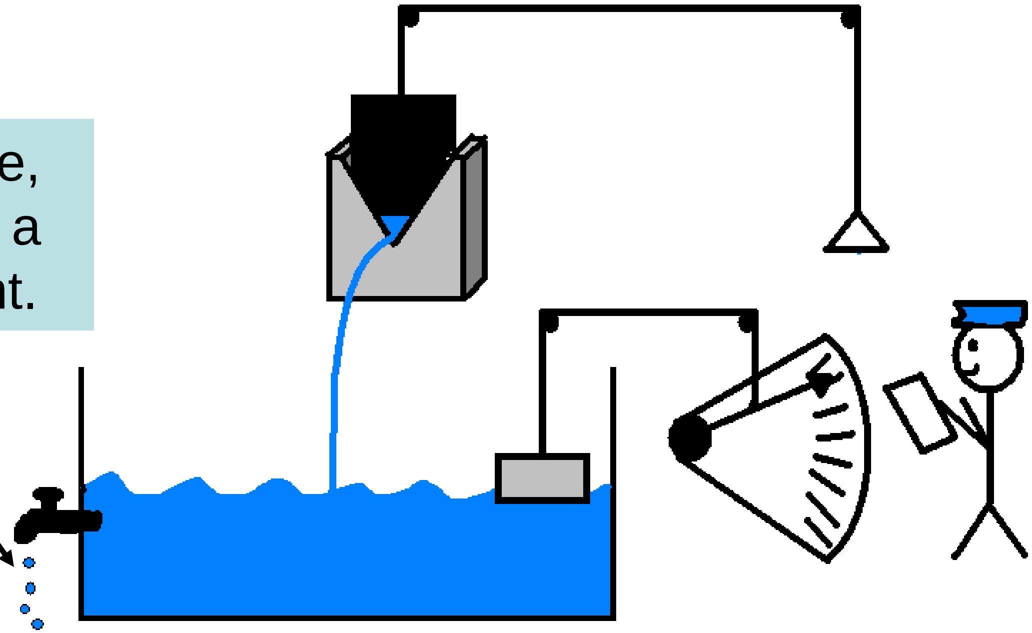


Operation principle of the pre-amplifyer

Readout cycle in three steps:

First step: Readout-electronic-Man gives a Reset

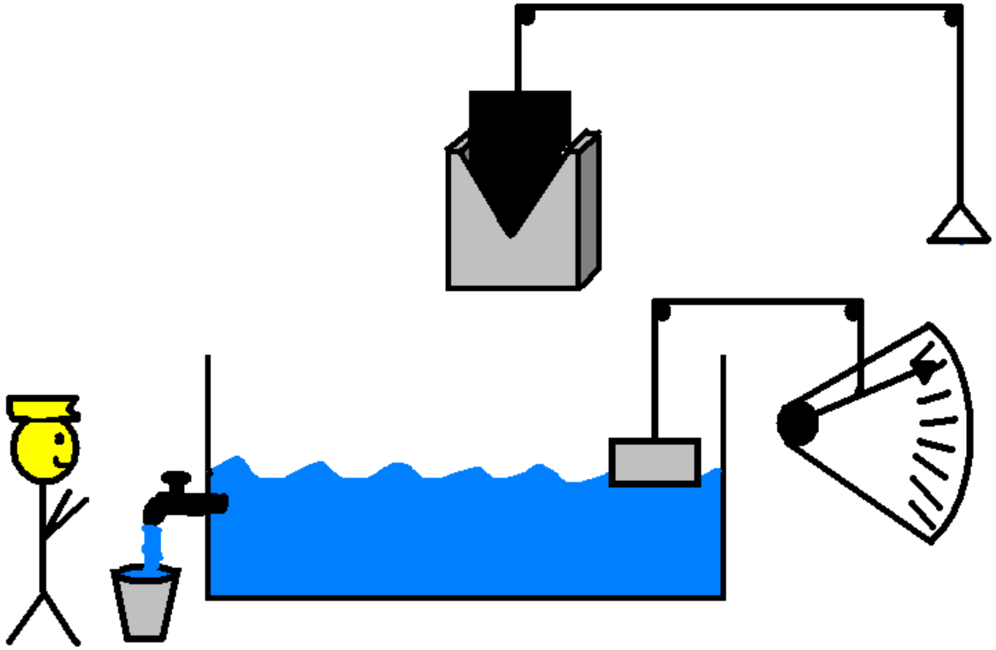
At a photodiode, once observes a leakage current.



When the basin is fully recharged, the water level is noted for reference.

Operation principle of the pre-amplifyer

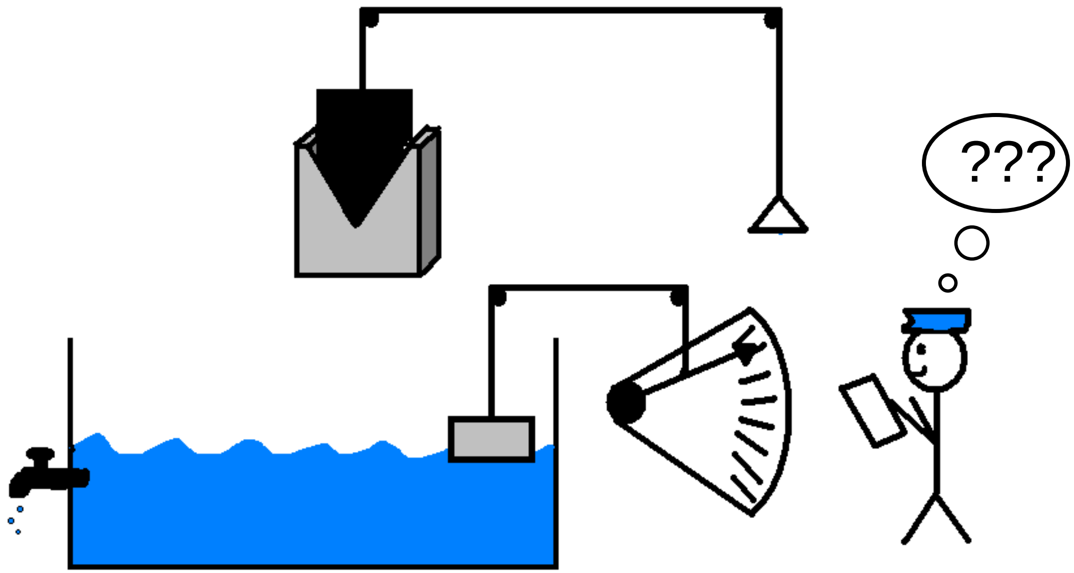
Second step: Readout-elektronic-man has care for his other pixels now



Sometimes MIP-man passes by to take bucket of positiv charge (electrons are collected by the diode after a hit).

The operation principle of the pre-amplifyer

Third step: Readout-elektronik-man returns to check the water-level in the basin.



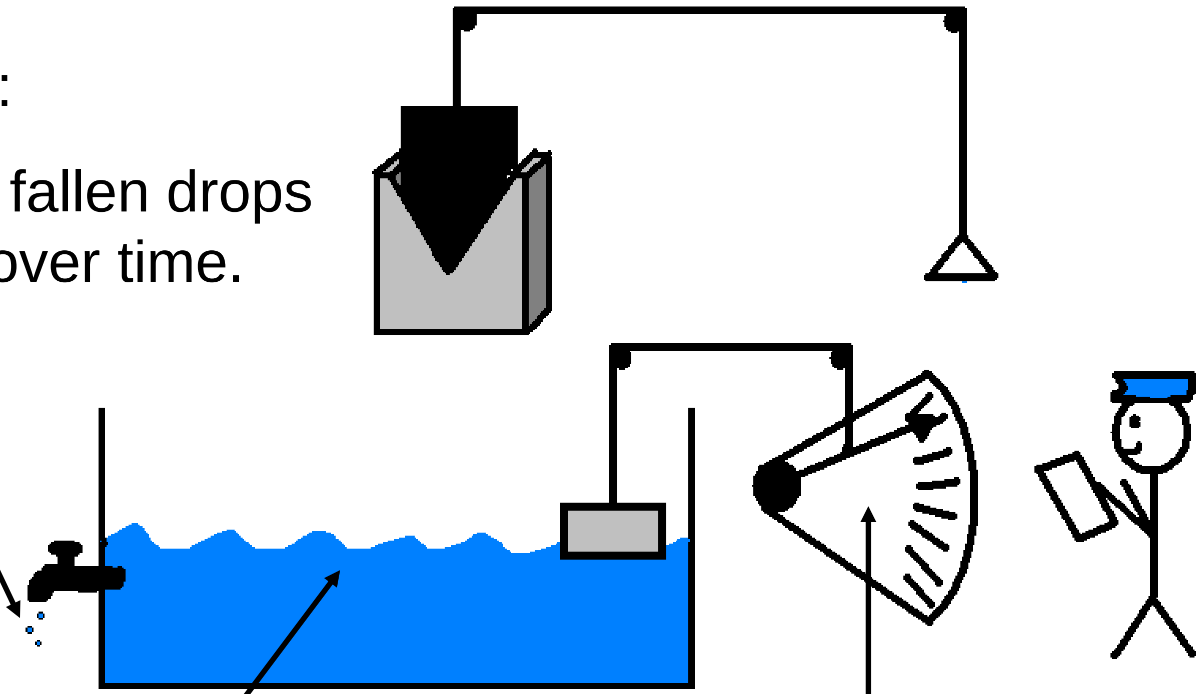
The level has dropped => MIP-man must have passed by.

MAPS pixels may measure even if they are disconnected from readout electronics and power supply.

Some sources of uncertainty

Shot noise:

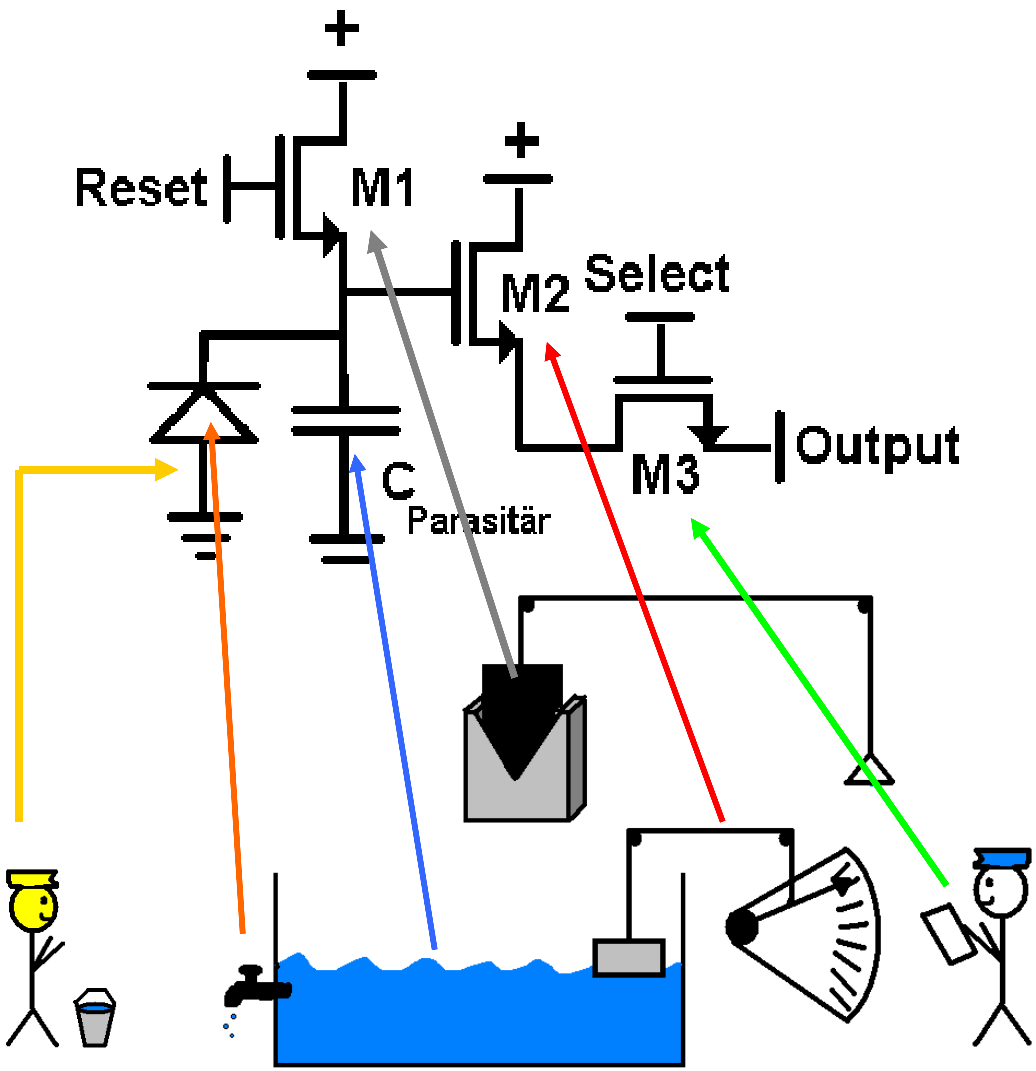
Number of fallen drops fluctuates over time.



Noise

Gain of the indicator is different for each pixel

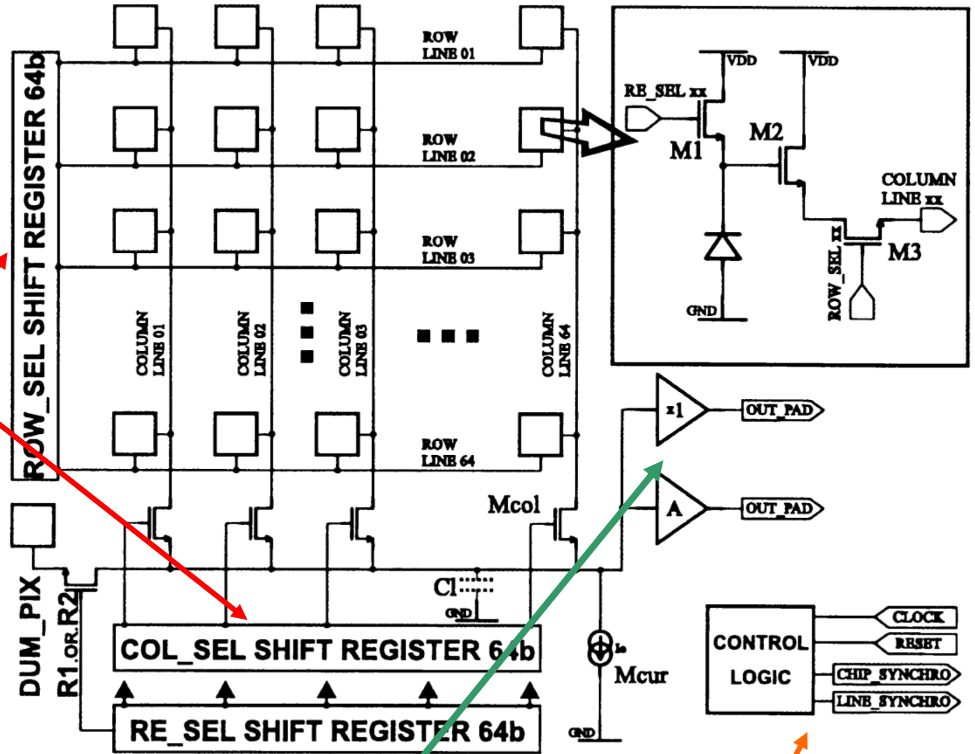
Relation between model and schematics



Readout system of early MAPS

Architecture of MIMOSA I

X- and Y-shift registers to select pixels.

