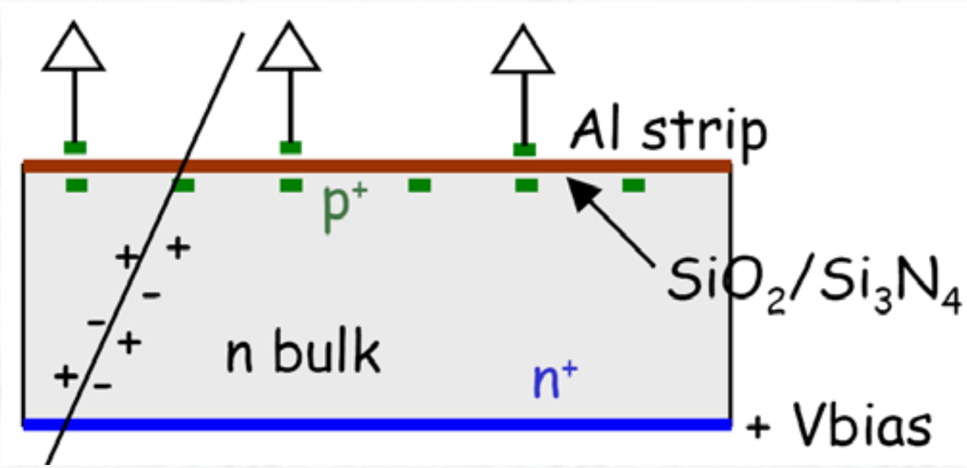
2.3 Silicon Semiconductor detectors

- Semiconductor Detectors (mainly Silicon)
  - Motivation and history

- Basic Si properties
  - p-n-junction

- Strip Detectors

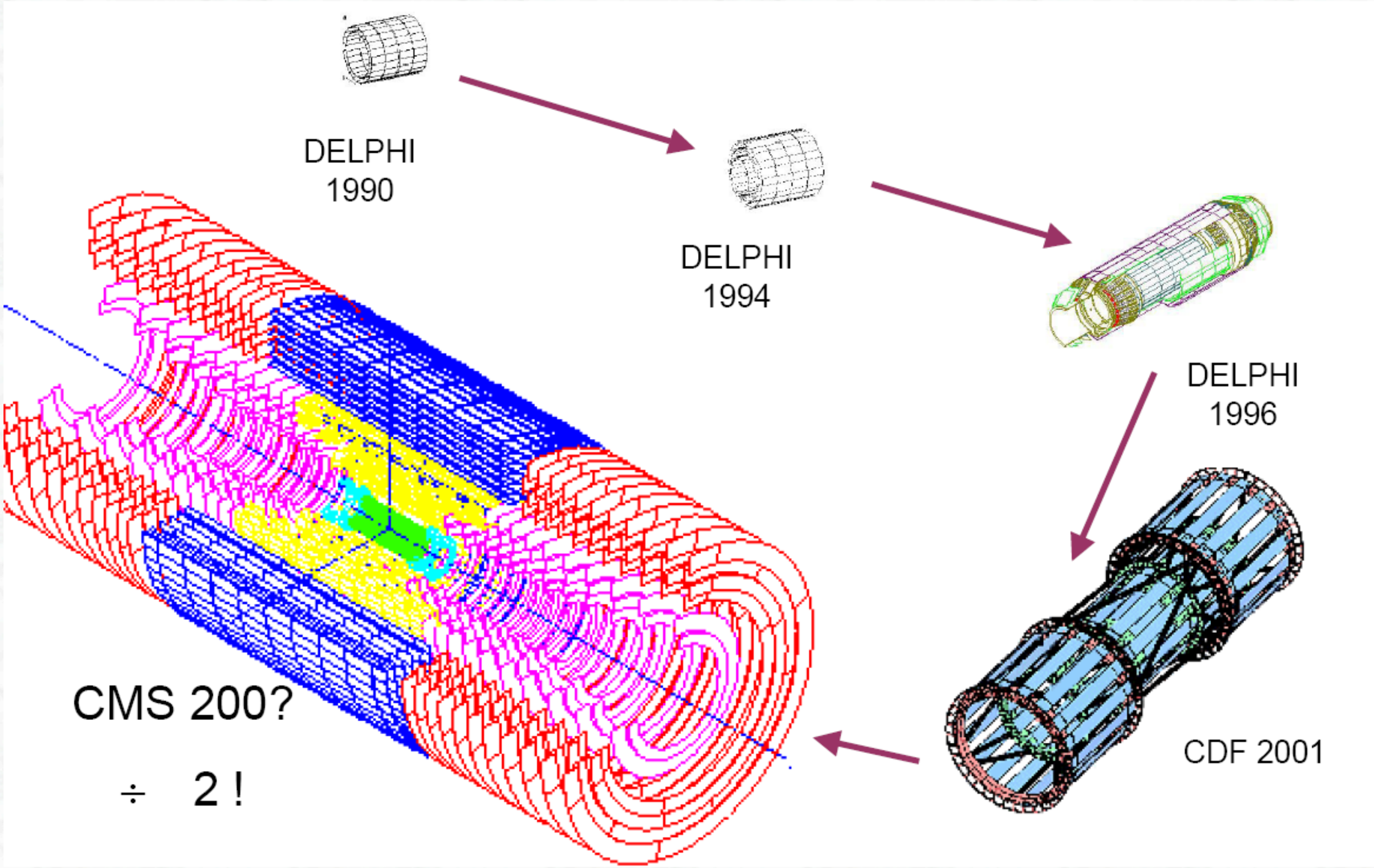
- Pixel Detectors



Use of Silicon Detectors

- Silicon detectors: a kind of solid-state ionisation chamber
- Si-detector concepts started in the 80s, but expensive and difficult at first
- Increased commercial use of Si-photolithography and availabilty of VLSI electronics lead to a boom for Si-Detectors in the 90s – and it still goes on, though we need R&D on Si radiation hardness…
- Nearly all high energy physics experiments use Silicon detectors as innermost high-precision tracking device
- High energy physics experiments are now exporting Si-technology back to the commercial world (Medical Imaging)

Evolution in Si-Detector Area



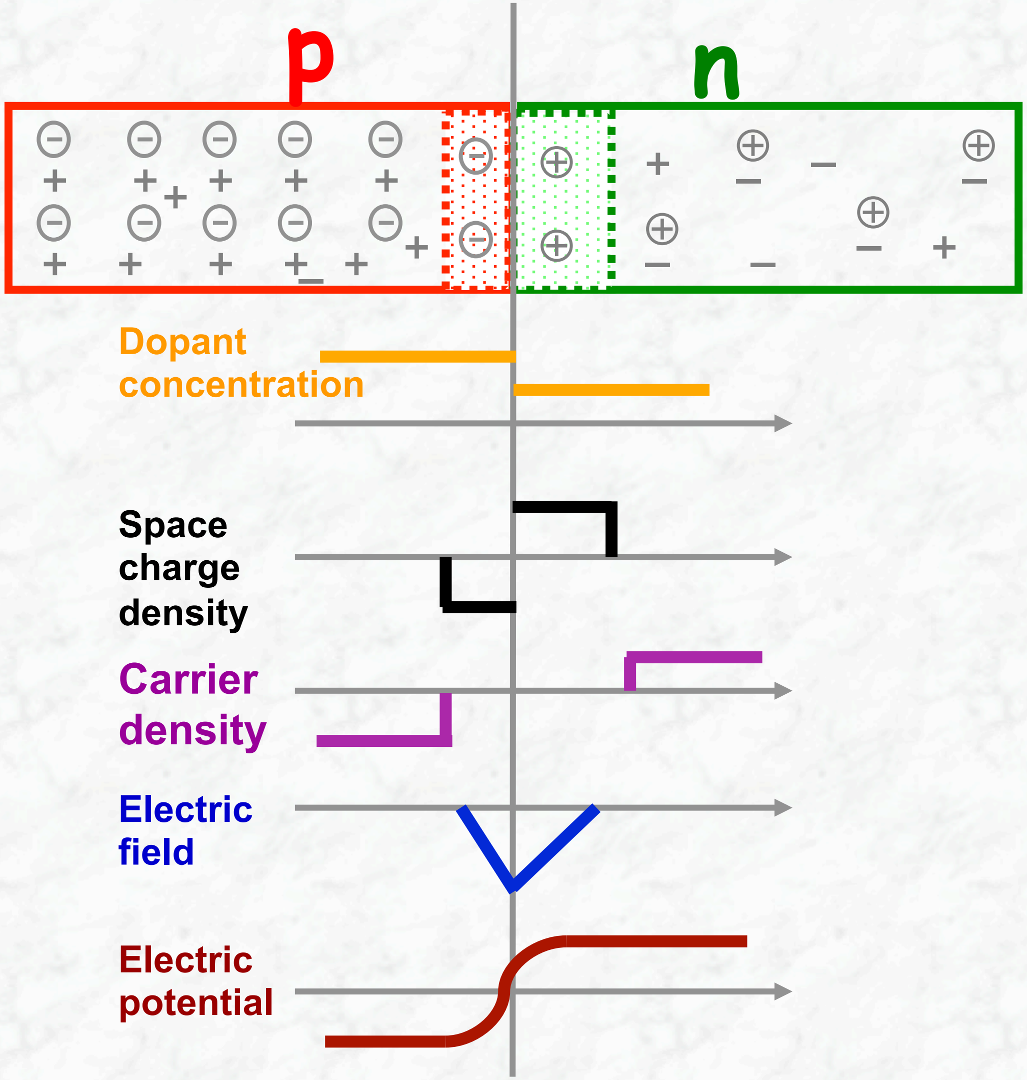
Basic Silicon Properties

- Silicon: type IV element, 1.1eV band gap

- Intrinsic conductivity very low $\sigma_i = e \cdot n_i (\mu_e + \mu_h)$
  - Carrier density at 300 K:
    - $1.5 \cdot 10^{10}$ cm^{-3} compared to $5 \cdot 10^{22}$ Si-Atoms per cm^{-3}
    - often dominated by impurities

- "Doping": Small admixtures of type III or type V elements increase conductivity
  - Donors like Phosphorous give extra electron -> n-type Si
  - Acceptors (e.g. Boron) supply extra hole -> p-type Si
  - Contact between p- and n-Si forms p-n-junction
  - Doping dominates conductivity as $n_i \ll n_D$
  - for n-type Si: $\sigma_D = e \cdot n_D \cdot \mu_e$