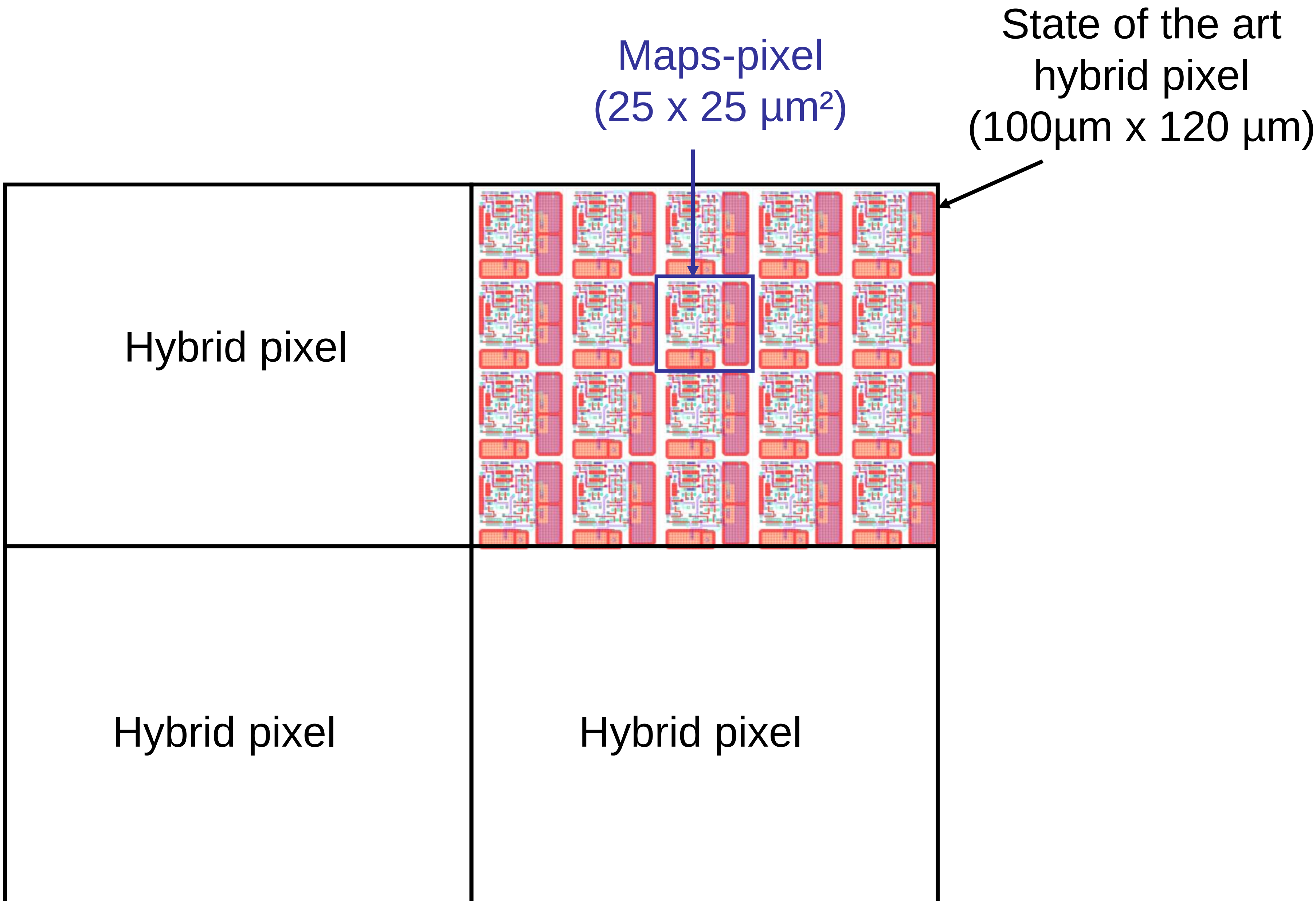


Common Amplifier

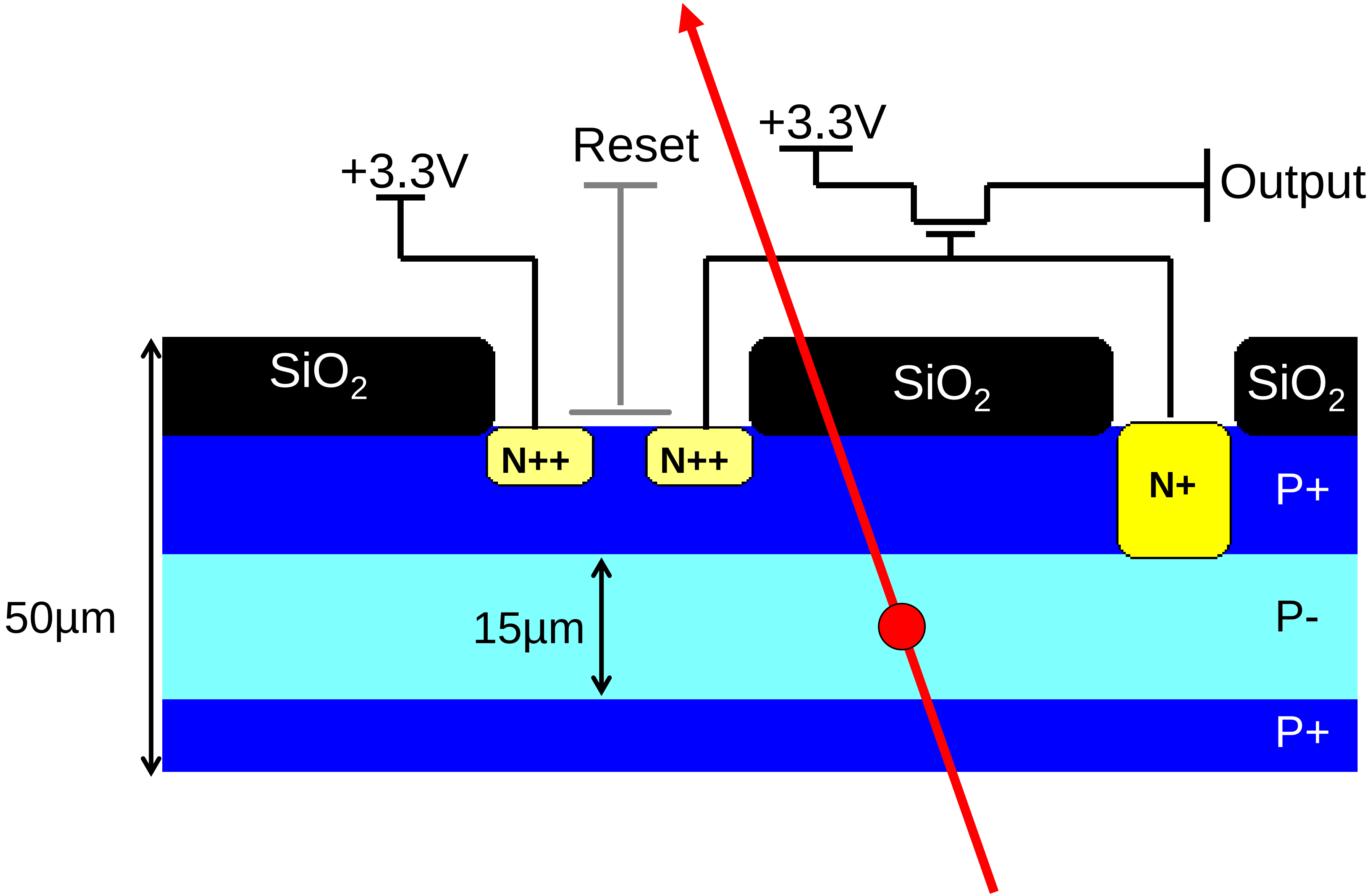
IO-Signals needed:

Clock, Reset, Synchro and analogue output

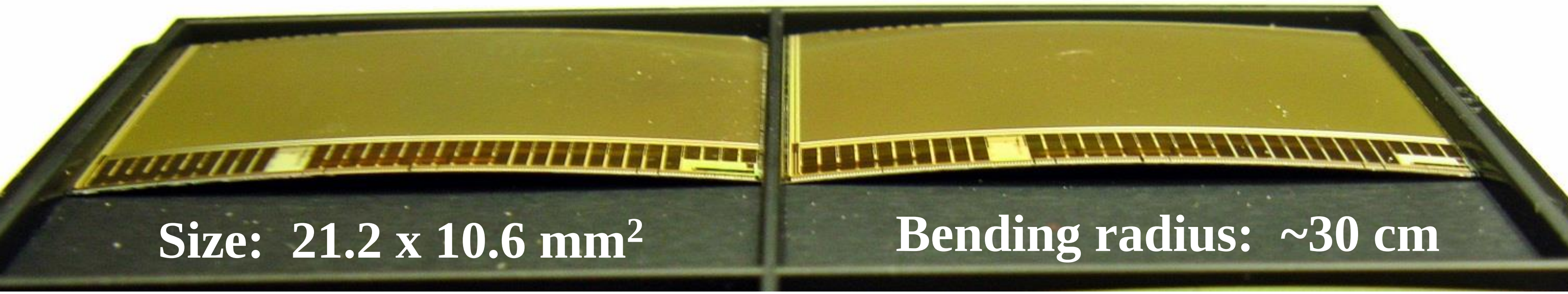
Comparing pixel sizes



MAPS: The operation principle

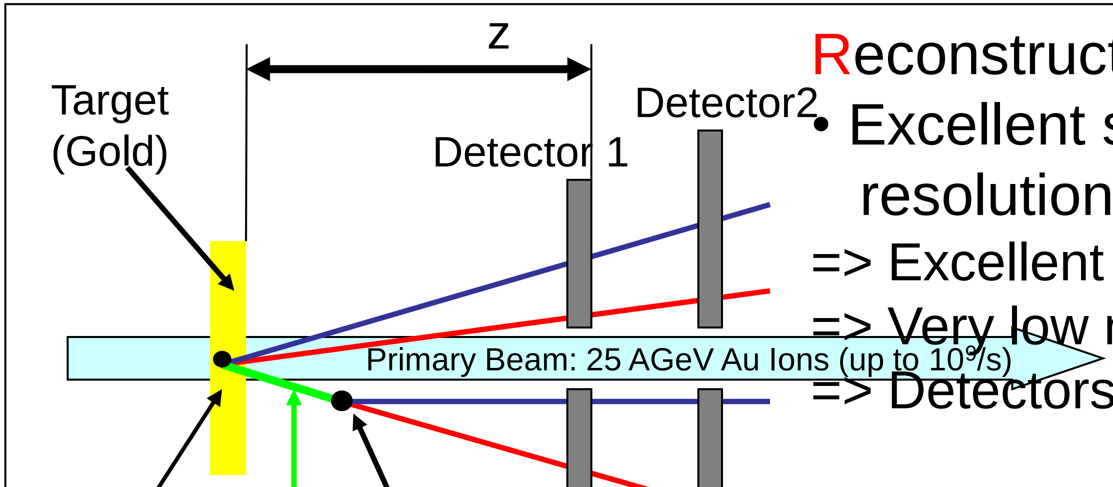


The meaning of thin…



- 50 µm thickness
- Bended due to inner tensions
- Flexible silicon!

Open charm reconstruction: Concept



Reconstructing open charm requires:

- Excellent secondary vertex resolution (~ 50 µm)

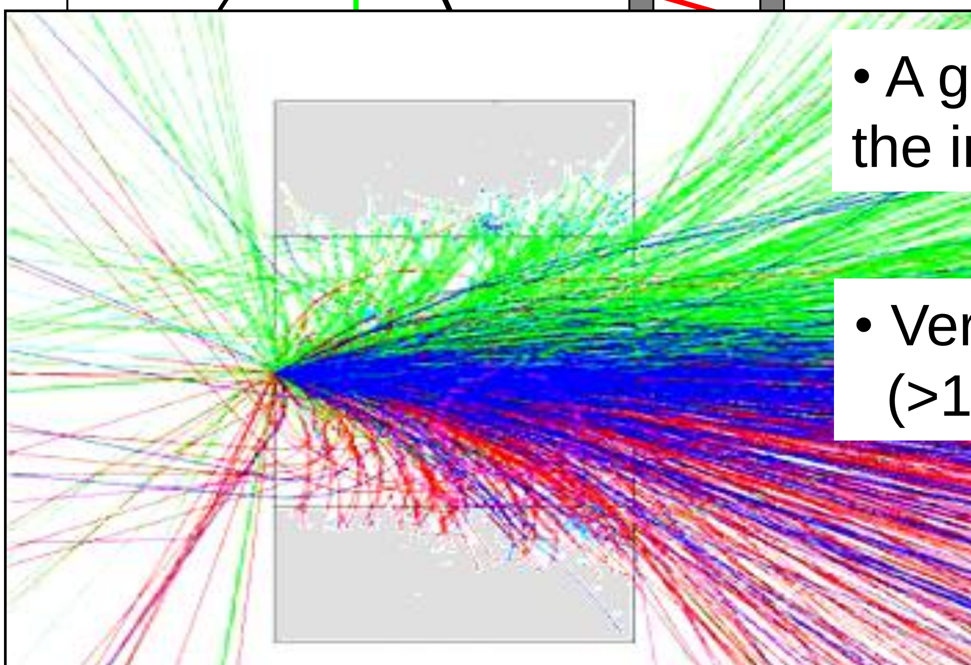
=> Excellent spatial resolution (~5 µm)

=> Very low material budget (few 0.1 % X_0)

=> Detectors in vacuum

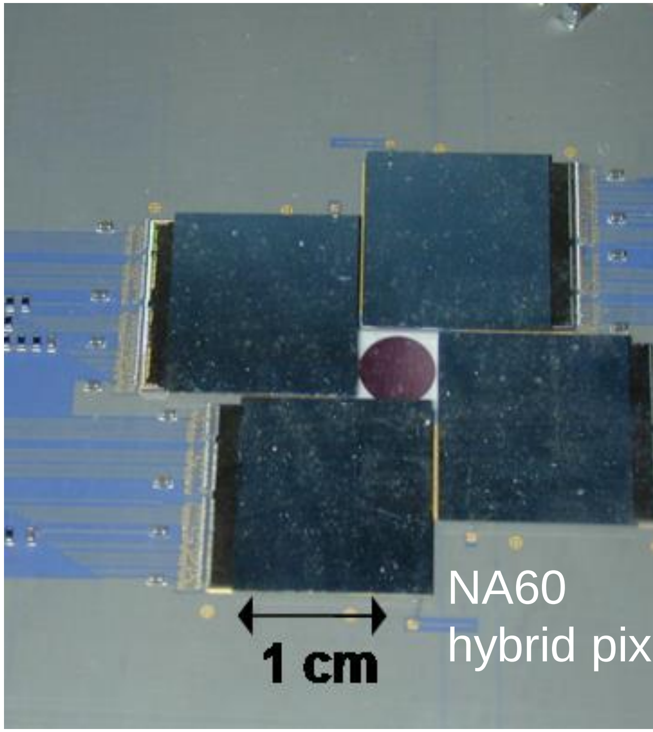
- A good time resolution to distinguish the individual collisions (few 10 µs)

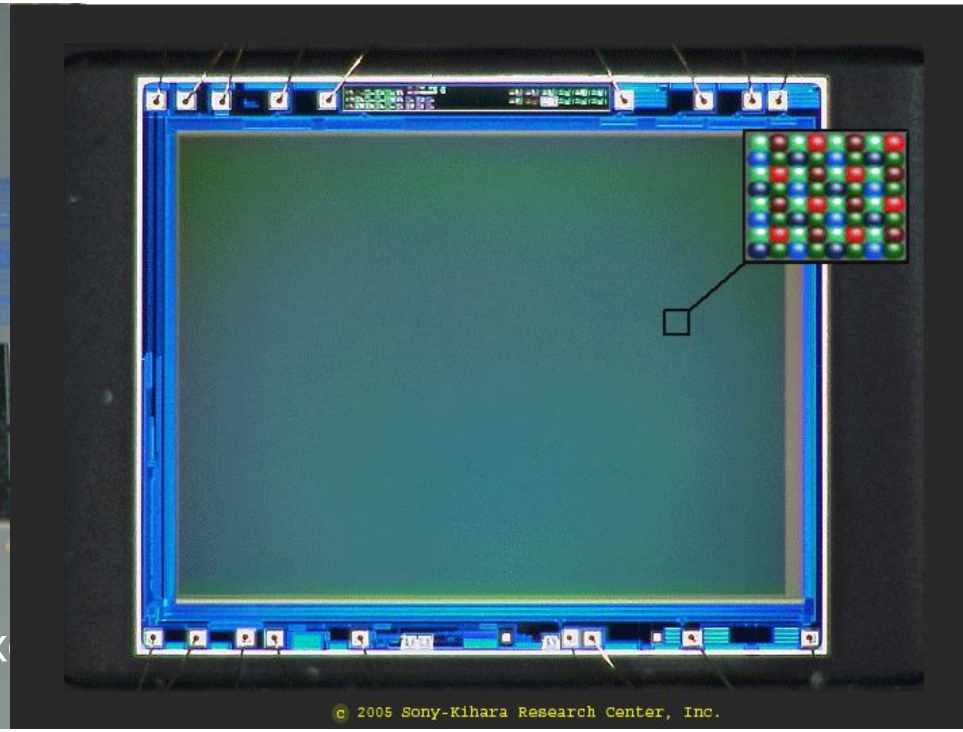
- Very good radiation tolerance ($>10^{13}$ n_{eq}/cm^2)



Central Au + Au collision (25 AGeV)

Established pixel detector technologies (2003)



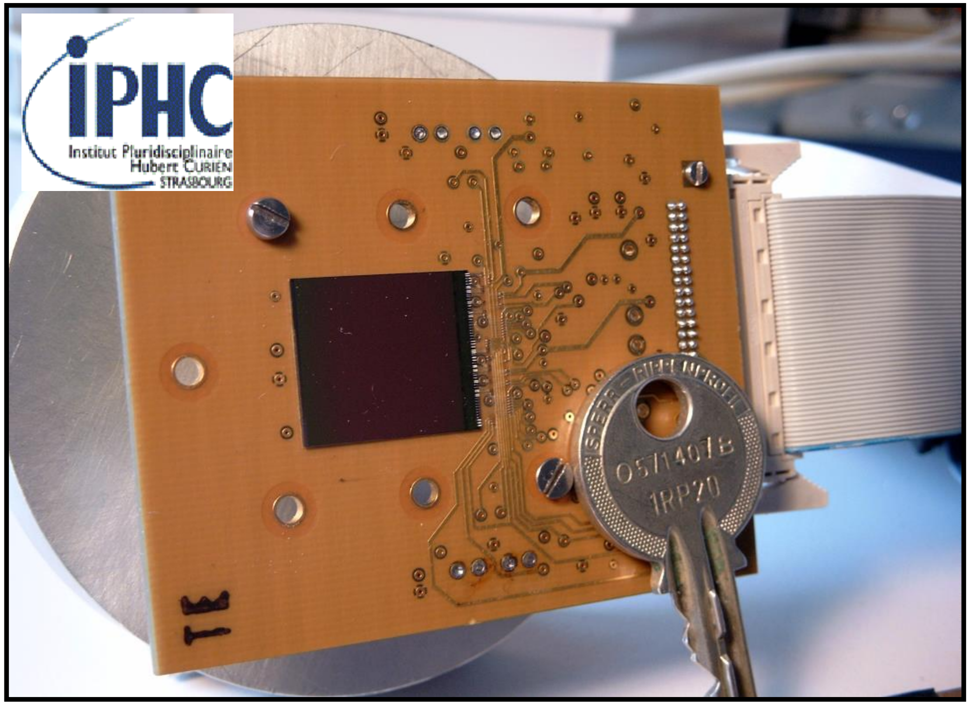


	Required (CBM)	CCD
Single point res. [µm]	~ 5	~ 5
Material budget [X_0]	~ 0.3%	~0.1%
Time resolution [µs]	few 10	~100
Rad. hardness [n/cm²]	> 10^{13}	<< 10^{10}

Requirements vs. detector performances (2003)

	Required	Hybrid pixels	CCD
Single point res. [µm]	~ 5	~ 30	~ 5
Material budget [X_0]	~ 0.3%	~ 1%	~ 0.1%
Time resolution [µs]	few 10	0.025	~100
Rad. hardness [n/cm²]	> 10^{13}	>> 10^{14}	<< 10^{10}

Performances of MAPS (2003)

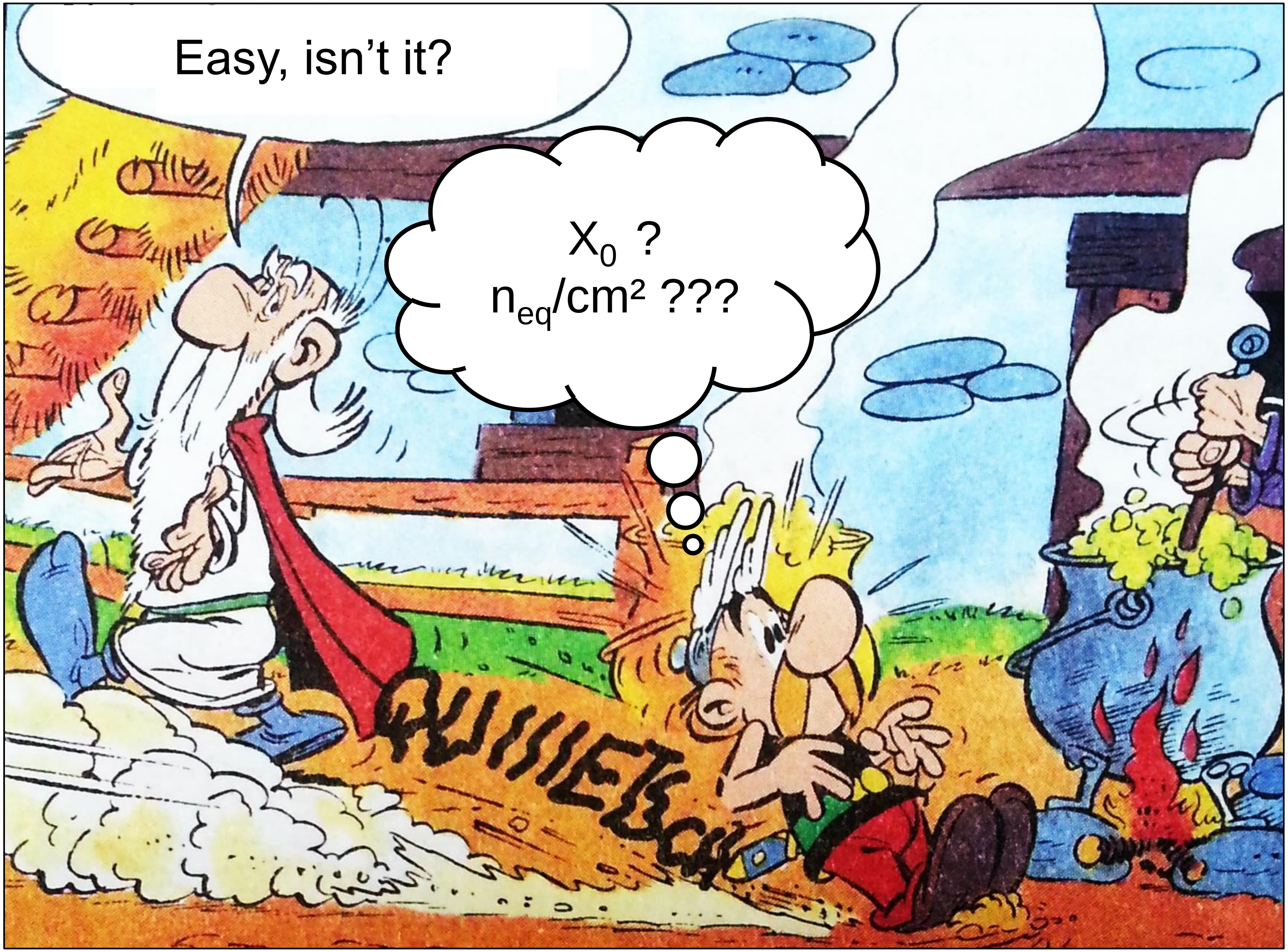


MAPS provide an unique compromise between:

- sensitivity
- high rate capability

	Required	Hybrid pixels	CCD	MAPS** (2011)
Single point res. [µm]	~ 5	~ 30	~ 5	3.5
Material budget [X_0]	~ 0.3%	1%	~0.1%*	~0.05%*
Time resolution [µs]	few 10	0.025	~100	~10000
Rad. hardness [n/cm²]	> 10^{13}	>> 10^{14}	<< 10^{10}	> 10^{12}

*Sensor only **Best of all prototypes

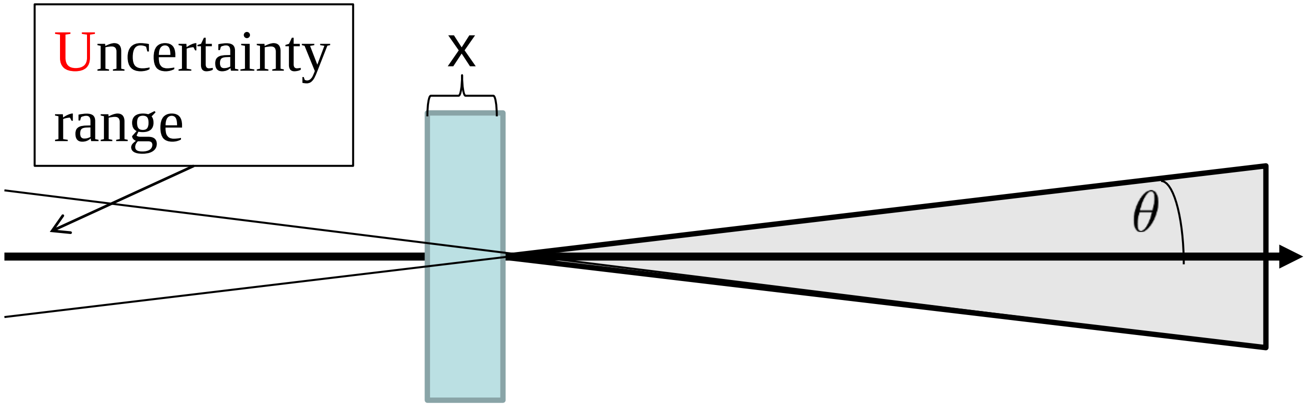

Easy, isn't it?
X_0 ?
n_{eq}/cm^2 ???

X_0 and multiple scattering

Definition of the radiation length (X_0):

- Distance in a material, which decelerates charged particles with $\gamma \gg 2000$ to 1/e of its energy.
- Material constant, tables available at http://pdg.lbl.gov

Relevance of the radiation length (X_0):

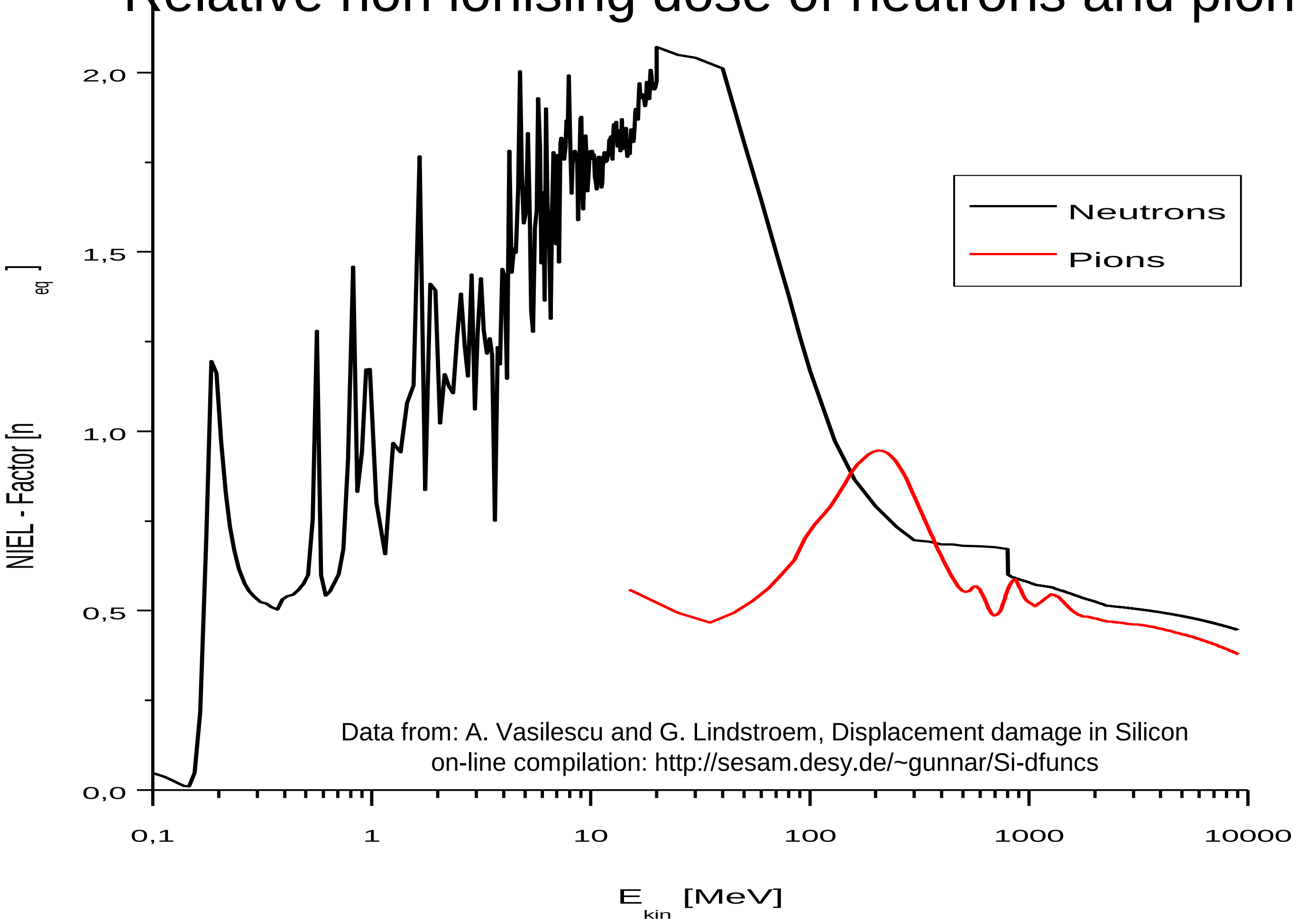


$$\theta = \frac{13.6 \text{ MeV}}{p\beta c} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln(x/X_0)\right]$$

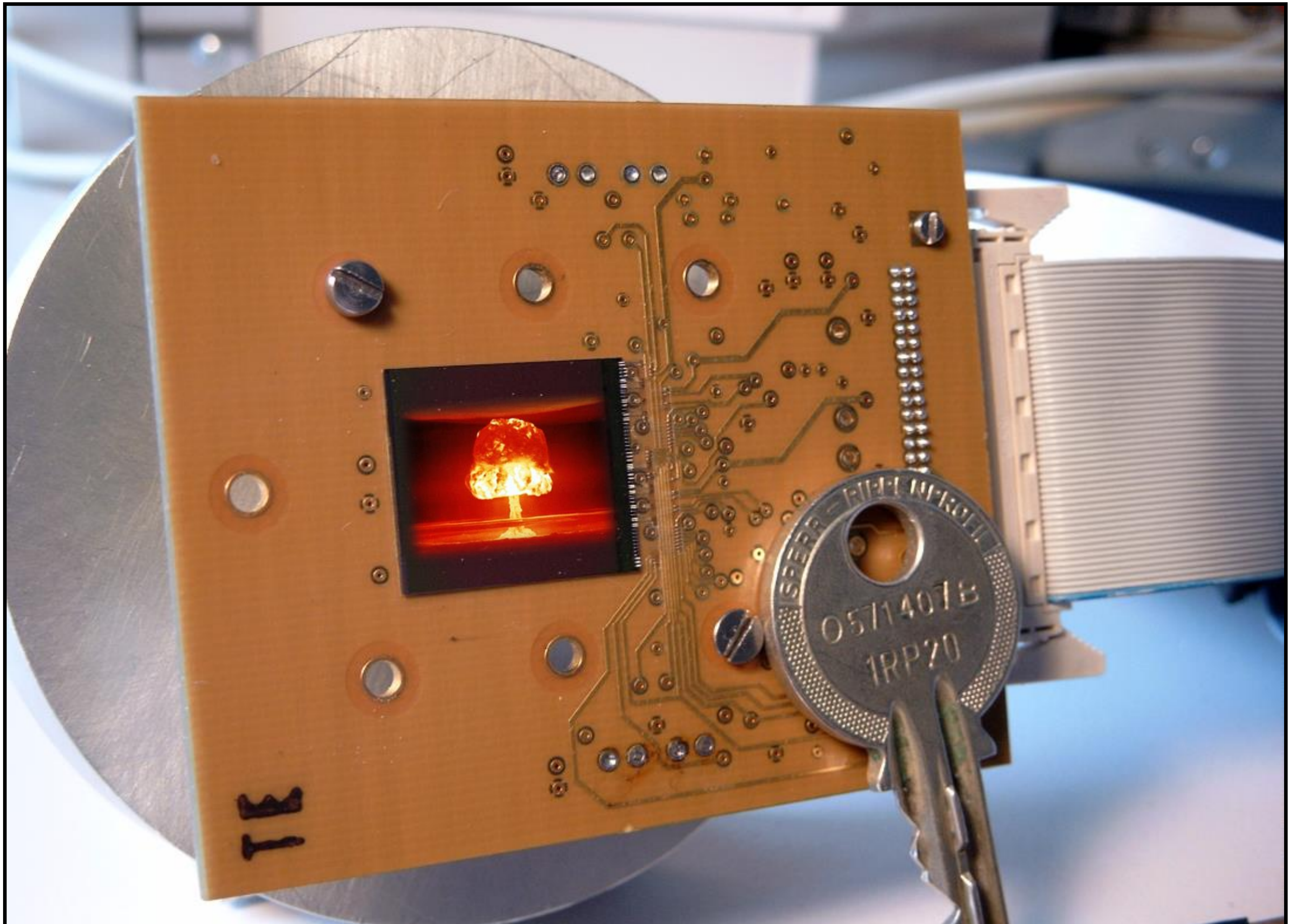
1) The thinner, the better.
2) 1% X_0 = 1mm silicon

What means n_{eq}/cm^2?

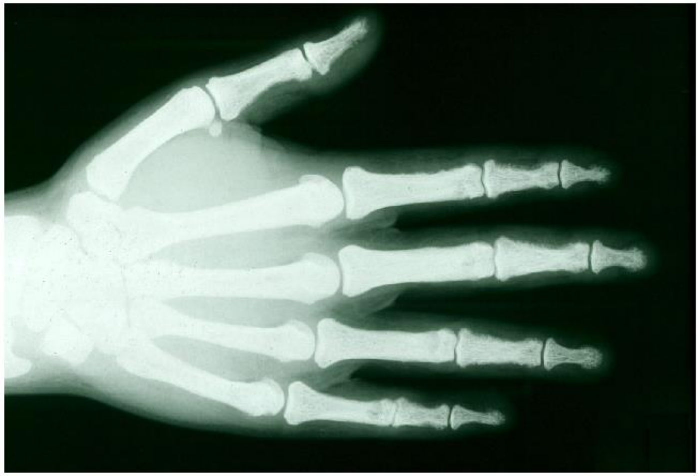
Relative non ionising dose of neutrons and pions



Radiation tolerance

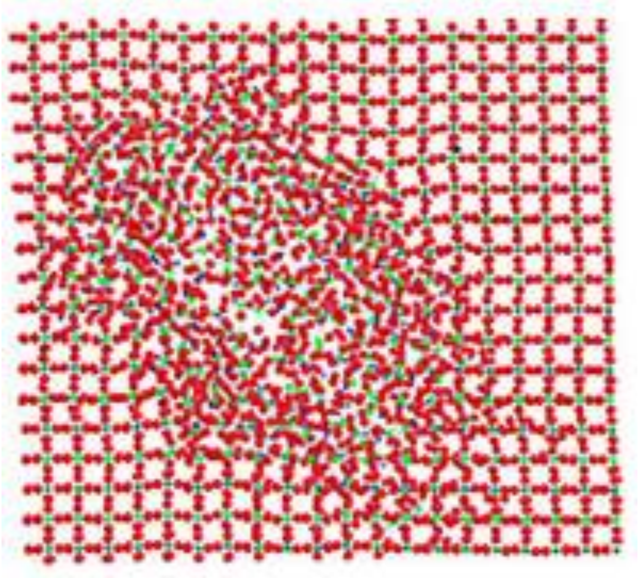


What about radiation hardness?