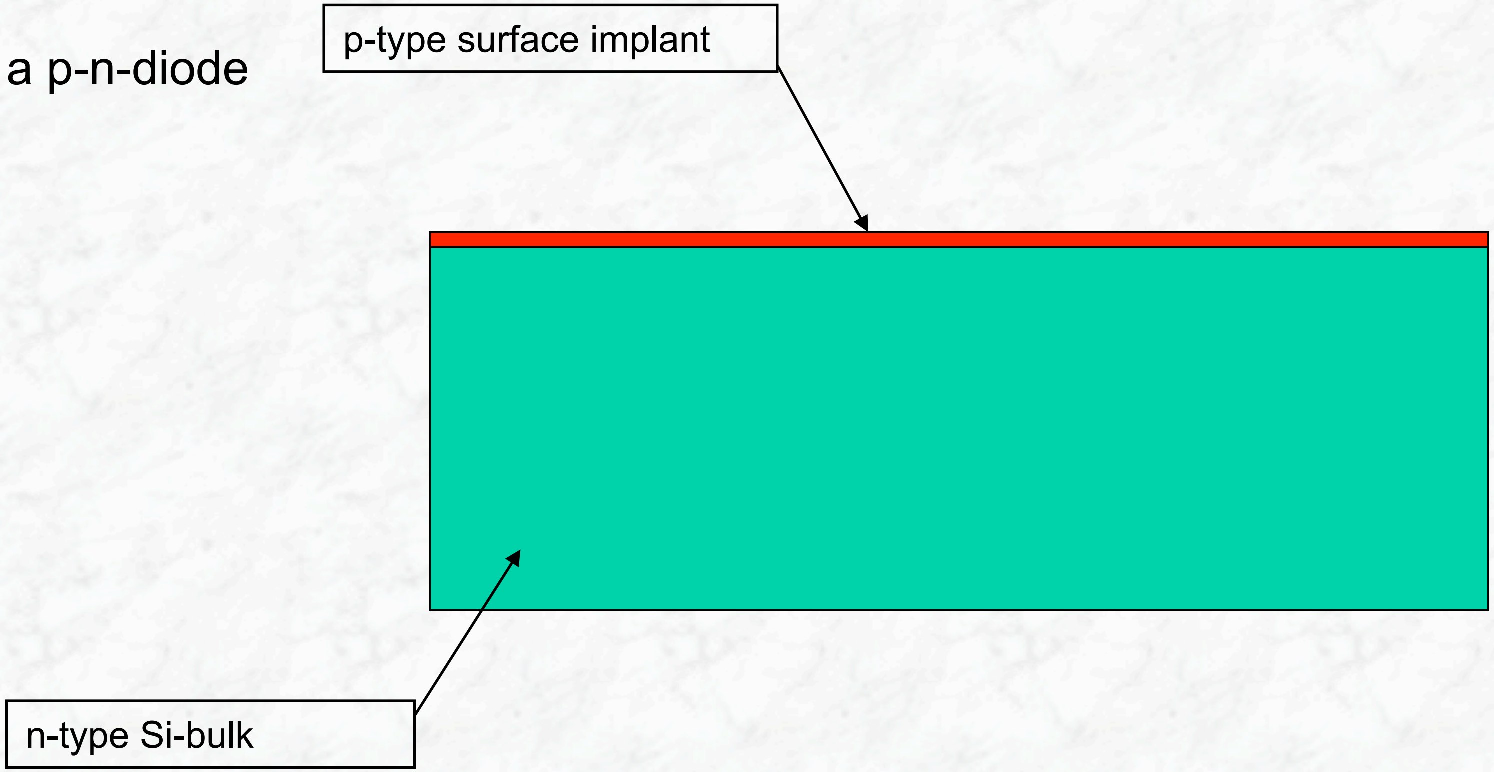
p-n-Junction



- Diffusion of e^- from n-side and h^+ from p-side
- Recombination on other side, free charges disappear around junction ("depletion")
- Neutral p- or n-Si becomes charged → E-Field
- External field can increase or decrease depletion zone
- Depletion is what we want for detectors!