Ionising radiation:

- Energy deposited into the electron cloud
- May ionise atoms and destroy molecules
- Caused by charged particles and photons

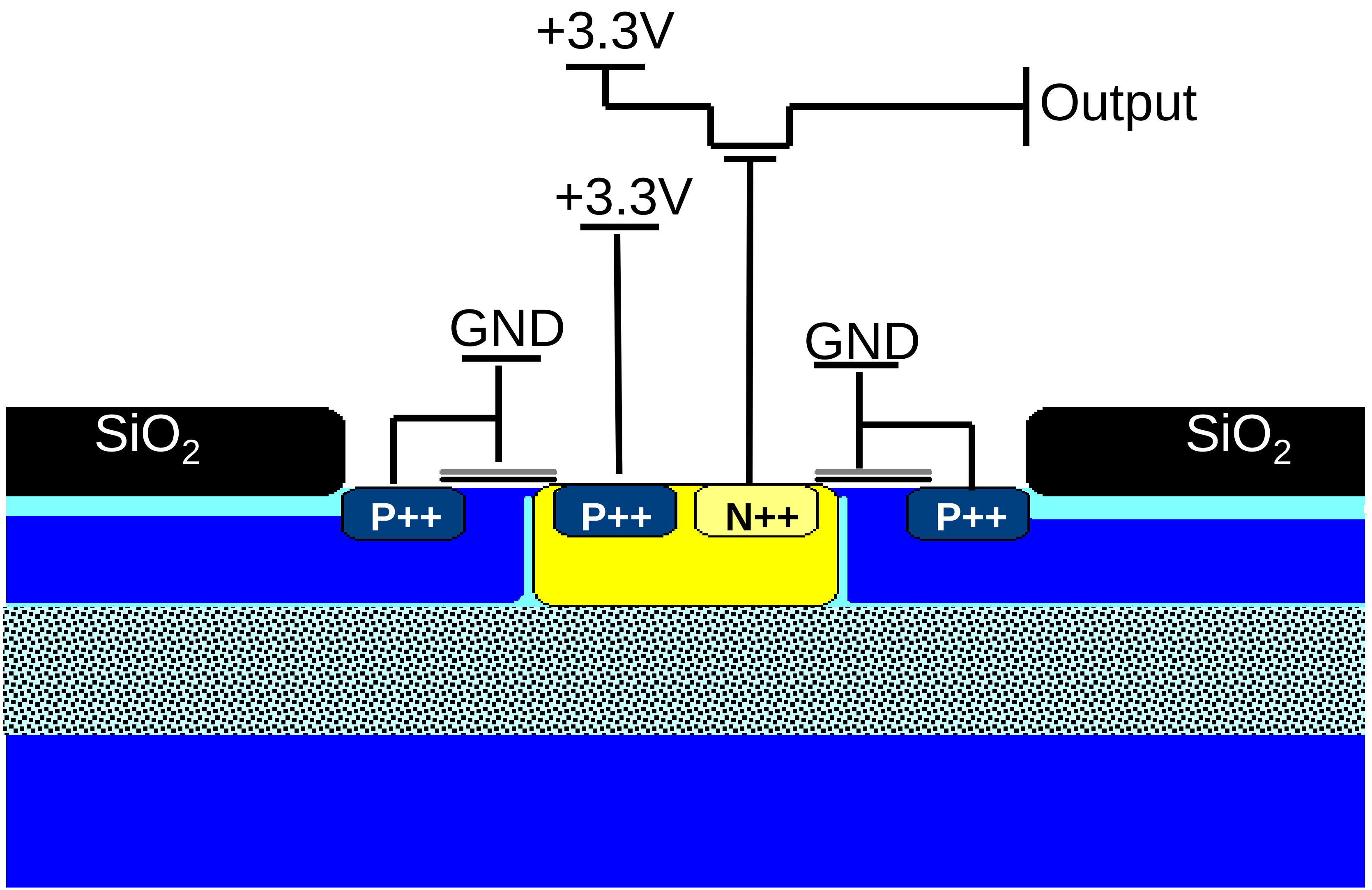


Non-ionising radiation:

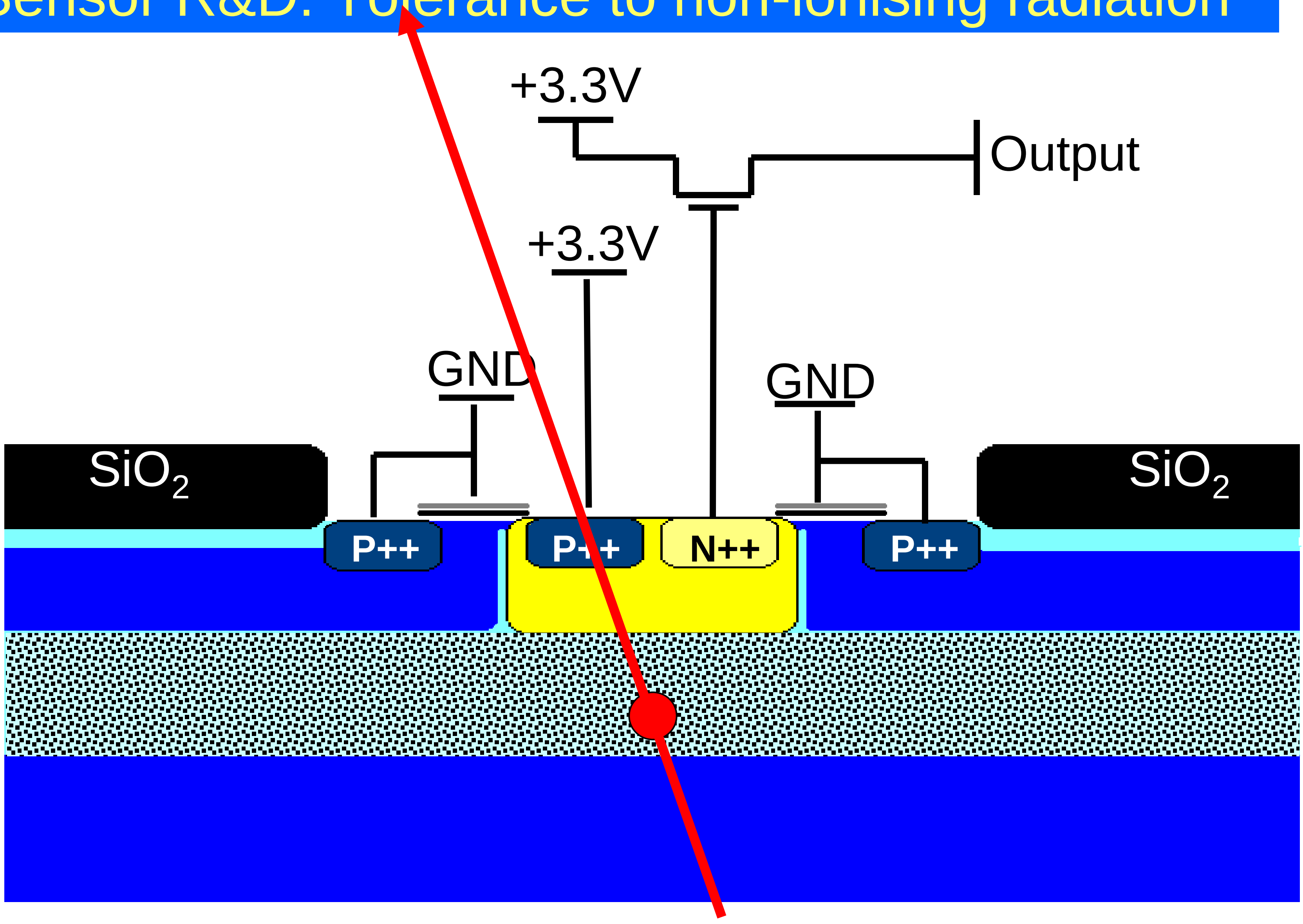
- Energy deposited into the crystal lattice
- Atoms get displaced
- Caused by heavy (fast leptons, hadrons) charged and neutral particles

Farnan I, HM Cho, WJ Weber, 2007. "Quantification of Actinide α-Radiation Damage in Minerals and Ceramics." *Nature* 445(7124):190-193.

Sensor R&D: Tolerance to non-ionising radiation

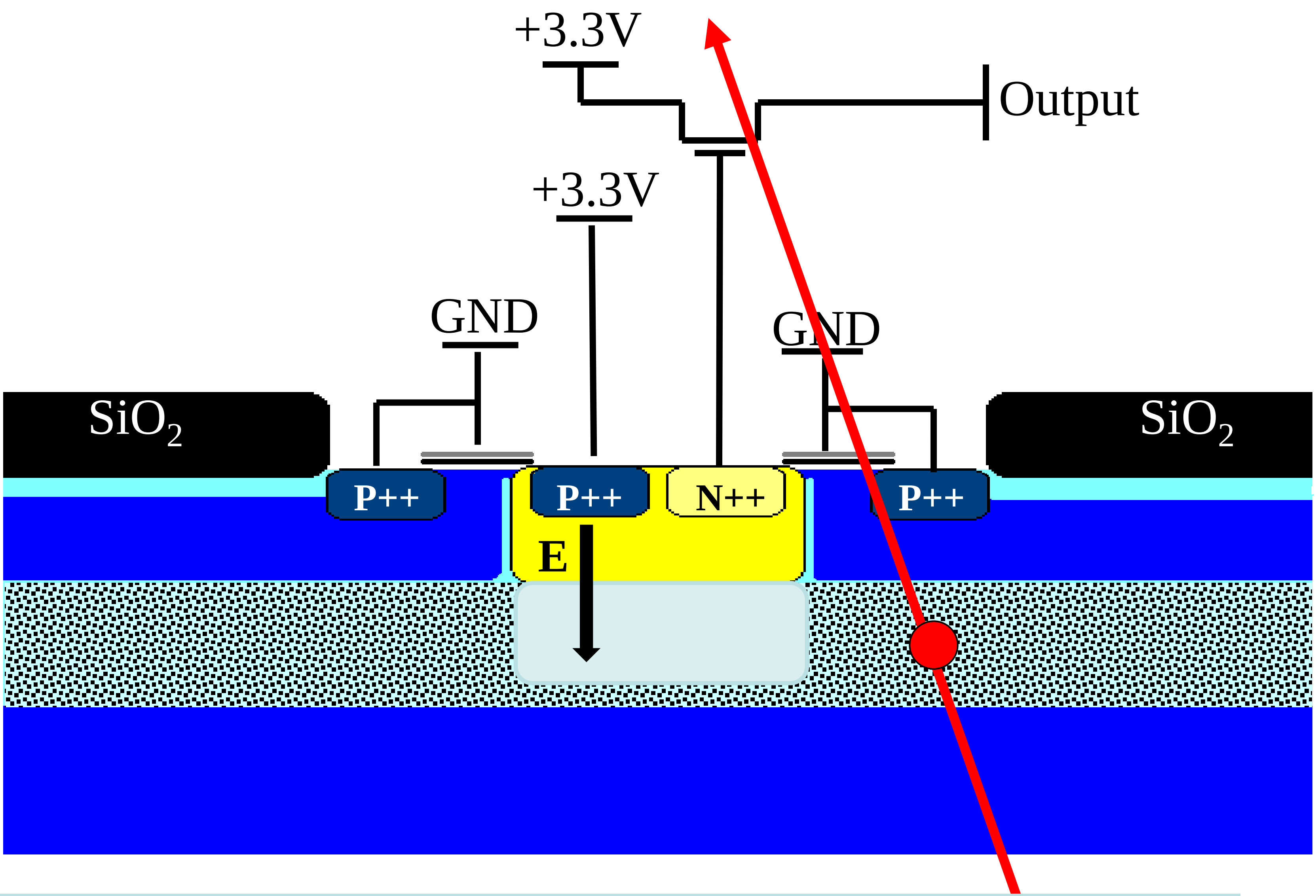


Sensor R&D: Tolerance to non-ionising radiation



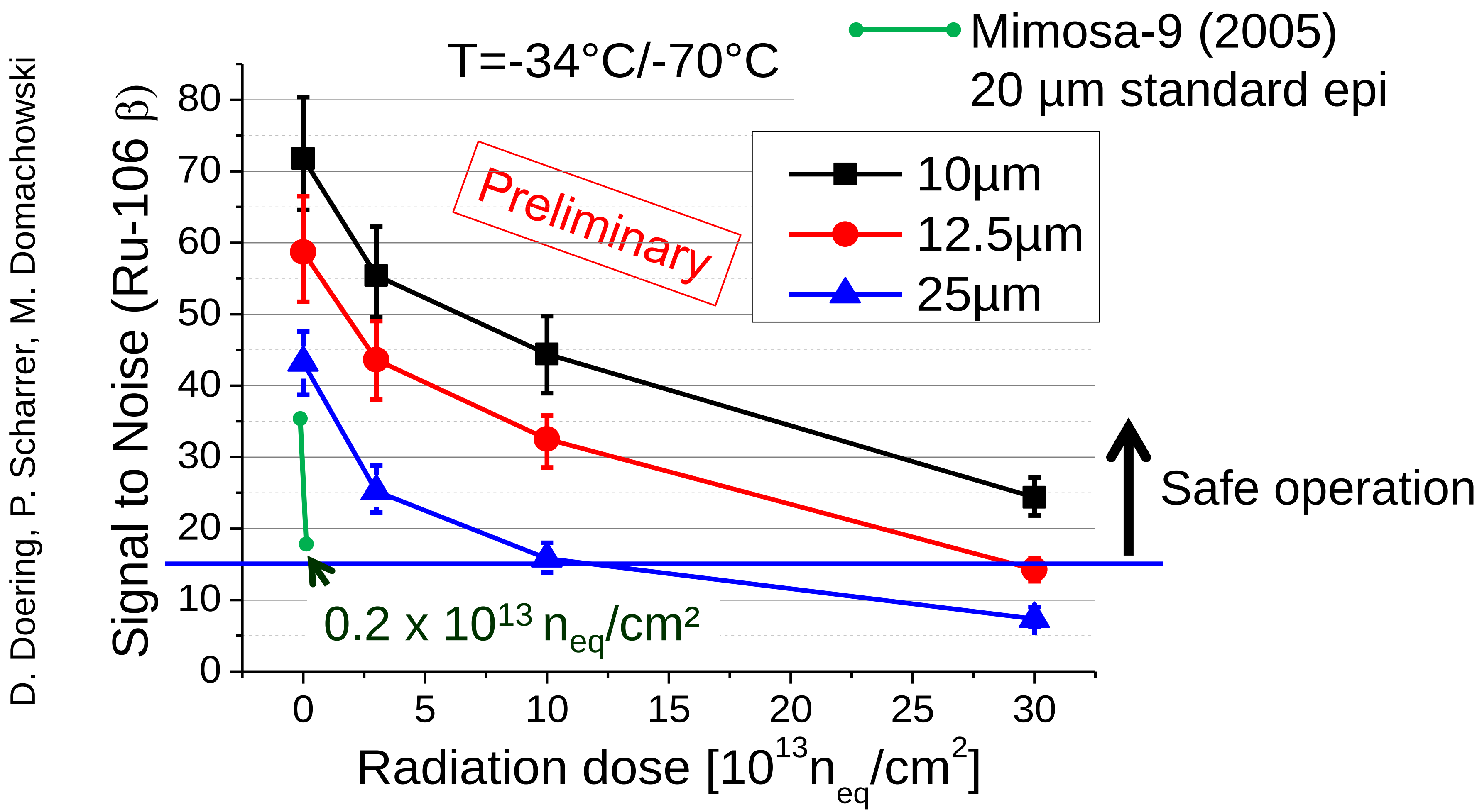
Key observation: Signal amplitude is reduced by bulk damage

Sensor R&D: Tolerance to non-ionising radiation



Electric field increases the radiation hardness of the sensor
Draw back: Need CMOS-processes with low doping epitaxial layer

S/N of MIMOSA-18 AHR (high resistivity epi-layer)

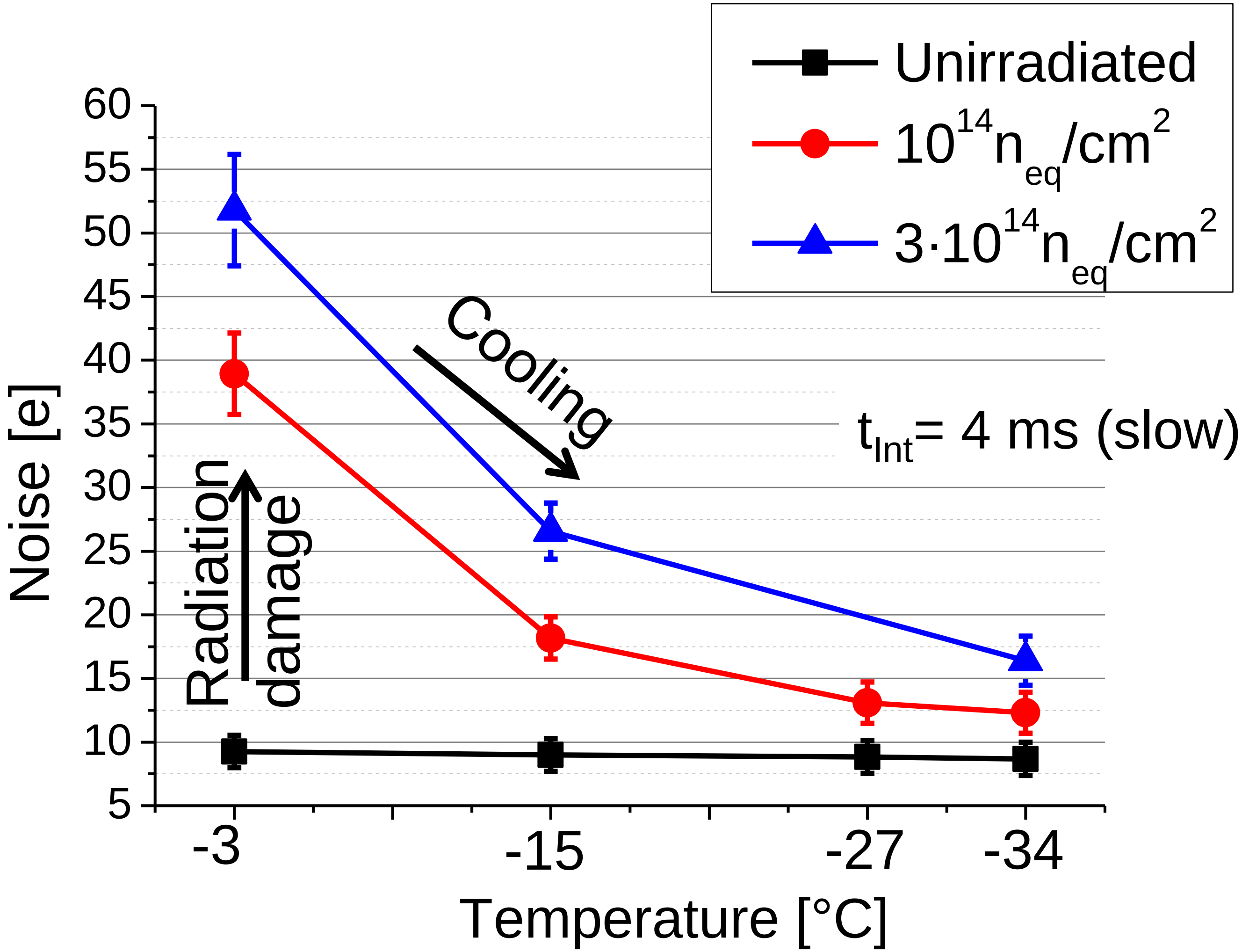


Sensor design: PICSEL Group, IPHC Strasbourg, et al.
Sensor test and plots: AG Stroth, IKF Frankfurt/M

Plausible conclusion: Radiation tolerance ~10^{14} n_{eq}/cm^2 reached

- Cooling required to operate heavily irradiated sensors

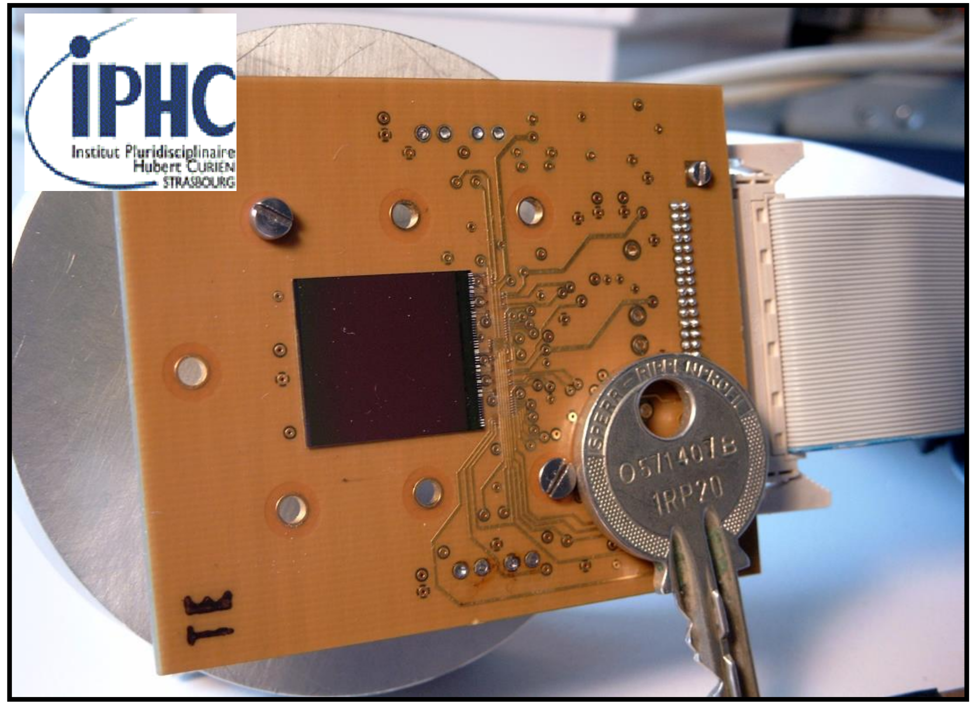
Noise and cooling



Cooling is needed to exploid the improved radiation tolerance
Alternative solution: Fast integration times help

Sensor design: PICSEL Group, IPHC Strasbourg, et al.
Sensor test and plots: AG Stroth, IKF Frankfurt/M

Performances of MAPS



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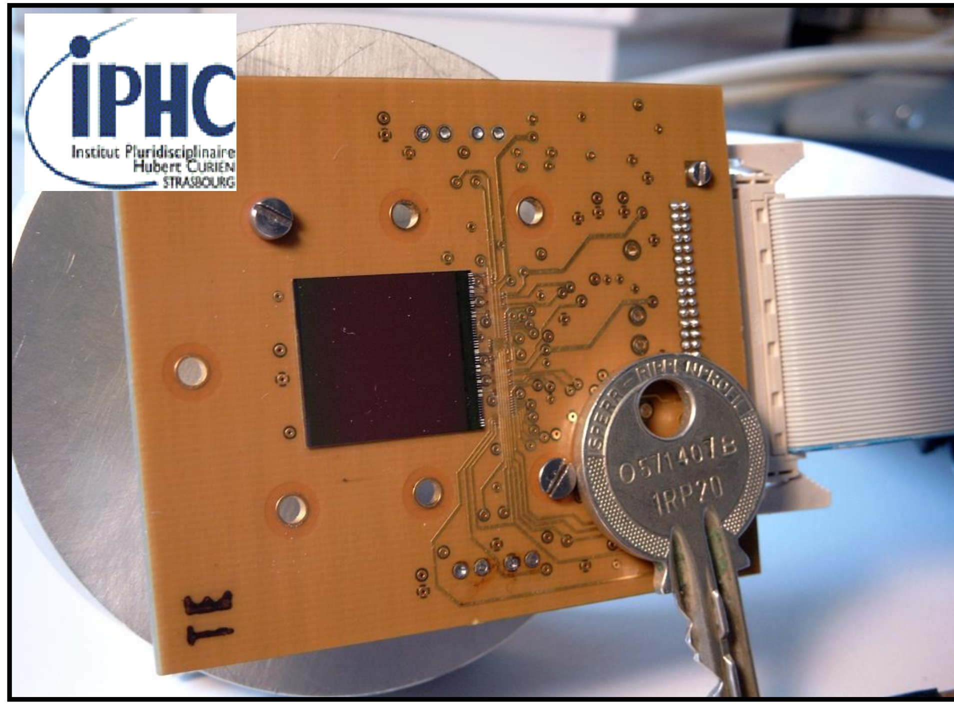
	Required	**Hybrid pixels**	**CCD**	**MAPS** (2011)**
Single point res. [µm]	~ 5	~ 30	~ 5	3.5
Material budget [X_0]	~ 0.3%	1%	~0.1%*	~0.05%*
Time resolution [µs]	few 10	0.025	~100	~10000
Rad. hardness [n/cm²]	> 10^{13}	>> 10^{14}	<< 10^{10}	> 10^{12}

*Sensor only **Best of all prototypes

Performances of MAPS



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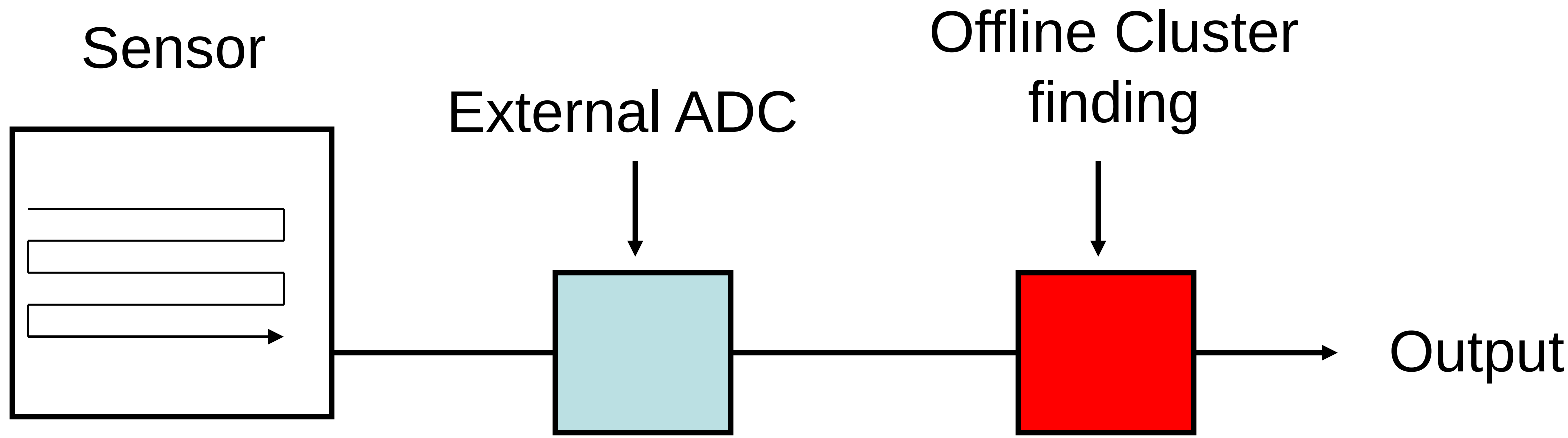
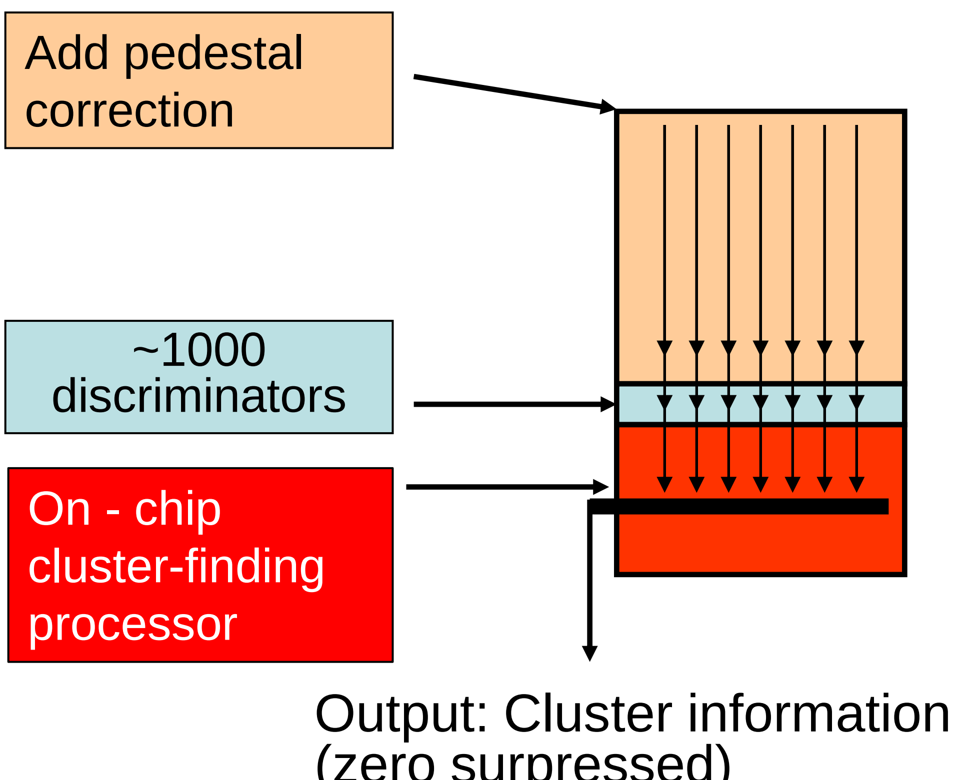
Sensor R&D: How to gain speed





MAPS are built in CMOS technology

Allows to integrate:

- sensor
- analog circuits
- digital circuits

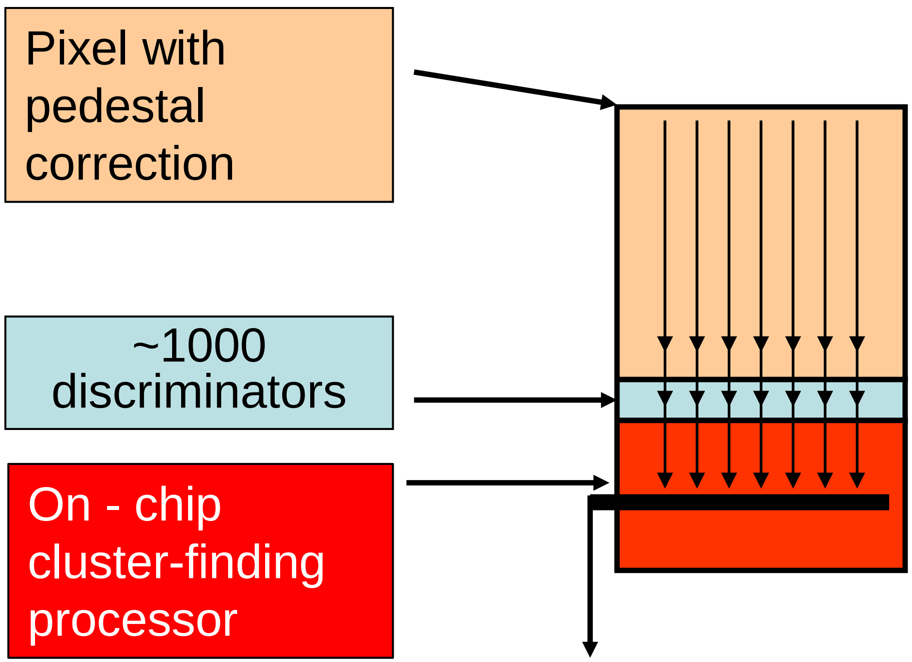
on one chip.

Sensor R&D: How to gain speed

Serial readout parallel

	MIMOSA-1 (2000)	MIMOSA-5 (2002)	MIMOSA-20 (2006)
Readout	Serial	Serial	Serial Mk. 2
Pixel/line/s	5M	20M	50M

Data/sensor: 1200 Mbps 160 Mbps



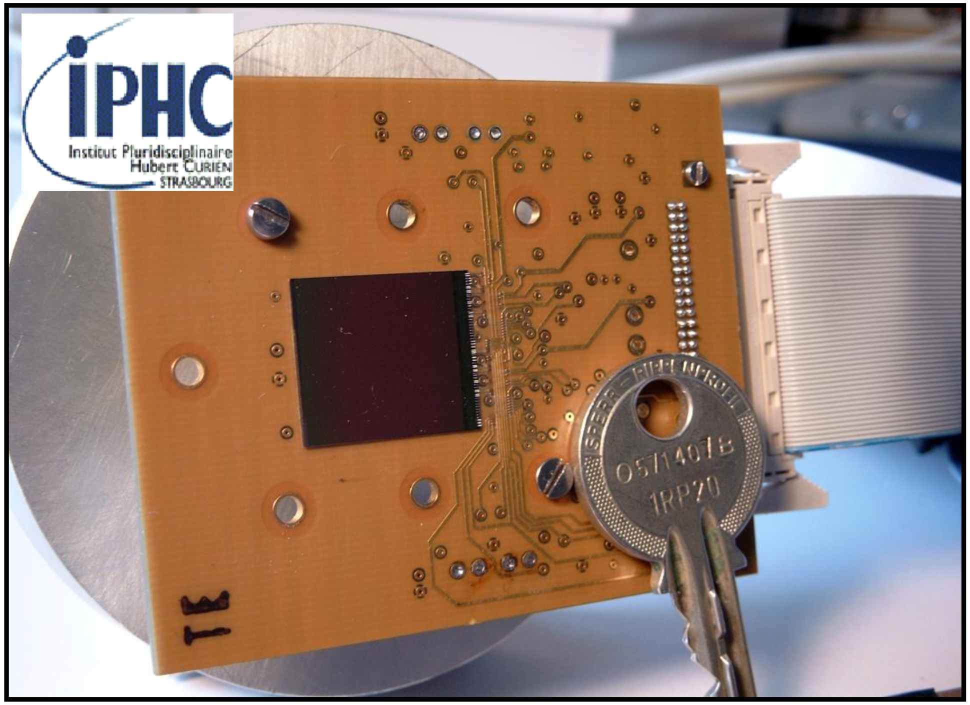
Output: Cluster information
(zero surpressed)

Readout time before: 1-20 ms
Readout time now: ~100 µs

Improve further with shorter columns.