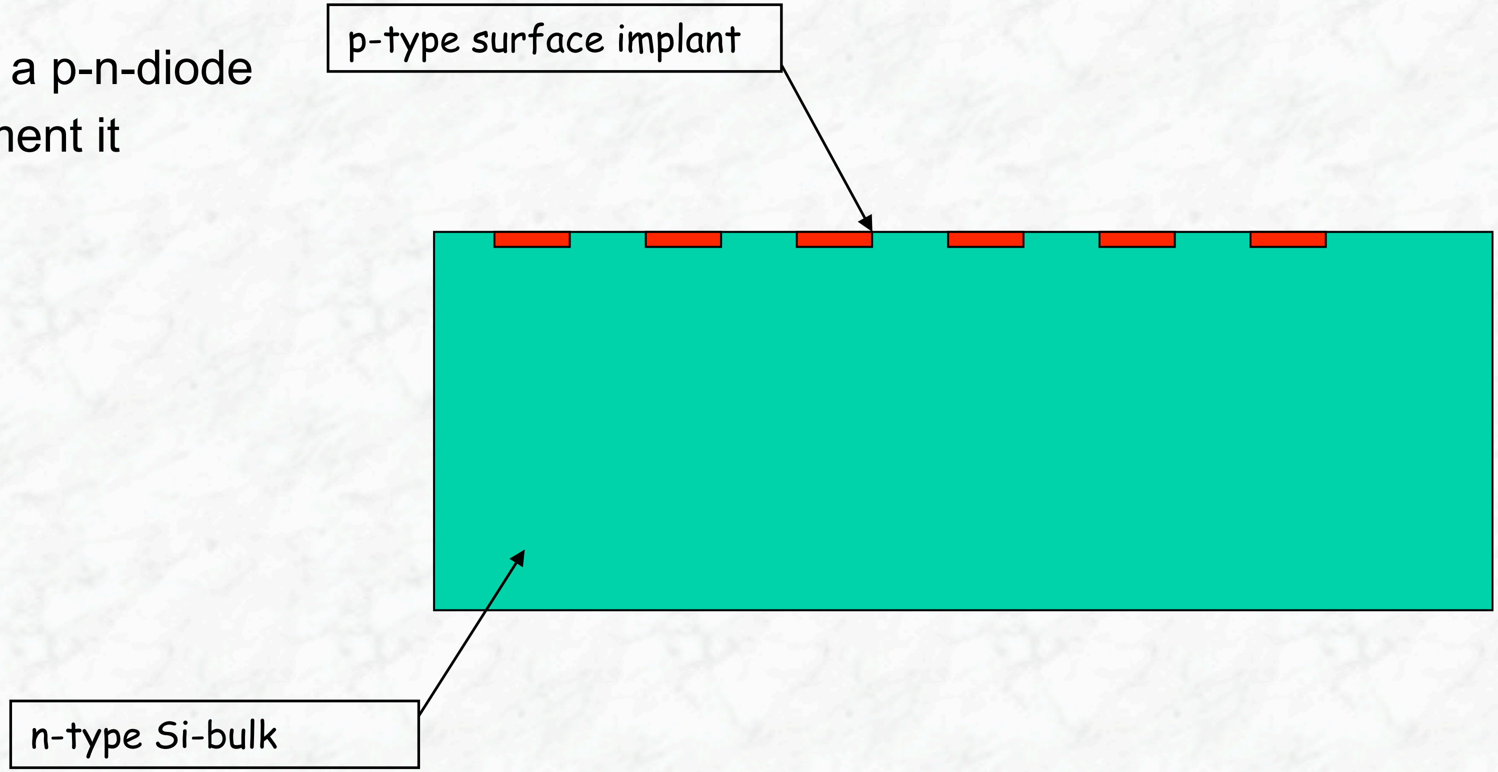
A Basic Silicon Detector

- Take a p-n-diode



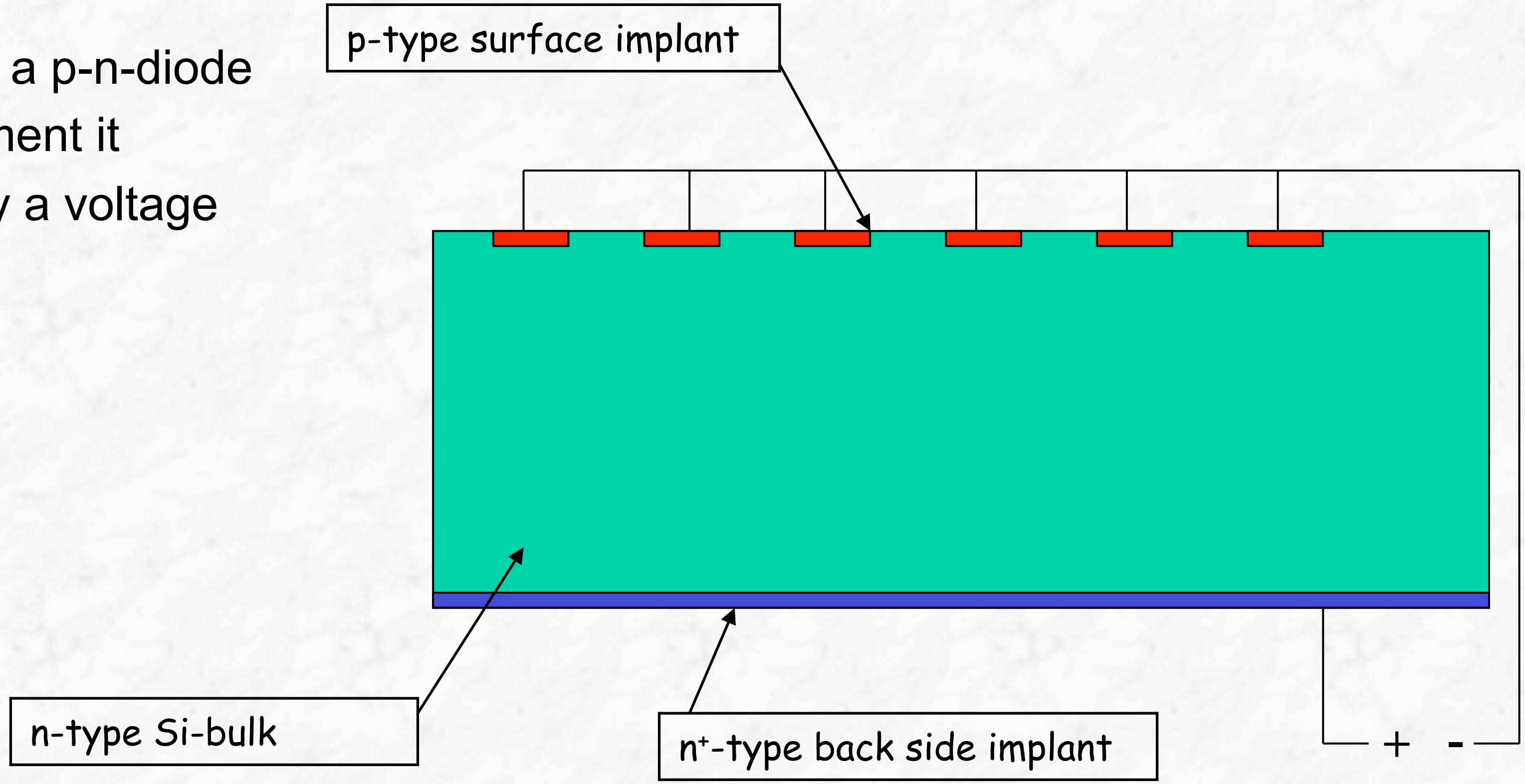
A Basic Silicon Detector

- Take a p-n-diode
- Segment it



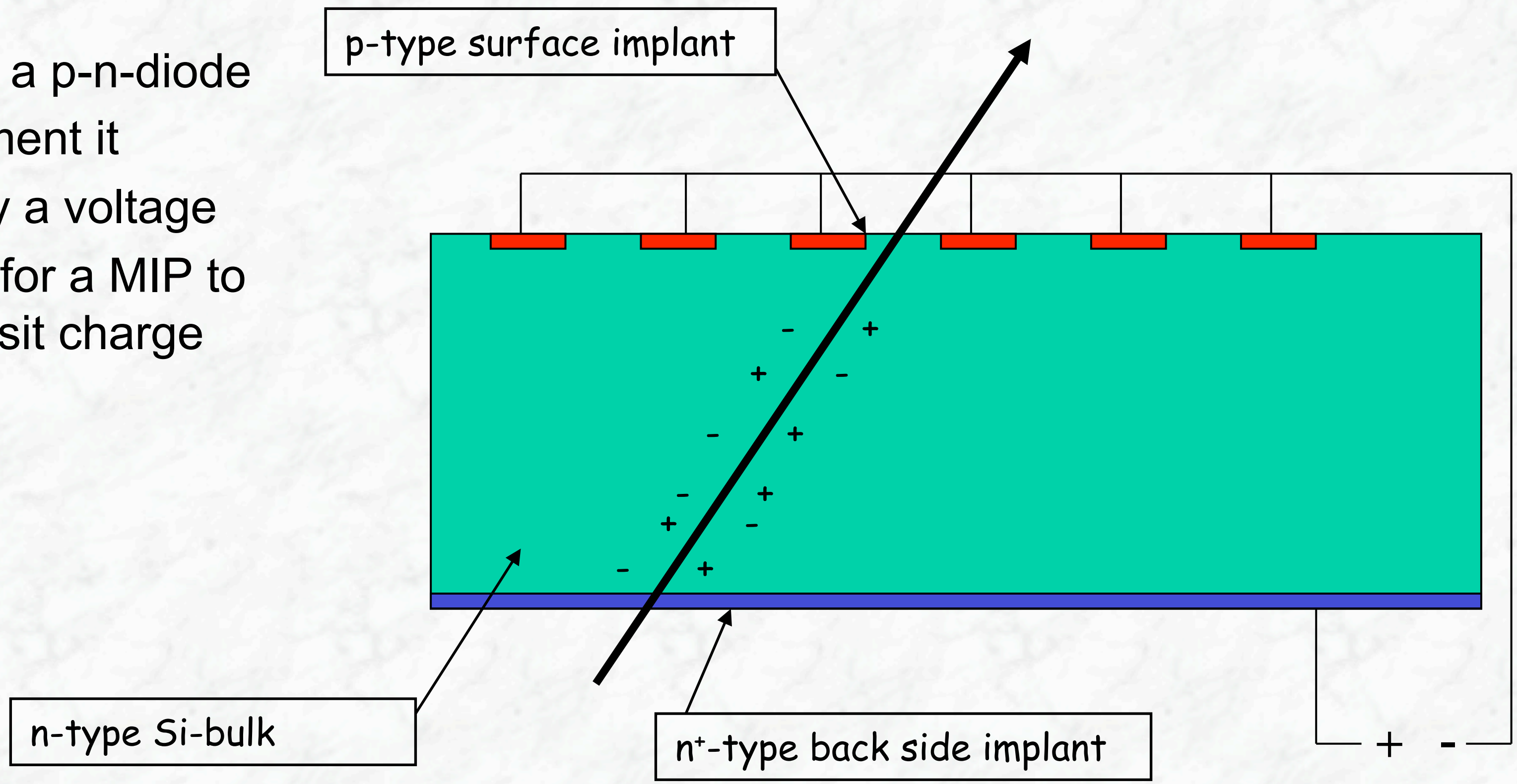
A Basic Silicon Detector

- Take a p-n-diode
- Segment it
- Apply a voltage



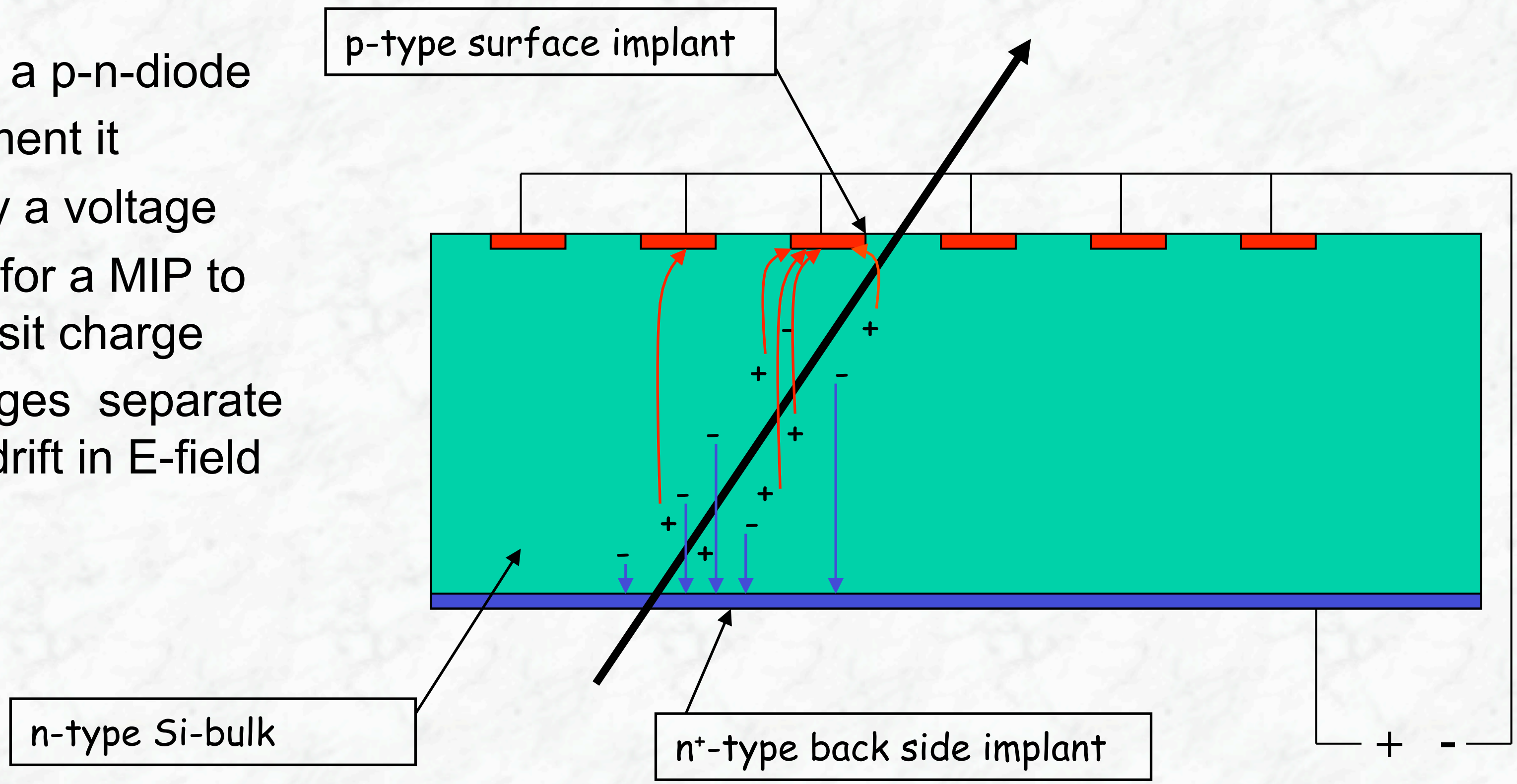
A Basic Silicon Detector

- Take a p-n-diode
- Segment it
- Apply a voltage
- Wait for a MIP to deposit charge



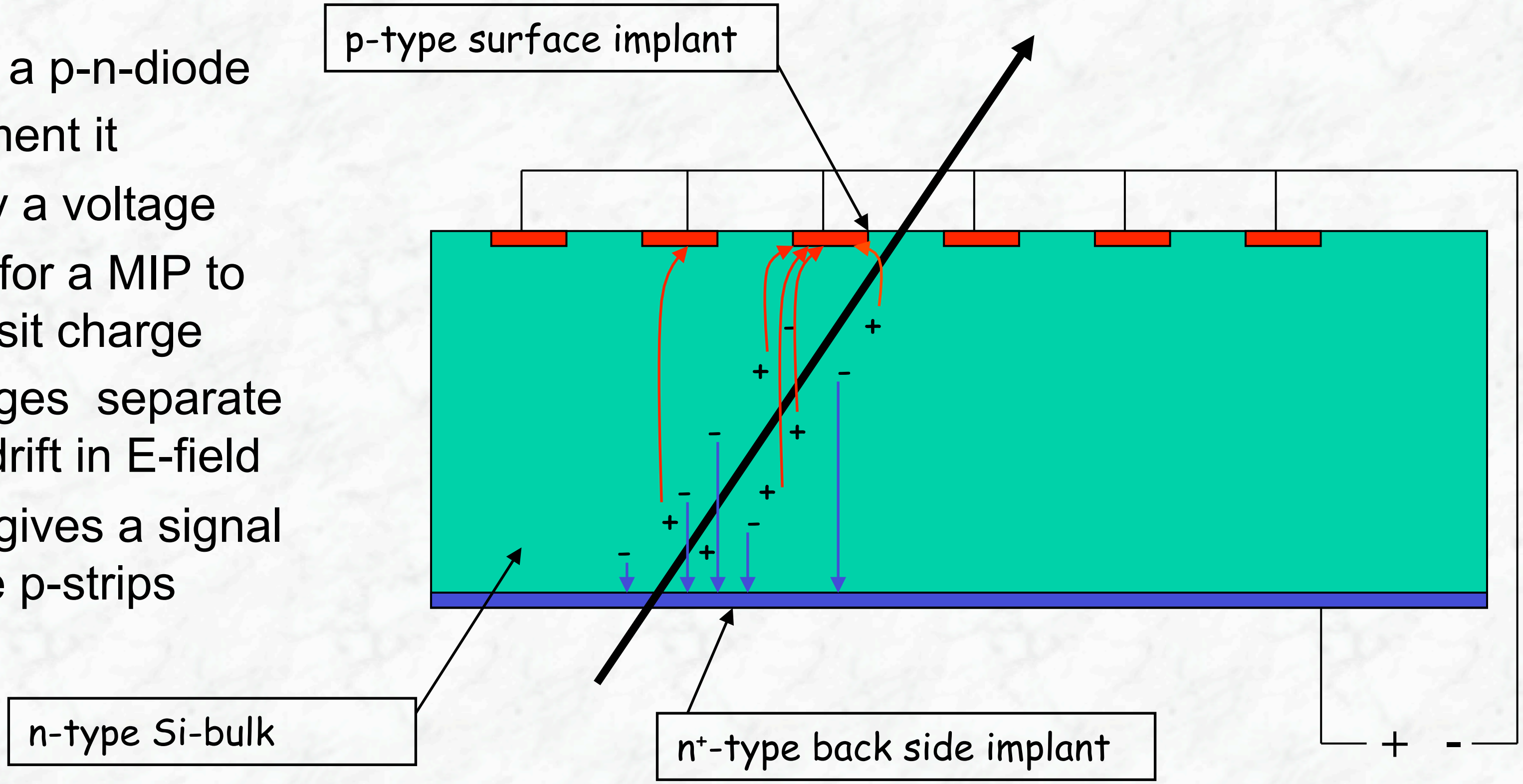
A Basic Silicon Detector

- Take a p-n-diode
- Segment it
- Apply a voltage
- Wait for a MIP to deposit charge
- Charges separate and drift in E-field