Sensor design: PICSEL Group, IPHC Strasbourg, et al.

Performances of MAPS



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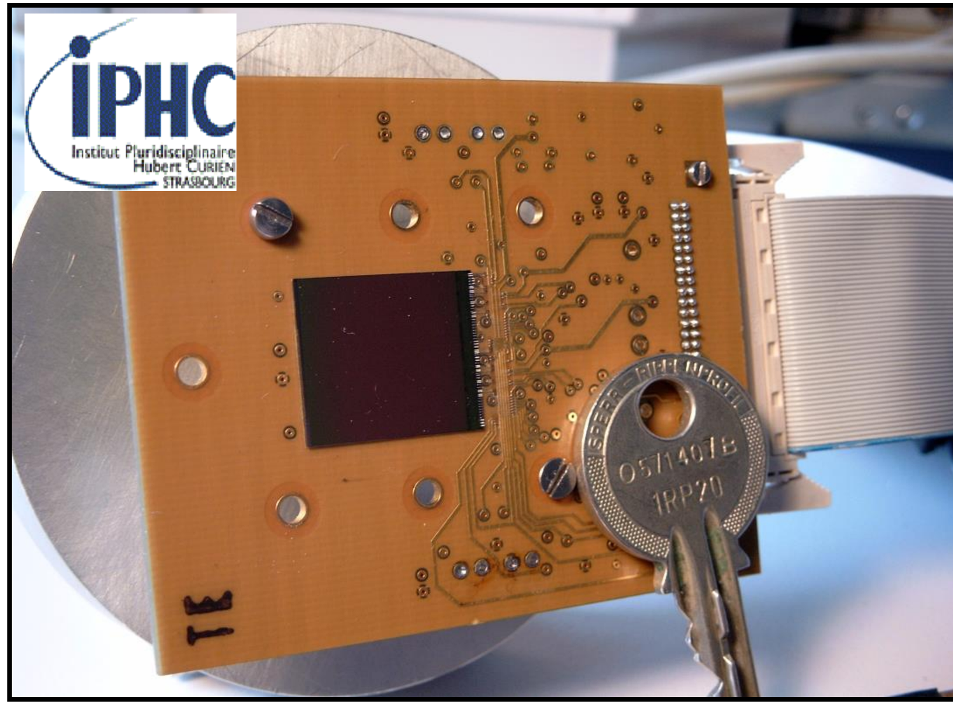
Performances of MAPS



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Time resolution [µs]	few 10	0.025	~100	30-100
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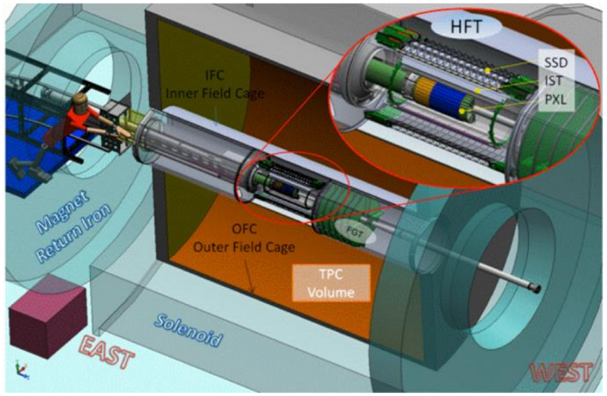
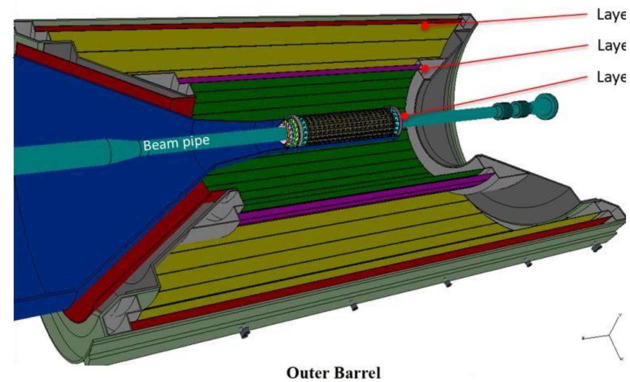
*Sensor only **Best of all prototypes

Applications of MAPS





STAR HFT

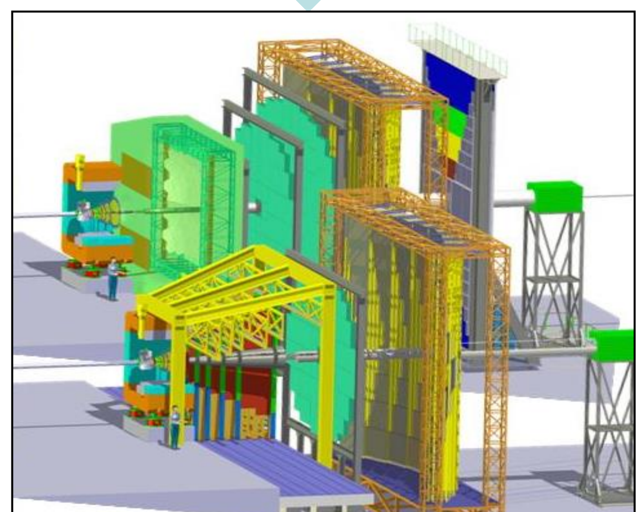
ALICE ITS?

2008 2013 2018

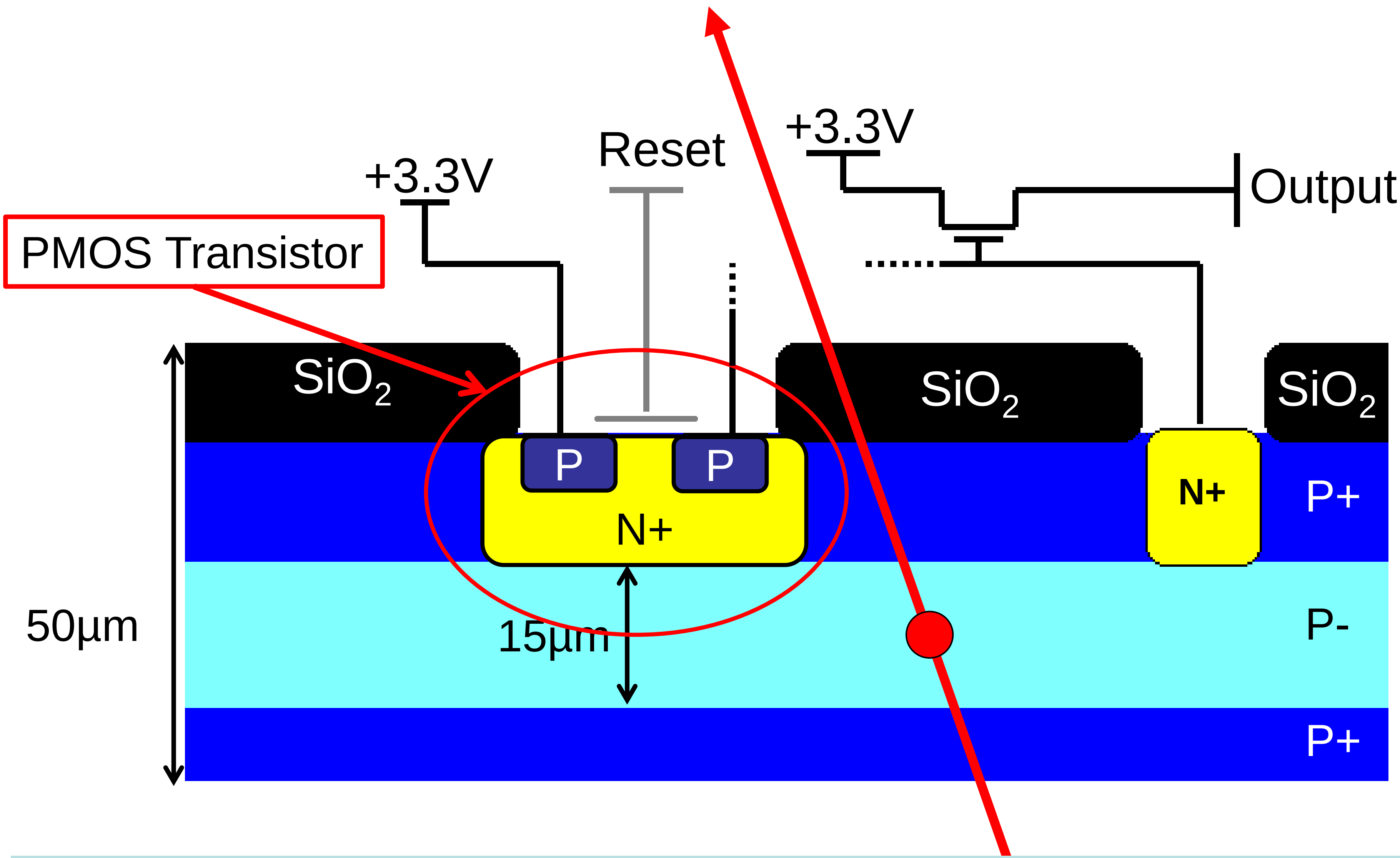
ILC?

EUDet
Telescope

CBM MVD

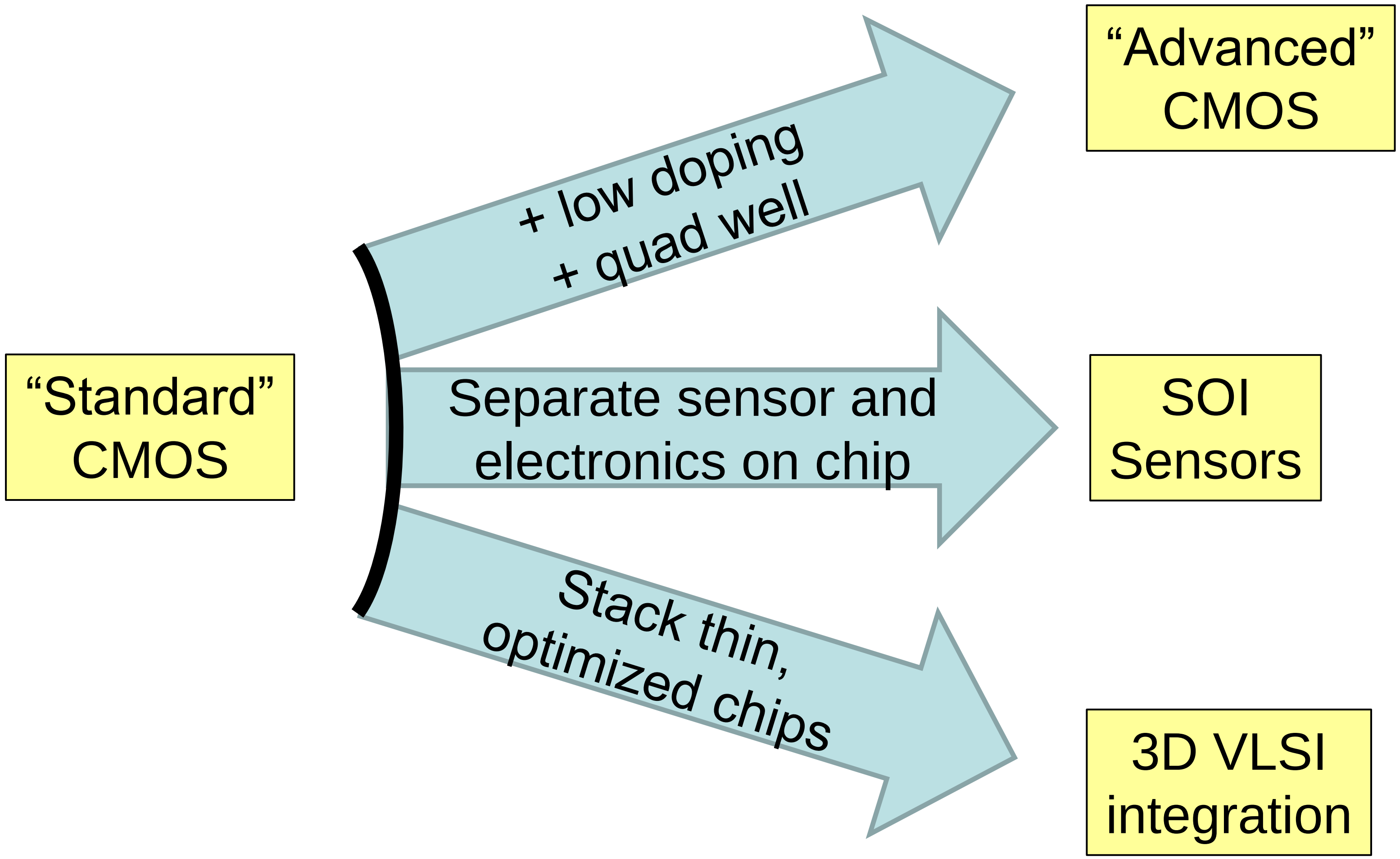


Need for Speed II: A new generation at the horizon

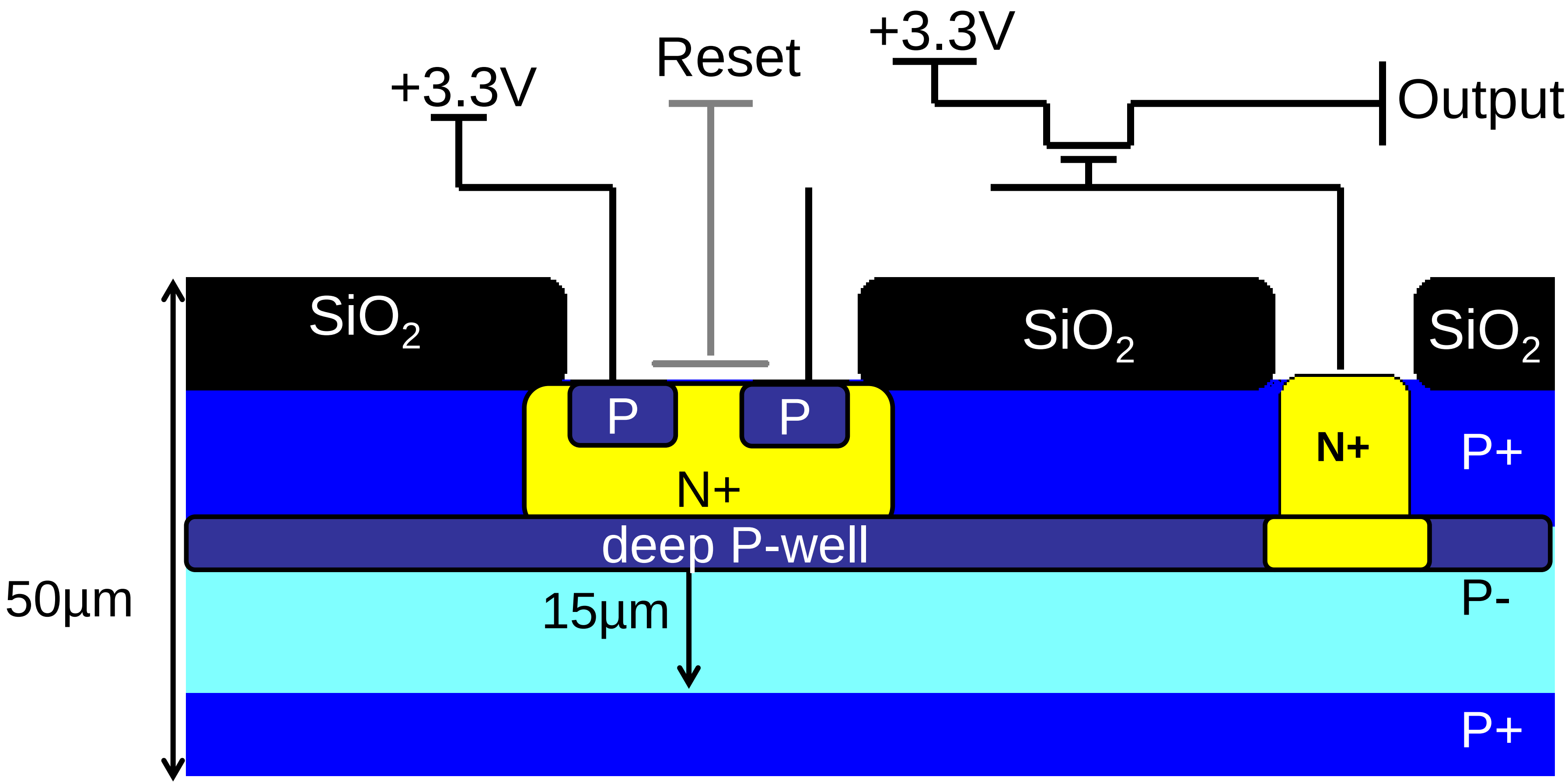


In standard CMOS sensors, no PMOS transistors are possible in pixel
=> No high level functions like discriminators … => “slow”

Going beyond rolling shutter



Advanced CMOS



Players among others: PICSEL Group, IPHC Strasbourg, et al.

Full CMOS is reached in modern 0.18µm processes with quad-well

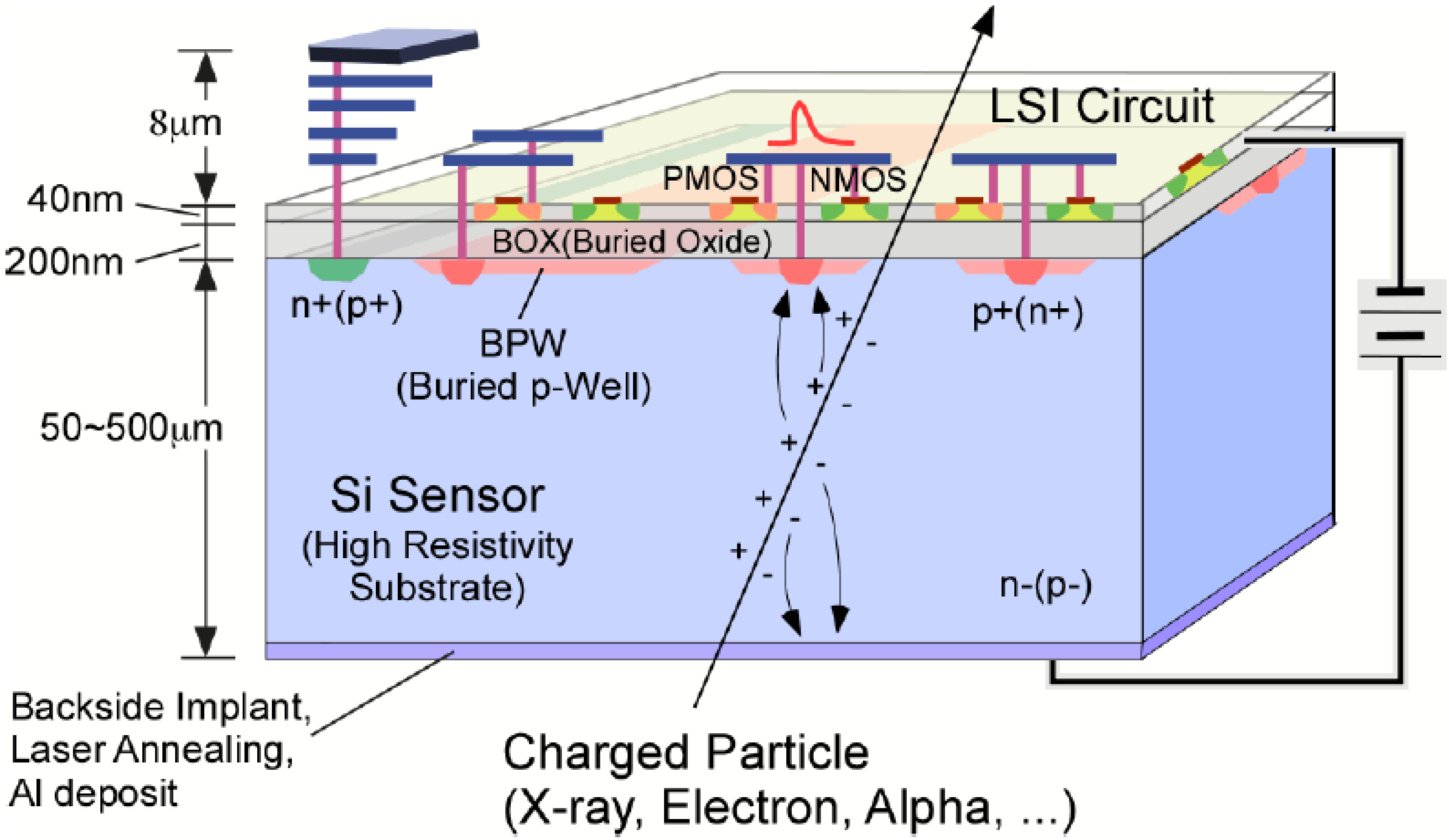
Exploited for IPHC – AROM sensors (discriminator on pixel)

\+ Simple, cost efficient, widely available in industry

\+ Industrial trend toward better epitaxial layers

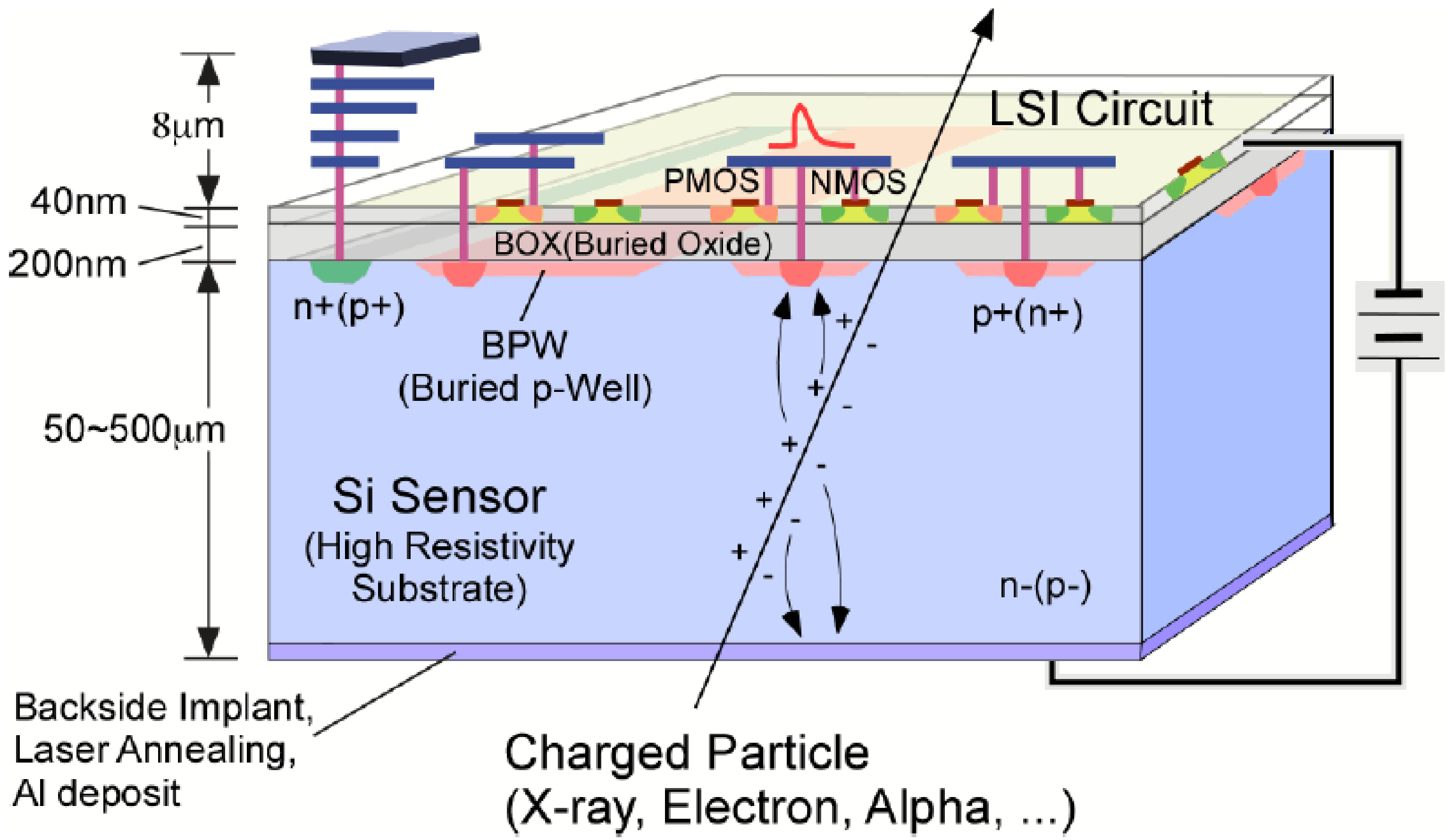
\- On pixel electronics limited by pixel surface

SOI - Pixels



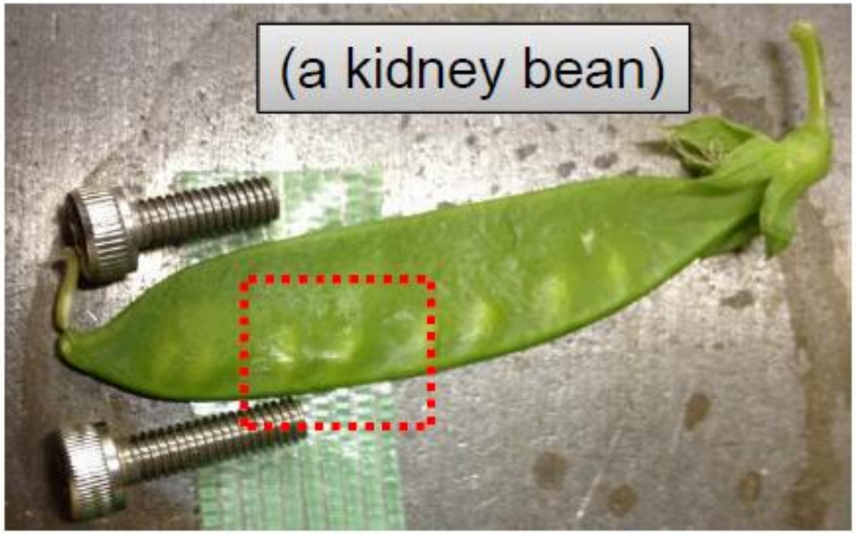
Silicon-On-Insulator Pixel Detector (SOIPIX)

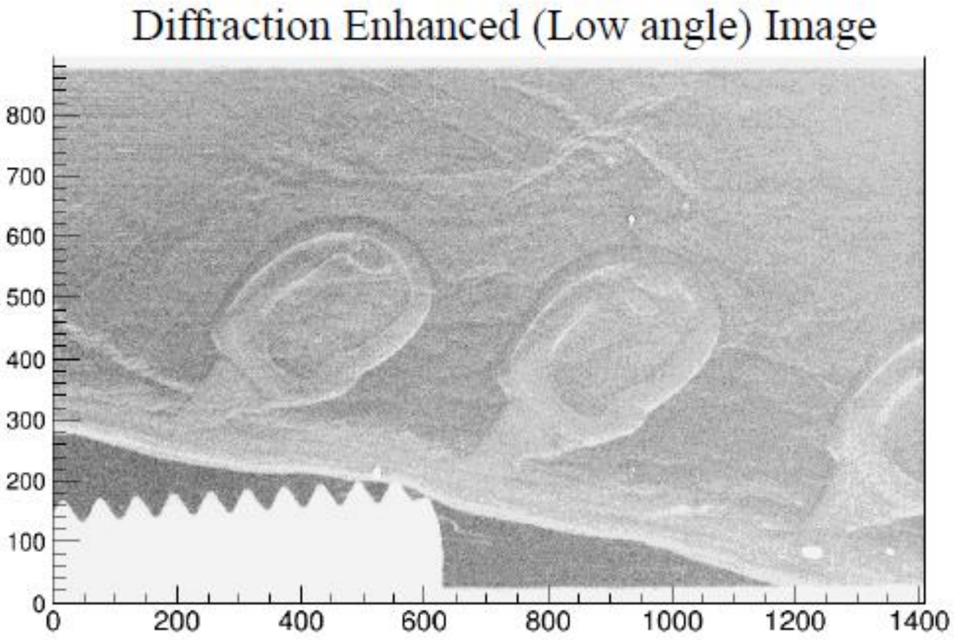
SOI - Pixels



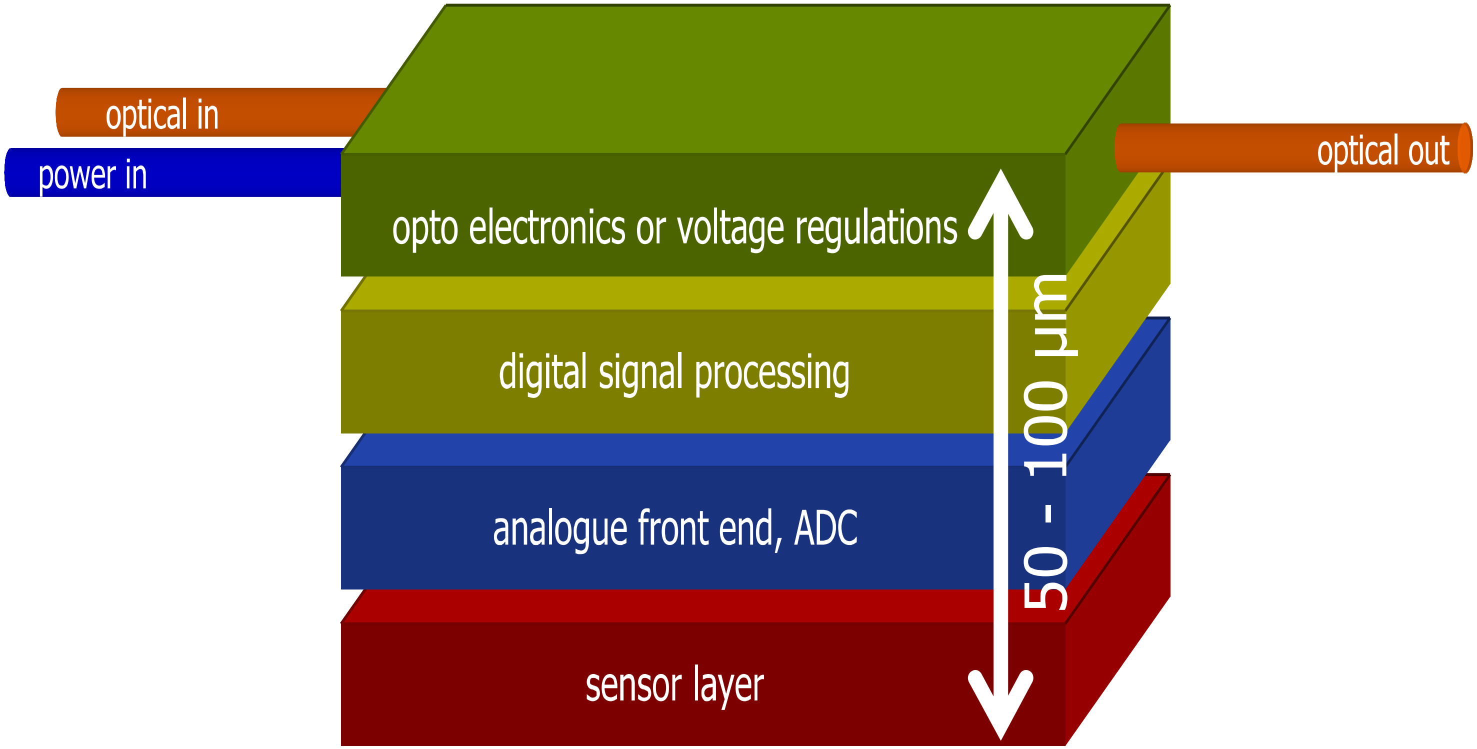
+ Dedicated sensor silicon + dedicated electronics silicon
+ Conceptually more radiation tolerance possible
- Thick BOX – Oxide may be vulnerable to radiation damage
- Still under early R&D, moderate industrial support

Latest news (Yasuo Arai, Vertex 2013)