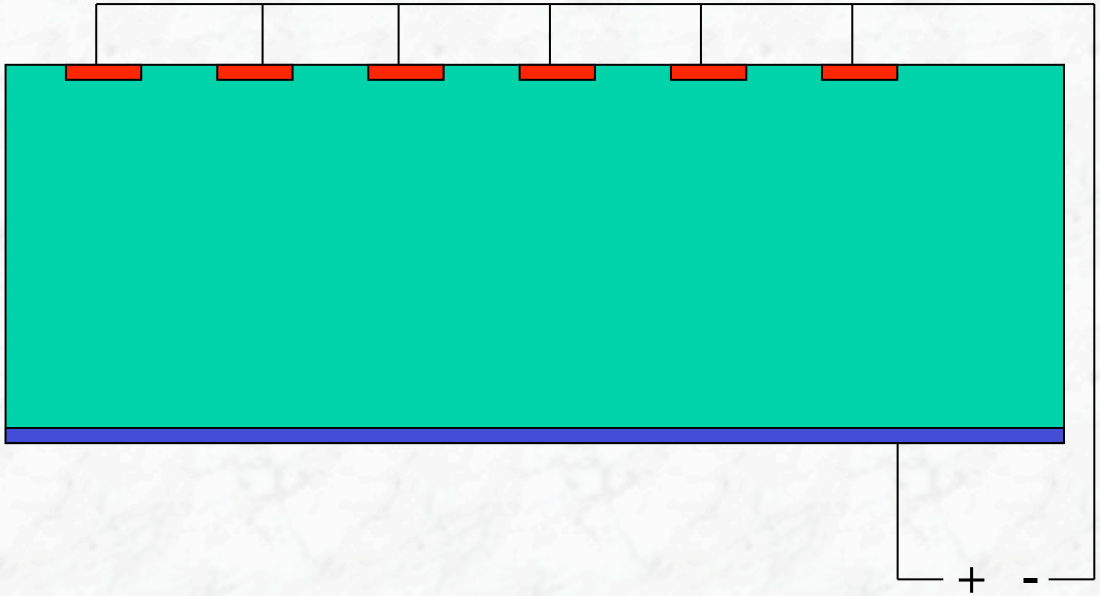
A Basic Silicon Detector

- Take a p-n-diode
- Segment it
- Apply a voltage
- Wait for a MIP to deposit charge
- Charges separate and drift in E-field
- This gives a signal in the p-strips



Depletion

- MIP charge in 300 µm Si is 4fC (22.000 e^-h^+-pairs)
- Free charge in 1 cm^2 Si-Detector 10^4 times larger (T=300K), so signal is invisible. Options:
  - Cryogenic operation
  - E-field to get rid of free charge
- Apply external Voltage to deplete Si from charges
- Depletion zone grows from p-n-junction towards the back side



$$w_{depletion} = \sqrt{2\varepsilon\rho\mu V_{bias}}$$

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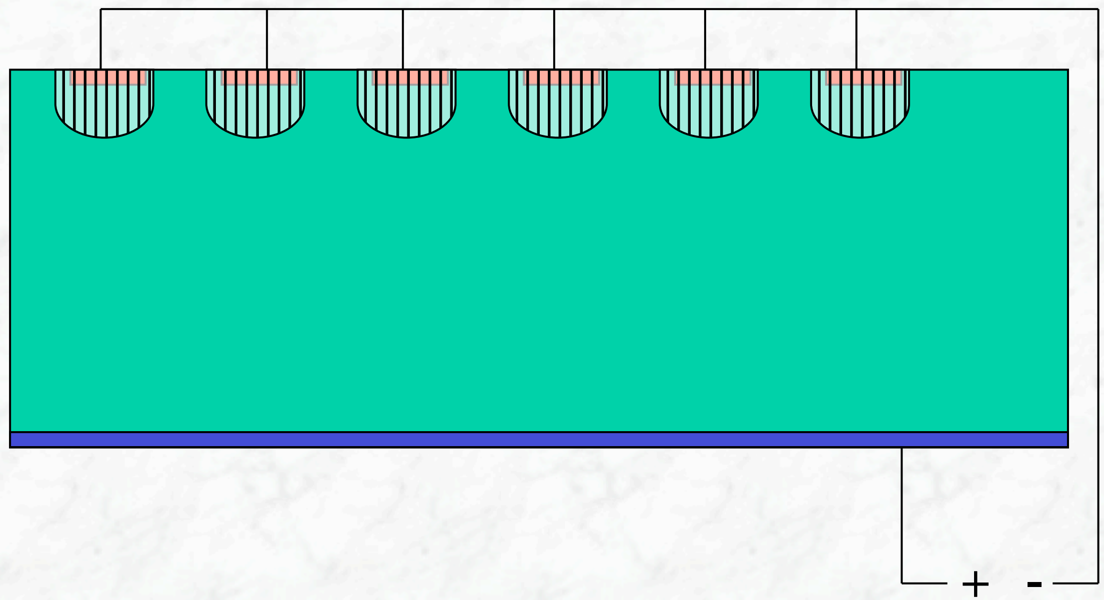

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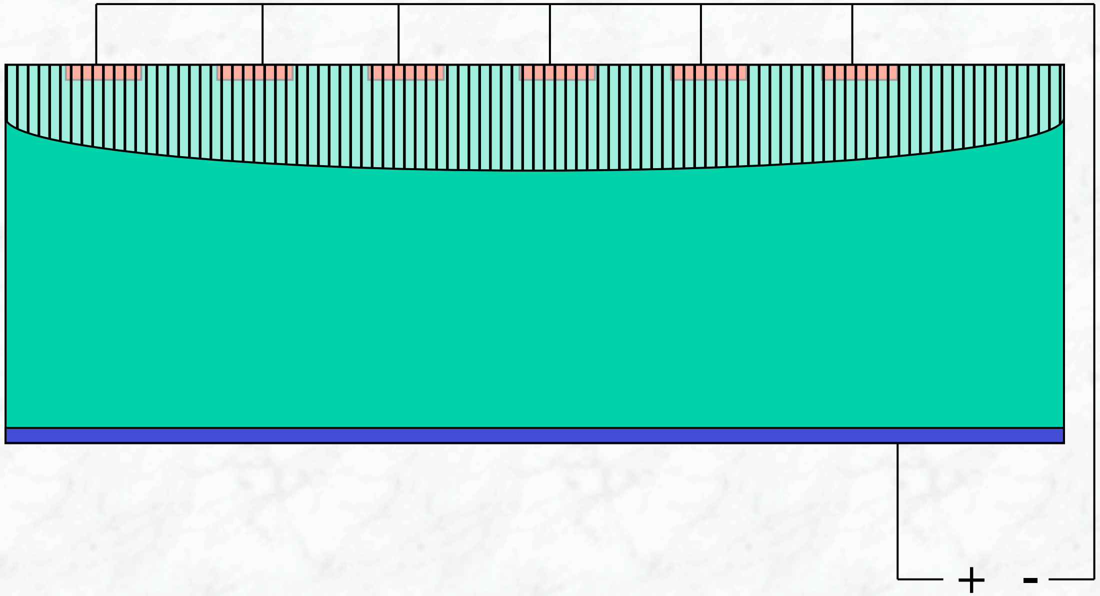

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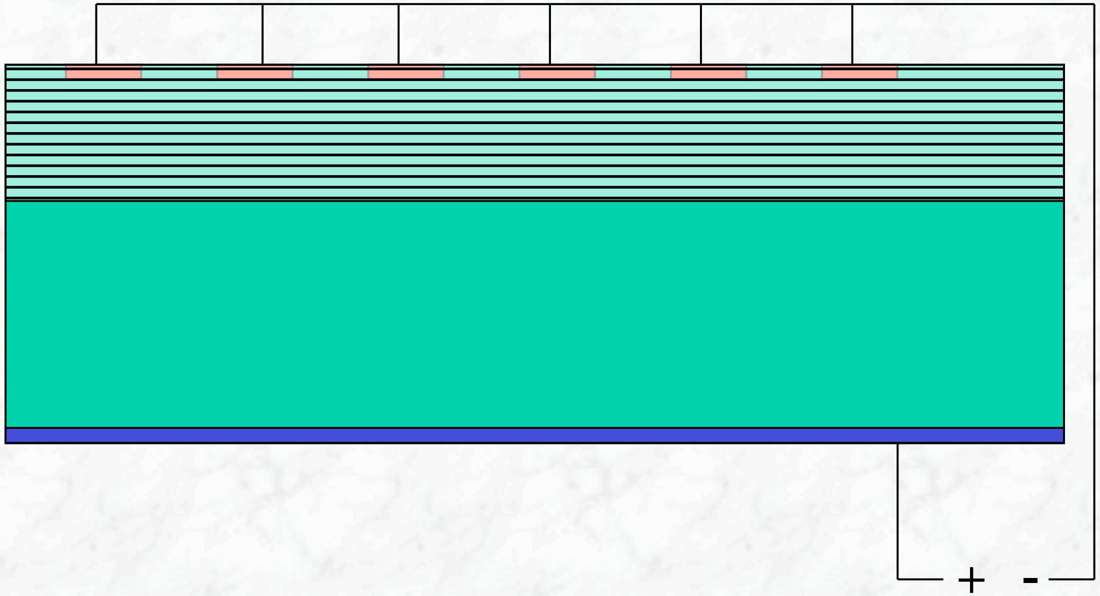

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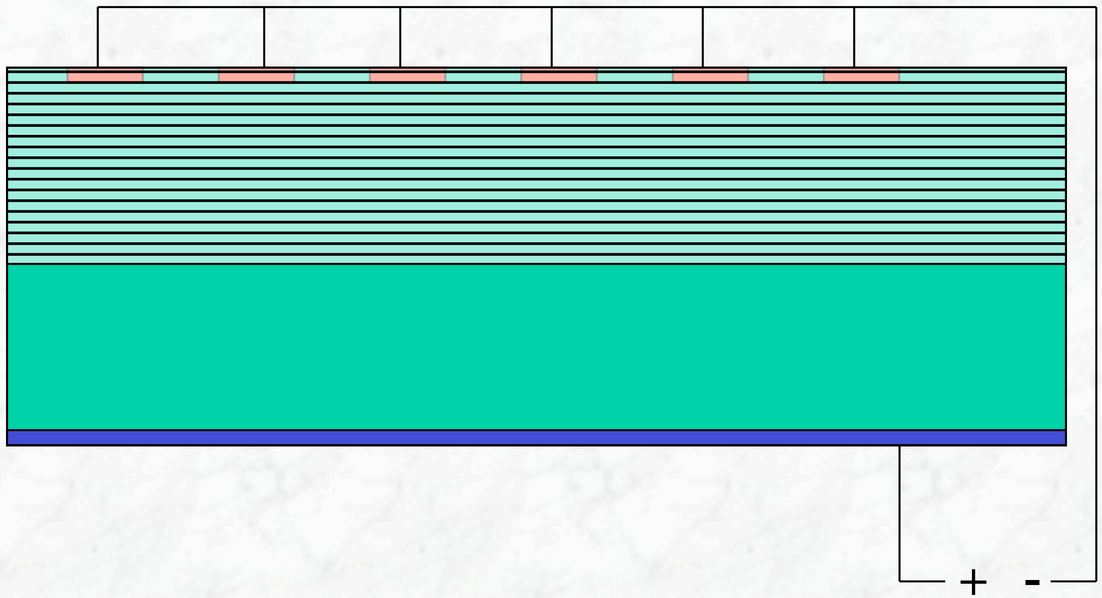

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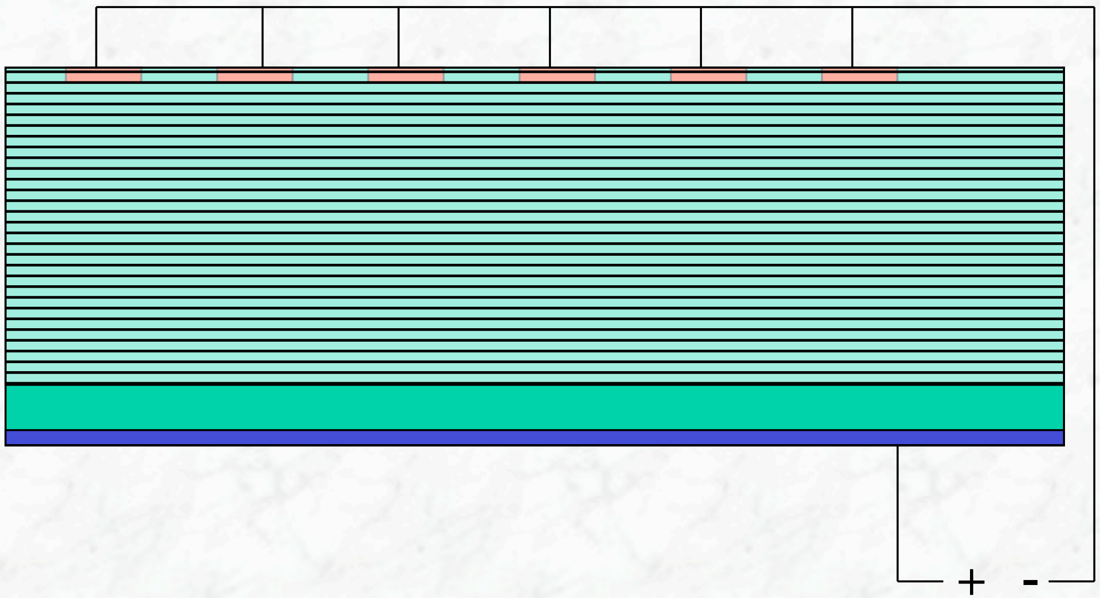

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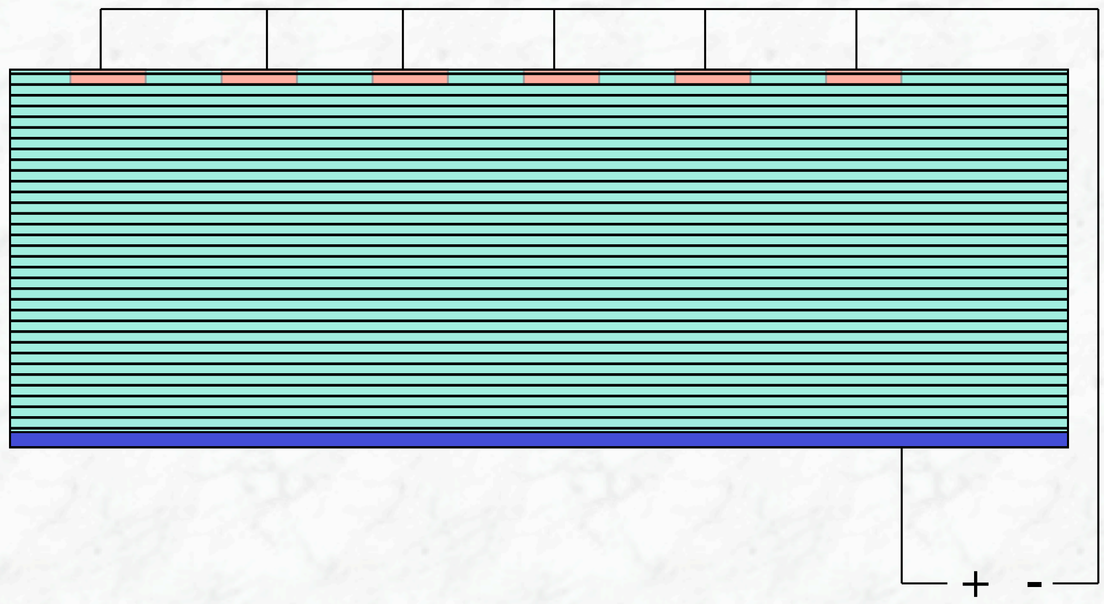

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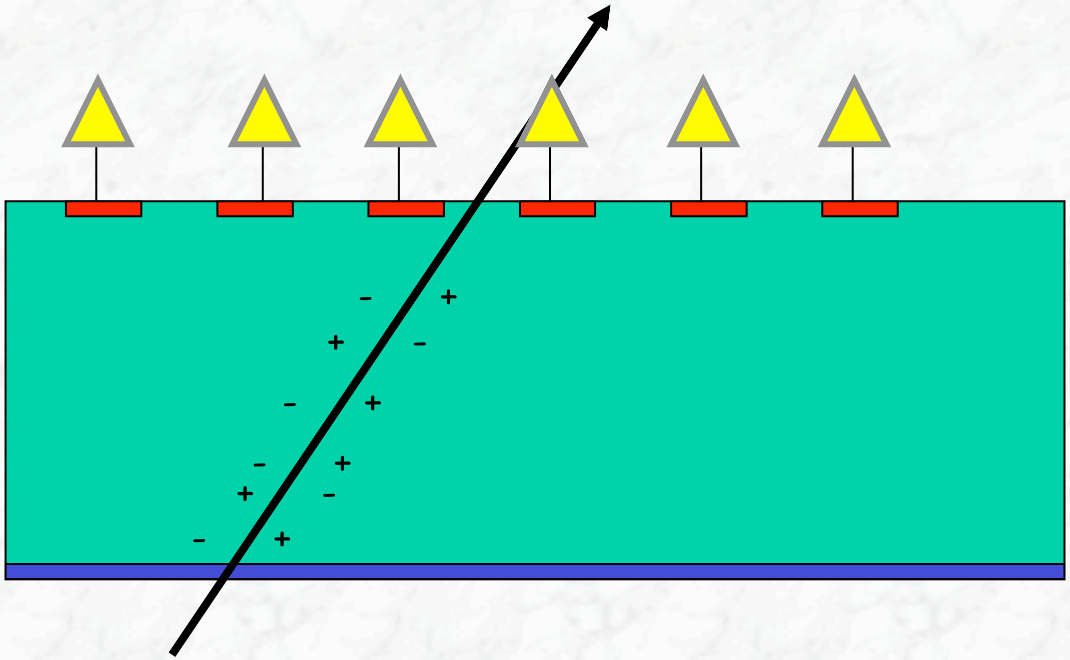
Signal

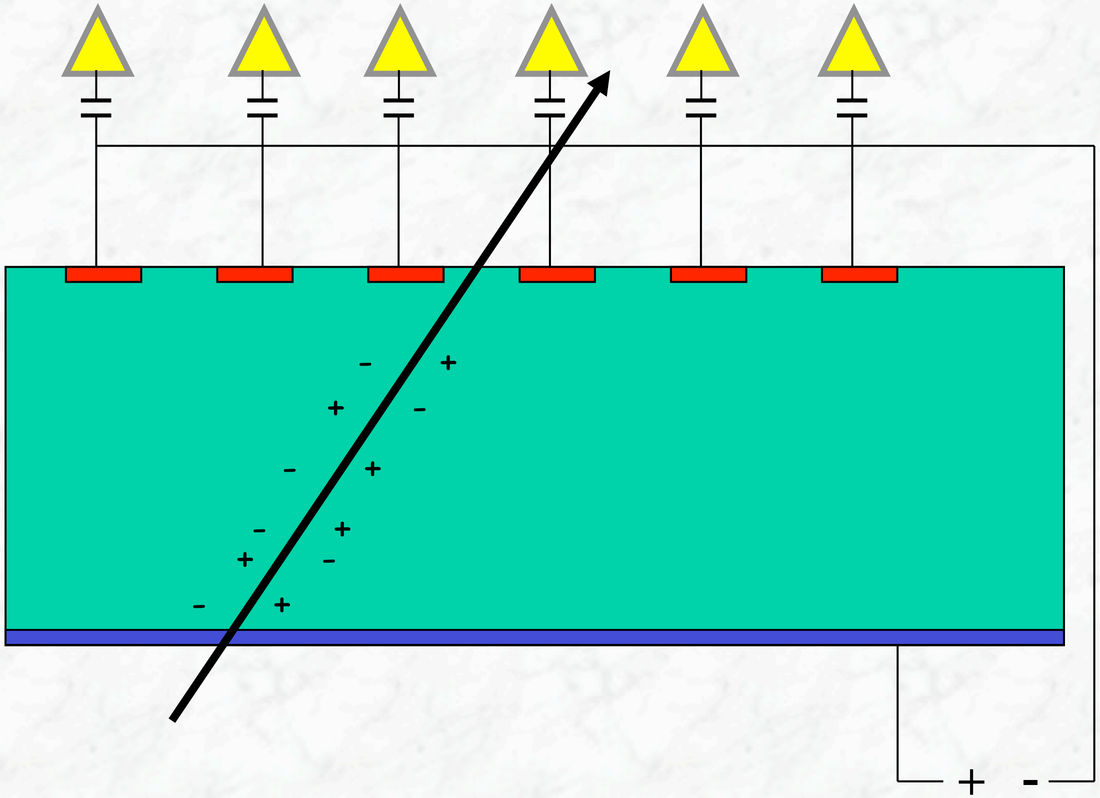
- Depleted piece of Si, a MIP generates $e^- h^+$-pairs…
- $e^- h^+$-pairs separate in E-field, and drift to electrodes
- Moving charges -> electric current pulse
- Small current signal is amplified, shaped and processed in ASICs ("chips") on read-out electronics