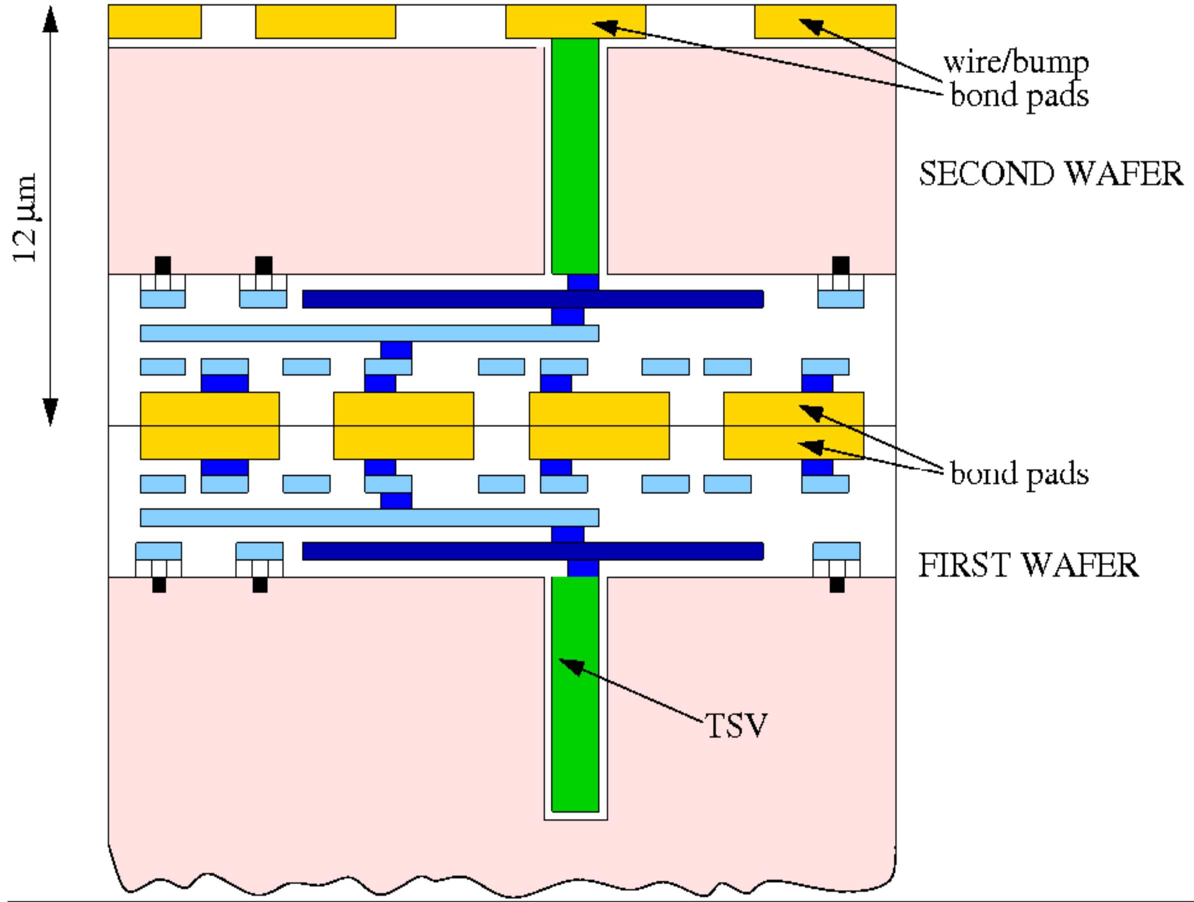
3D VLSI integration, the best of all worlds



Players among others: Fermilab, AIDA Collaboration

- Individual chips form always a compromise.
- 3D VLSI integration aims to pile chips and to connect them
- Potential: Get the best of all worlds

How to put chips together (simplified)

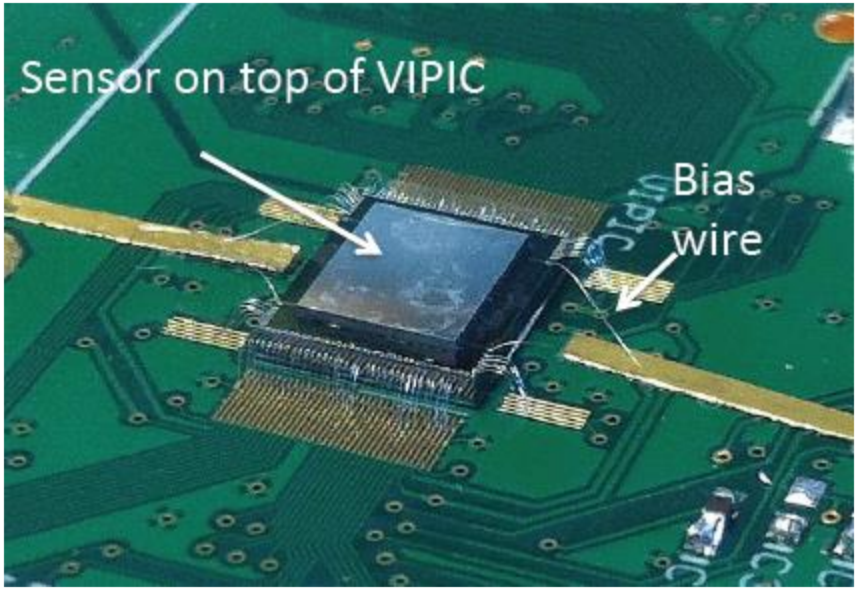


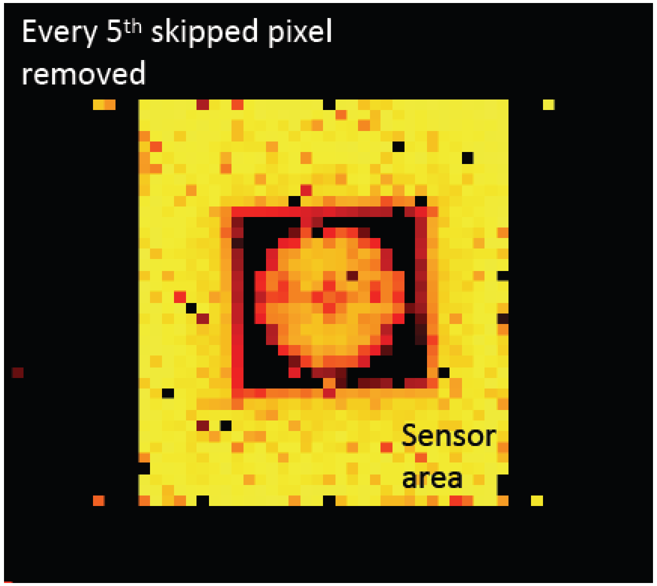
- Drill holes (via) deep into the chips and fill with metal
- Thin silicon until vias are seen on back side
- Add “bond pads” on the back side
- Bond chips

Players among others: Fermilab, AIDA Collaboration

Status: (Ray Yarema, VERTEX2013)

- Prototypes submitted by large community, coordinated by Fermilab
- Industry failed with bonding => Years of delays and desasters
- Finally, few months ago:





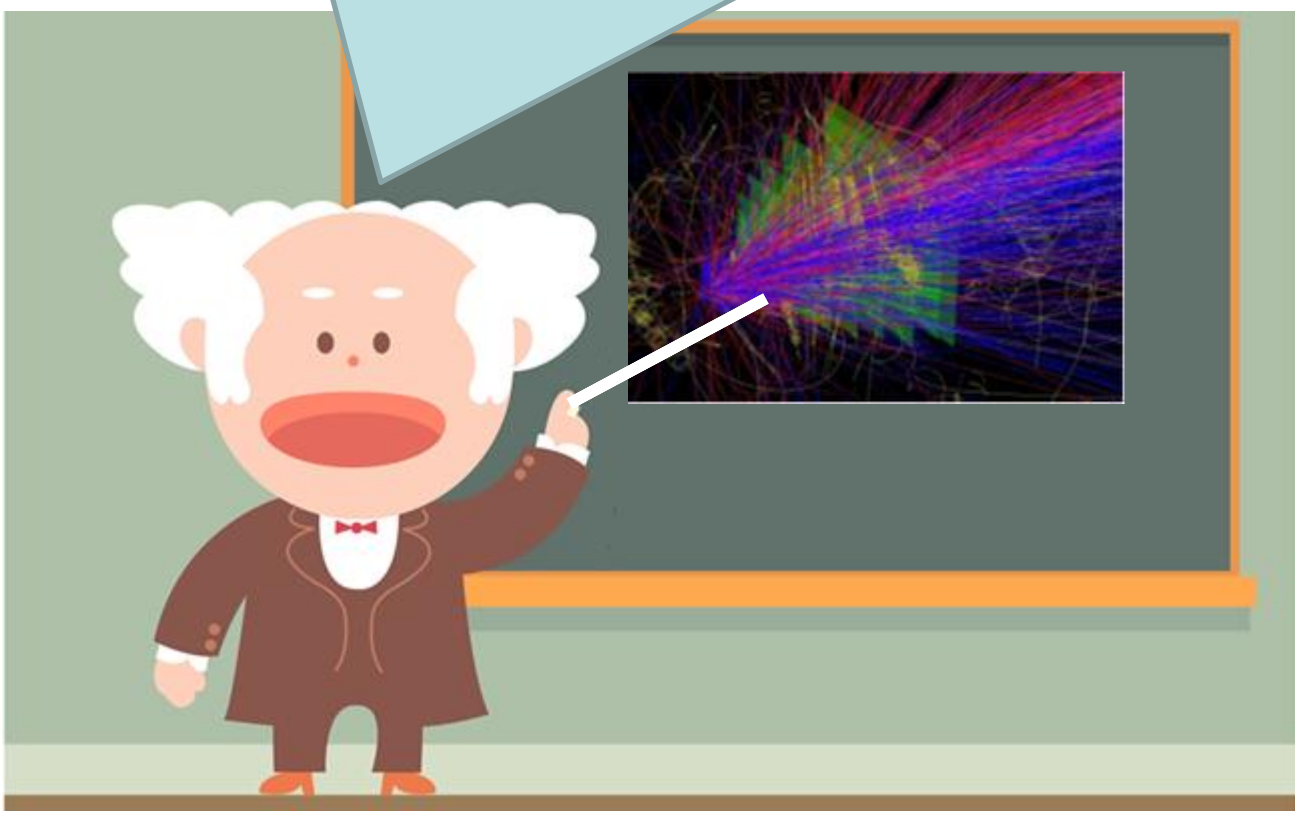
- First individual working devices delivered and tested
- Problems are understood:
  - a) Don't take industry by the letter
  - b) Use bigger "through vias" to ease alignment while bonding
- Future submissions should be much easier

Ray Yarema: In hindsight, … , we might have saved ~ 2 years and avoided a lot of grief. That's why it is called research.

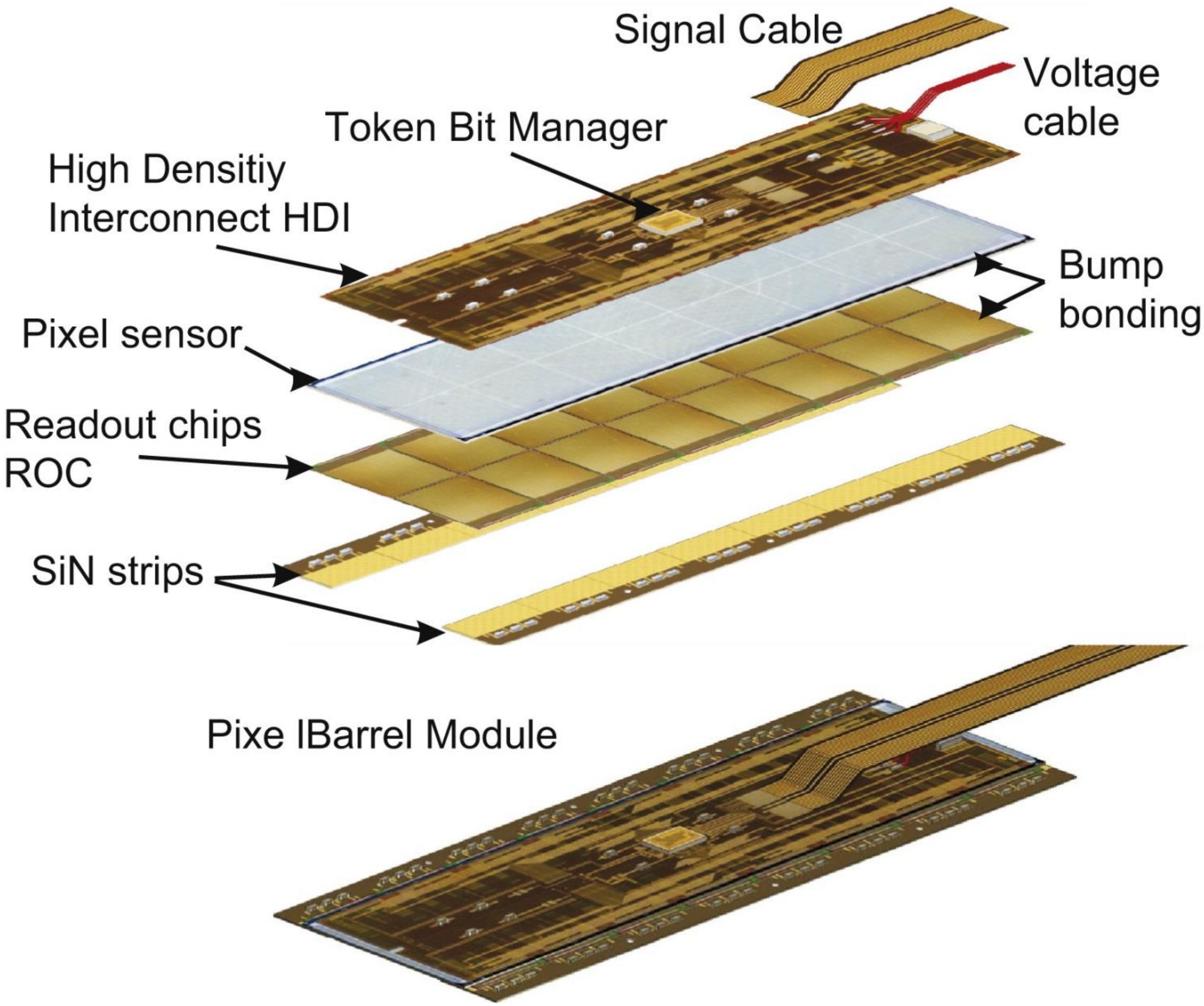
The final question: How to do system integration

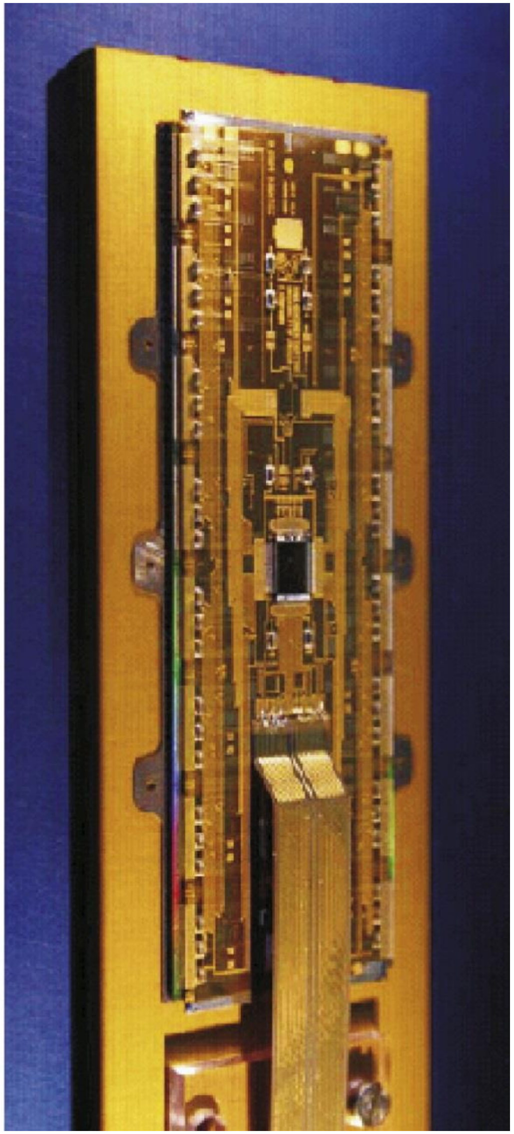
Again, this structure will be fixed with

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



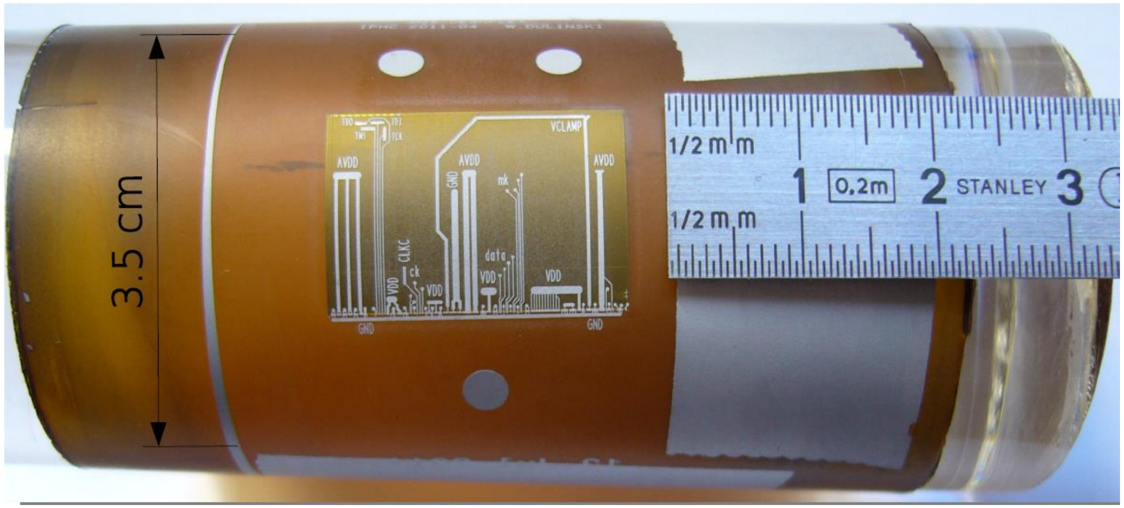
Outlook: The story has just started





Outlook: The story has just started

Idea from R. De Oliveira, W.Dulinski



SERNWIETE (mechanical demonstrator)
A bended MIMOSA-26 in a foil

My collaborators:

PICSEL group, IPHC Strasbourg

AG Prof. Stroth, Goethe University Frankfurt

What else should have been mentioned:

I. Peric, ZITI, Heidelberg – Partially depleted 2.5D MAPS

V. Re et al, INFN, Pavia, Bergamo – MAPS with discriminator/shaper

… ând many others…