ASIC = application specific integrated circuit

Some subtleties

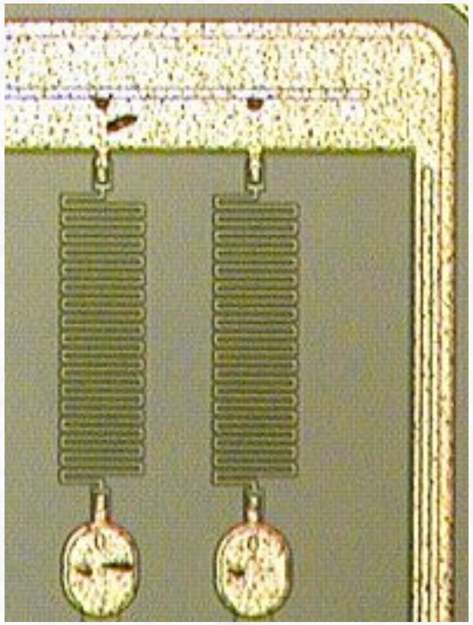
- Even under reverse bias, there is a permanent thermal current going into the amplifiers
- Amplifying this current consumes power, generates heat and noise
- Solution: decouple strips from amplifiers for DC signals only -> AC-coupling
- Integration of capacitors into Si-Detector possible (and common today)

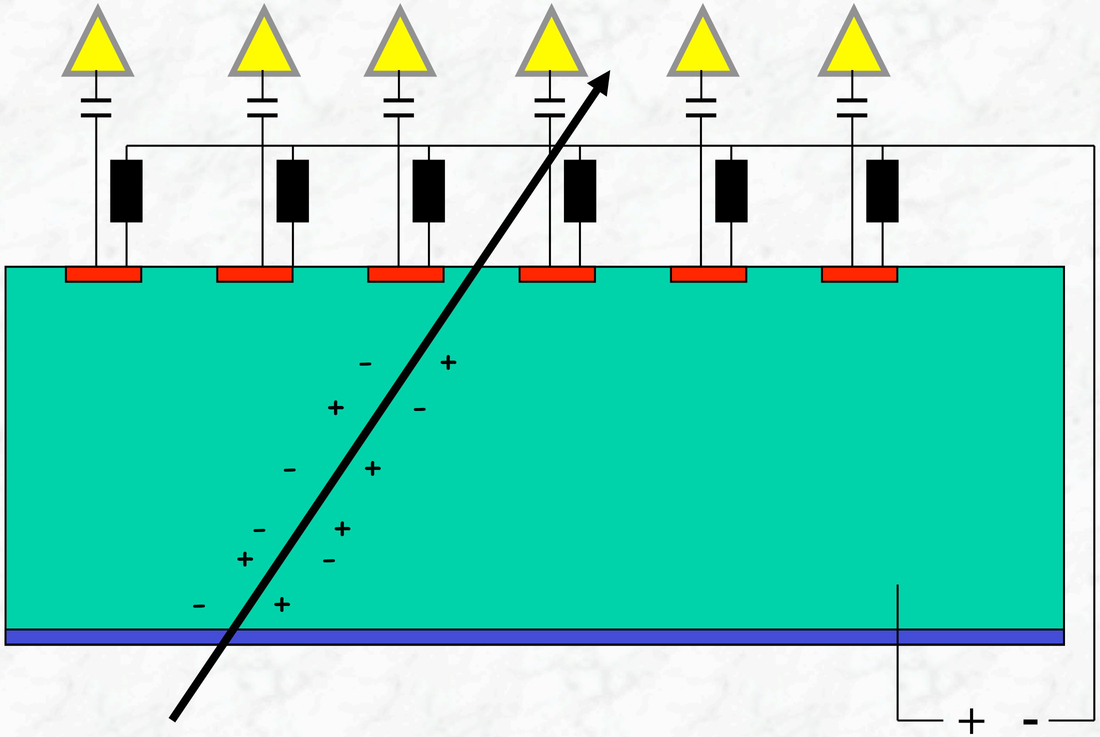


More Subtleties

- Diodes need to be on same potential but electrically separated (to avoid shorting them)

- Solution: decouple strips with bias resistors
  - ~ 1 MΩ





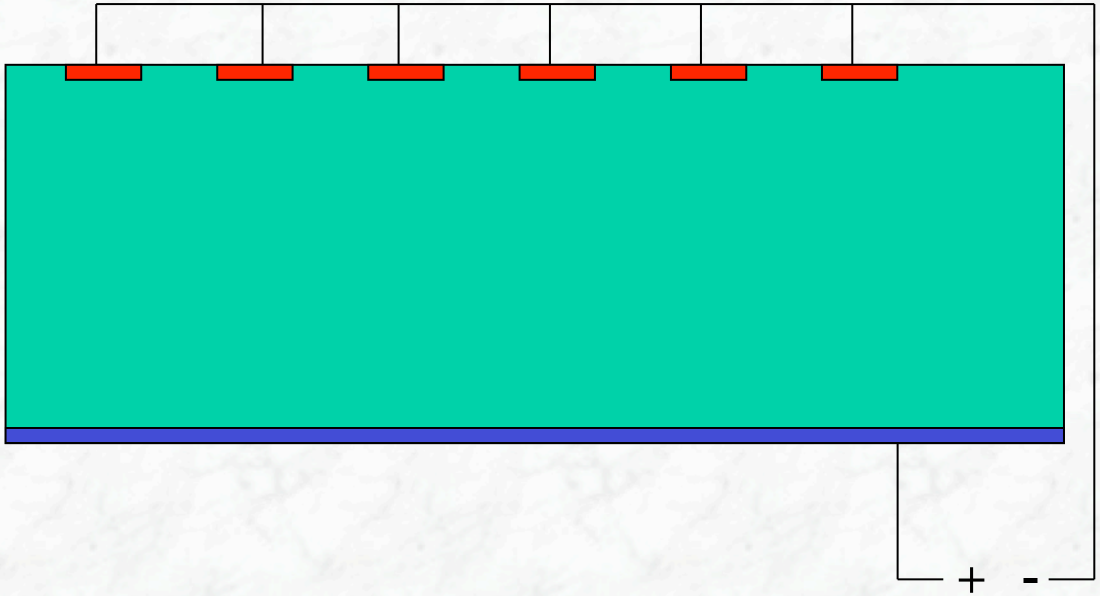
Schematic Si-Detector

- This detector will deliver 2D information – we need one more coordinate:

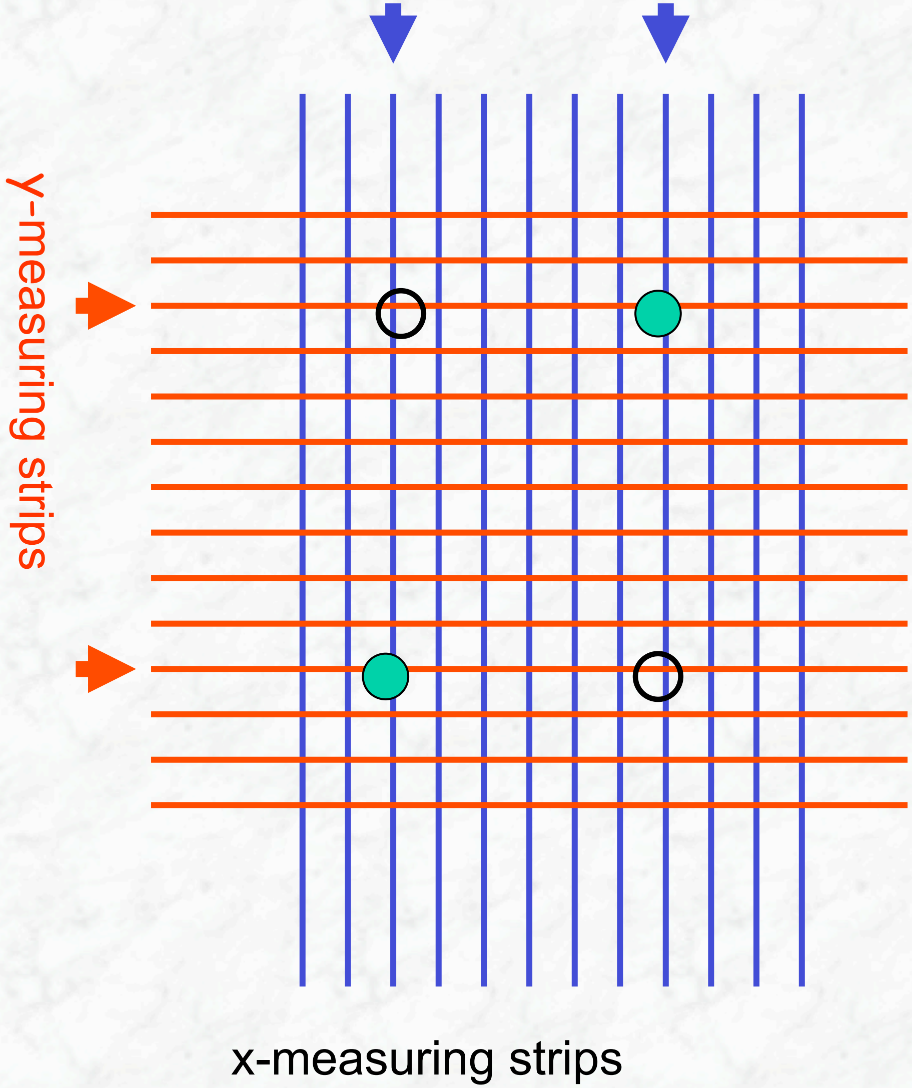
- Take another detector and place it on top with orthogonal strips

- Or segment the n-side
 (backside) as well
 -> double-sided detector

- Both will work – but one has to think a bit about the angle of the two Si-planes



Angle between two Si-Detectors



- Charge from MIP
- Signal strips
- “Ghost“ (combinatorial hit)

N hits per readout cycle generate N^2 ambiguities in hit position

Ambiguities are reduced by stereo angle < 90^o

ATLAS Reality: O(10) hits per detector module per 25 ns.

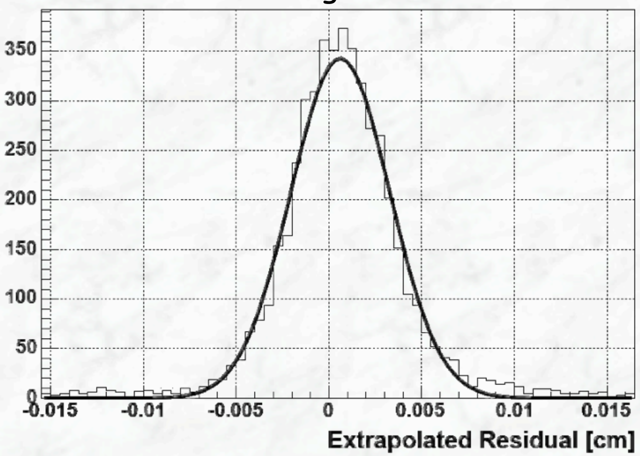
Stereo angle of few degrees.

Performance: Resolution & Rate

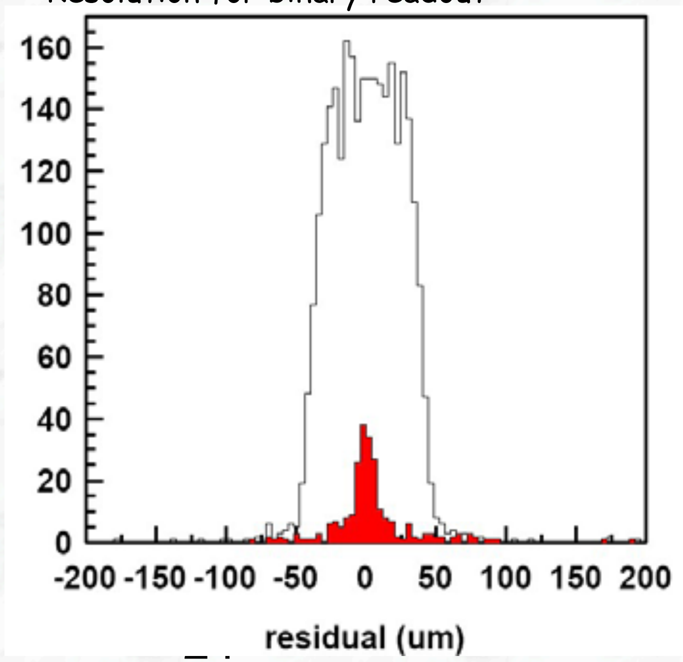
- Resolution σ :
  - Dominated by strip pitch d
  - Single strip hits: **$\sigma = d/\sqrt{12}$**
  - Double strip hits improve resolution (weighted average)
  - Ratio single/double hits gets worse for larger pitches –
    → Resolution worsens rapidly with increasing pitch
  - Higher S/N -> more two-strip hits –
    → better resolution
  - Analogue readout has better resolution than binary
- Rate:
  - signal collection $t_{collect}$ ~10ns
  - signal shaping in front end electronics: $t_{shape} \geq t_{collect}$
  - a lot of Si-detectors operate successfully at LHC speed (25ns)

d	σ
25 µm	2.6 µm
60 µm	9 µm
100 µm	29 µm

Resolution for analogue readout

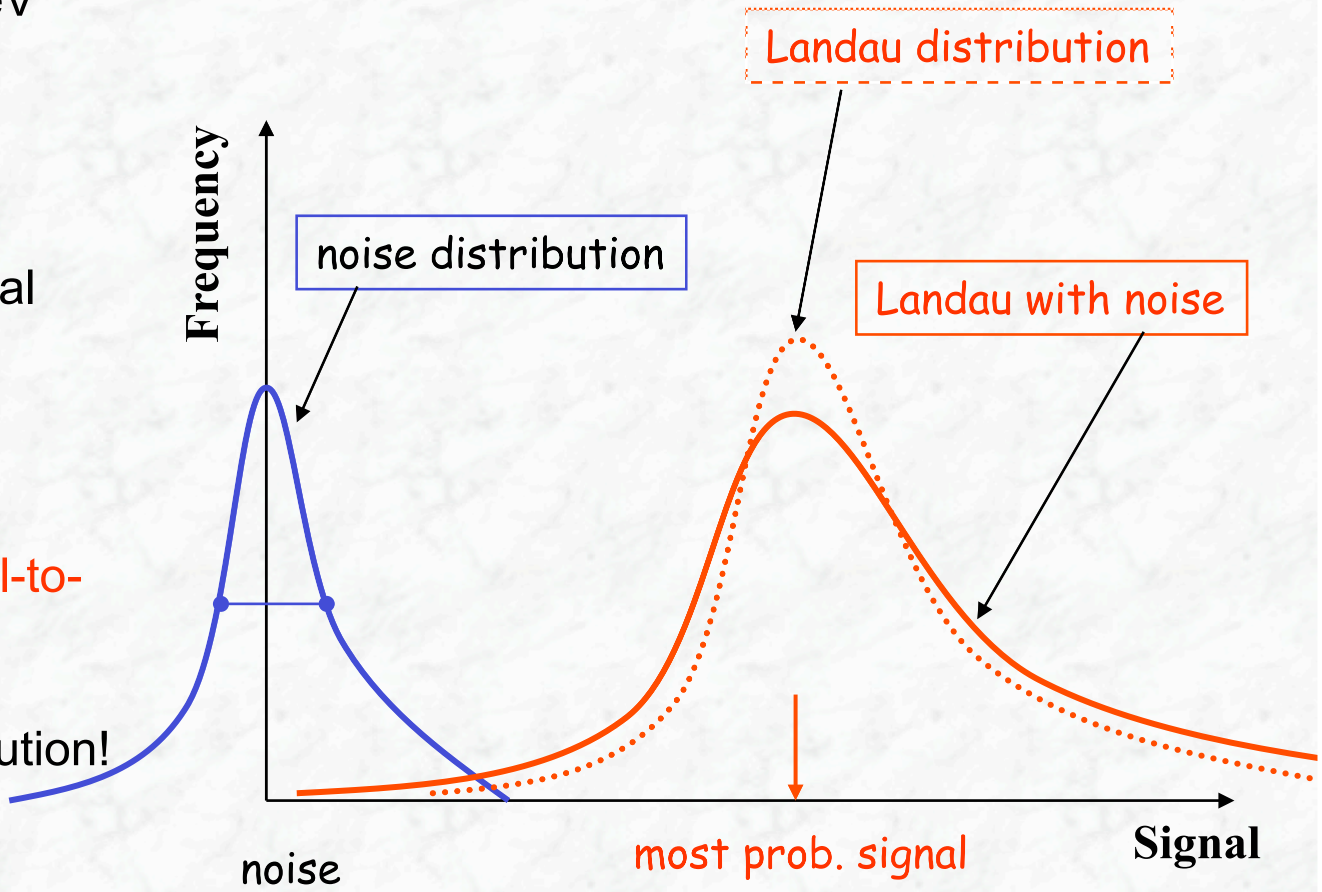


Resolution for binary readout



Signal and Noise

- Noise “Signal“ from strips has Gaussian shape
- MIPs deposit ~100 keV energy according to Landau distribution, broadened by noise
- Need to separate signal and noise
  → threshold value
  → efficiency
- Figure of merit: Signal-to-Noise ratio or S/N
- S/N also affects resolution!



Full Si-Detector System

- So far we only have a piece of Silicon with some electronics attached, which will give us a 3D space point…

- Will we find the Higgs with that?

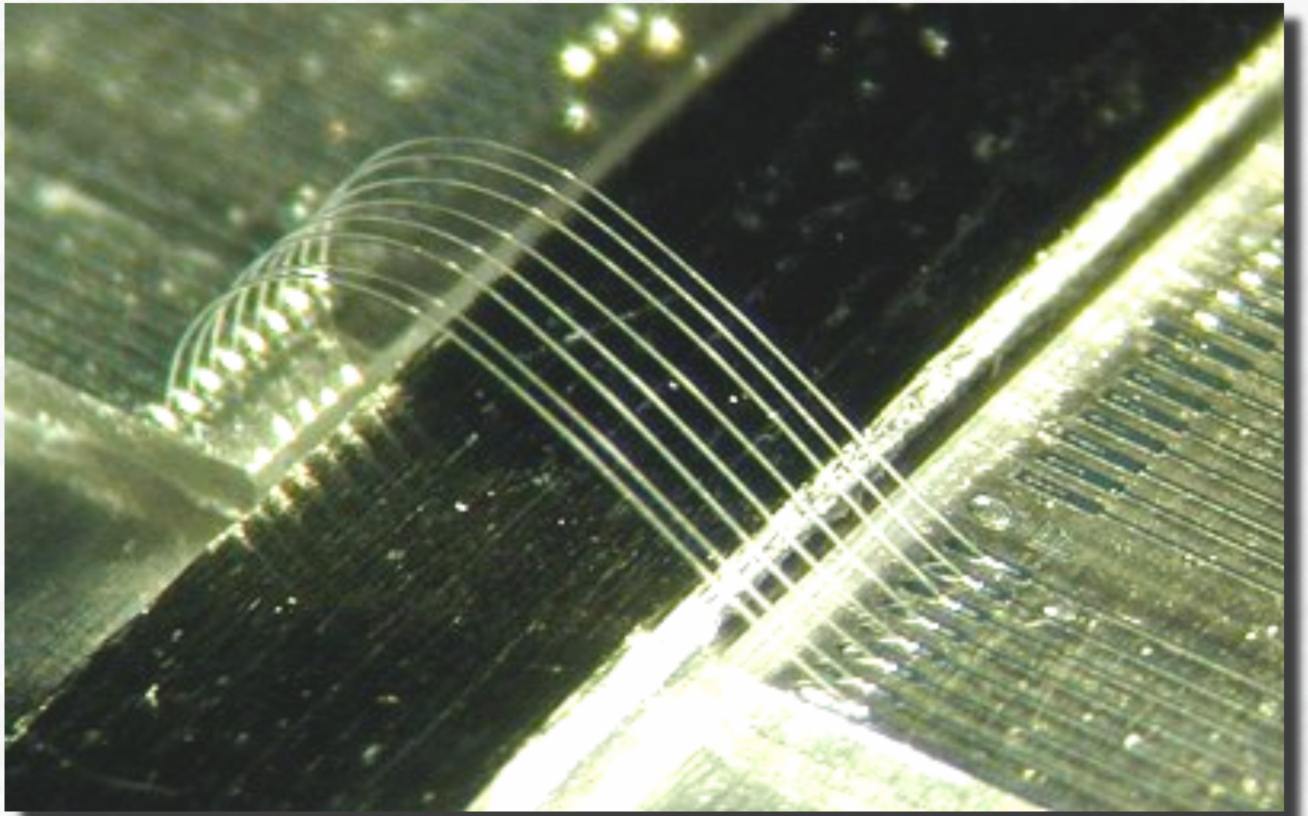
- Need to put many (thousands) of Si-Detectors together in a smart way

  - Require several space points → several layers
  - Need to see all charged tracks → hermetically closed
  - For collider experiments (e.g. ATLAS, CMS) this means a multilayer cylindrical structure

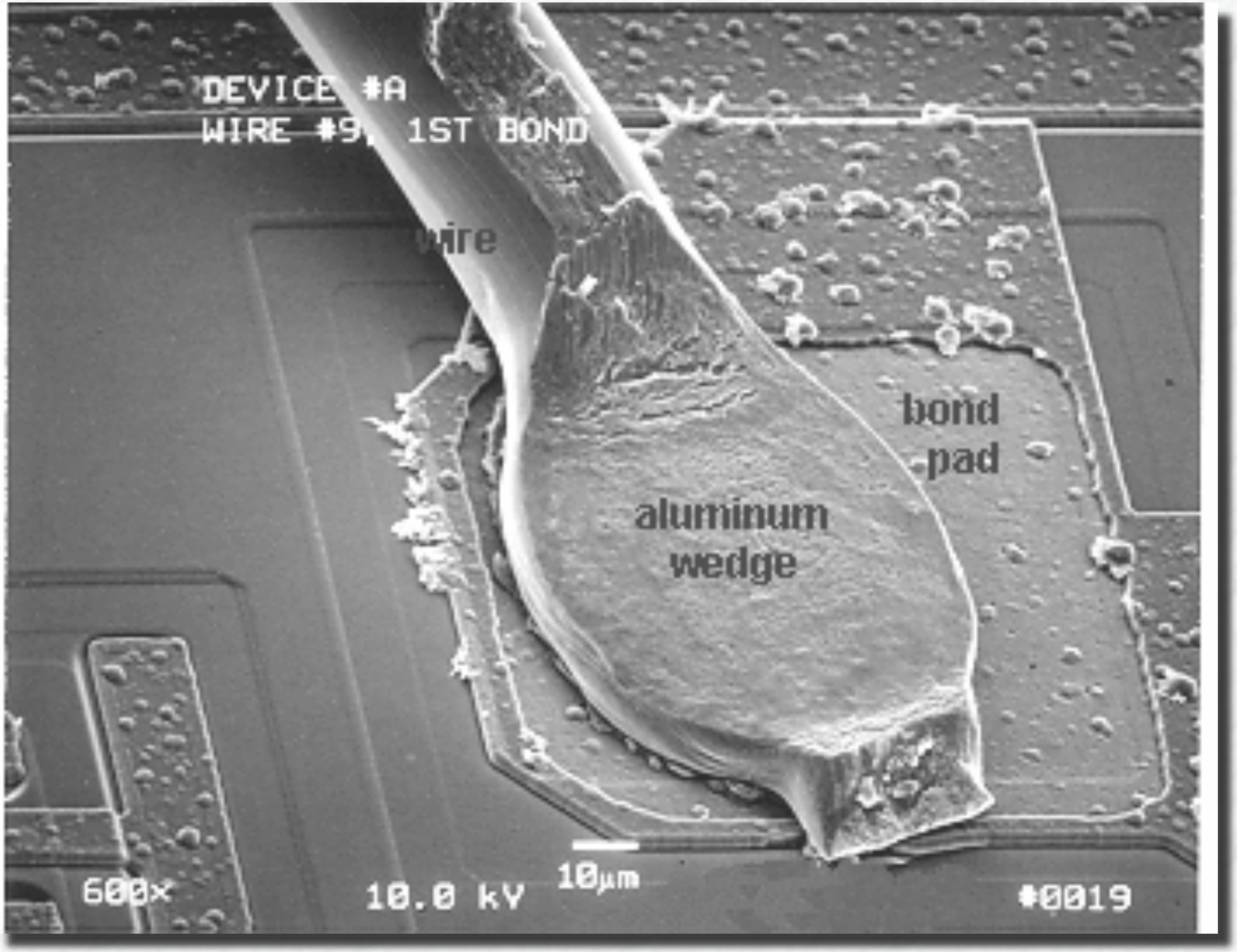
- Some examples will follow

Wire Bonding

- Si detector needs connection to readout electronics
- High connection density with O(15) wires per mm
- Ultra-sonic bonding of ~20μm wires with semiautomatic system



Single Wire Bond Foot



2.4 Silicon Pixel detectors

Basic concept: - segment a diode in 2 dimensions
- strips become pixels

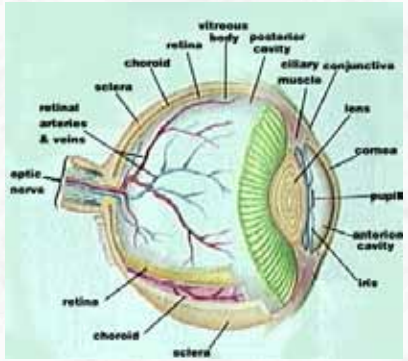
→ increased two-dimensional resolution → space points

Si-Pixel Detectors: CCD

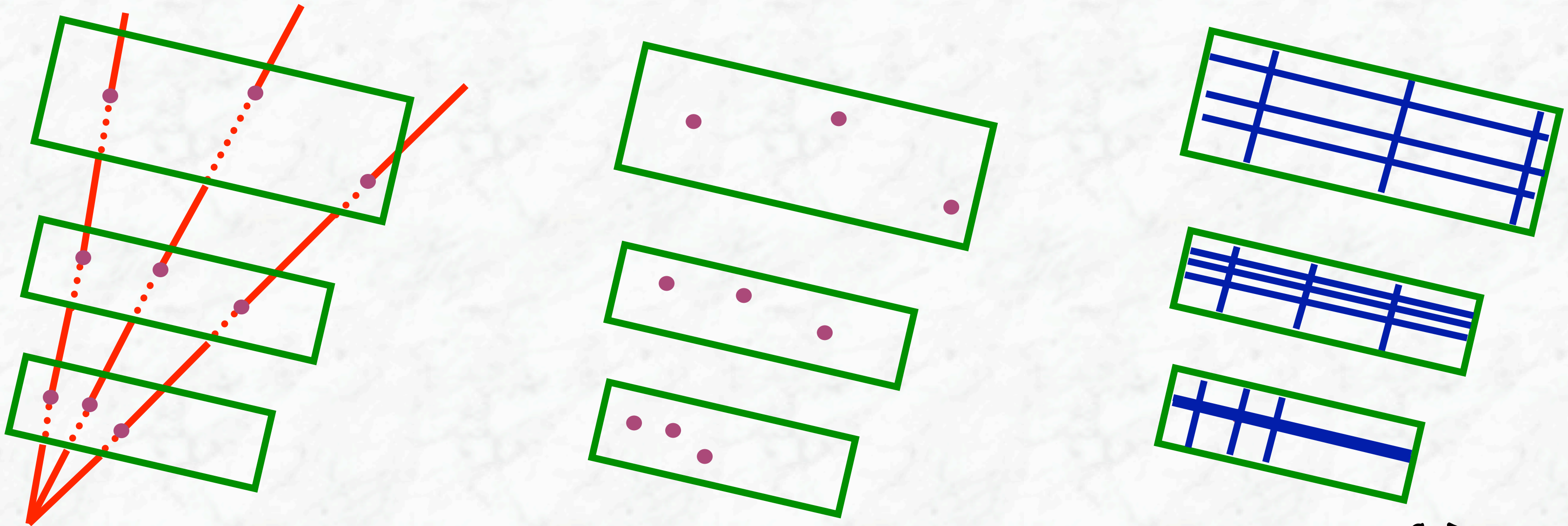
- Instead of strips measuring one dimension, have a matrix of points measuring two dimensions

as used in this

and in this



- Pattern recognition is much easier! Compare reconstructing

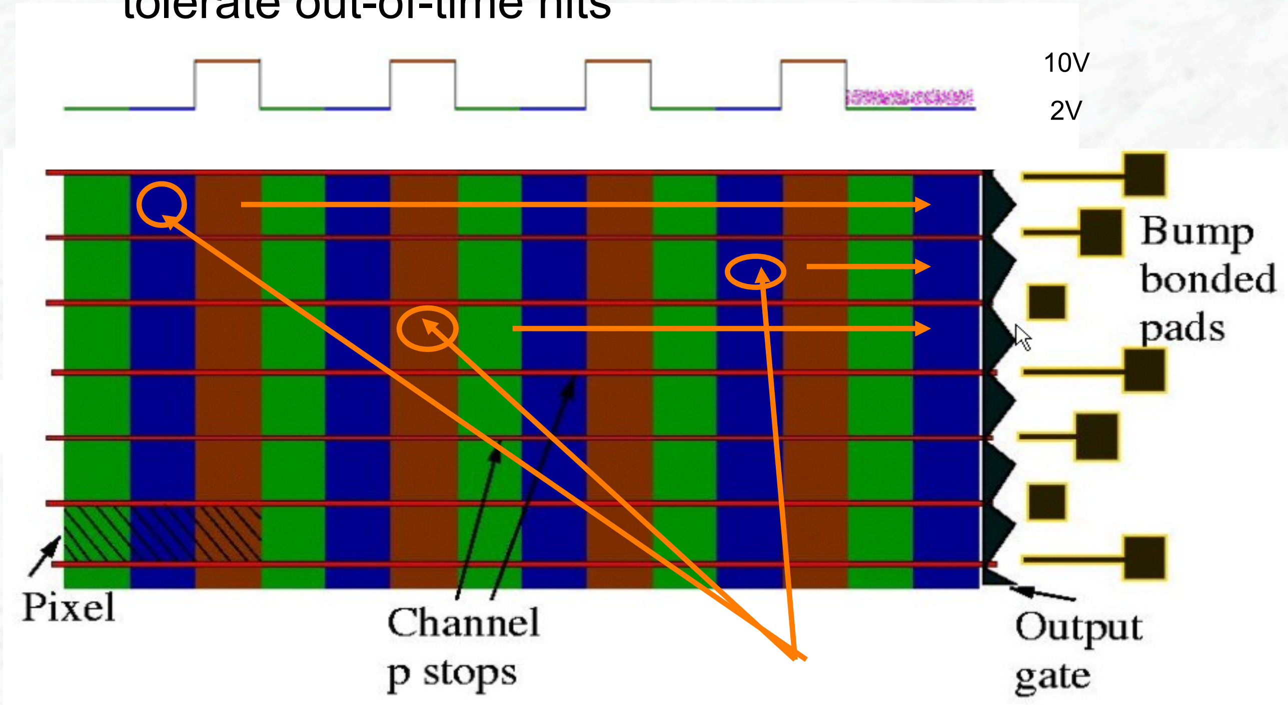


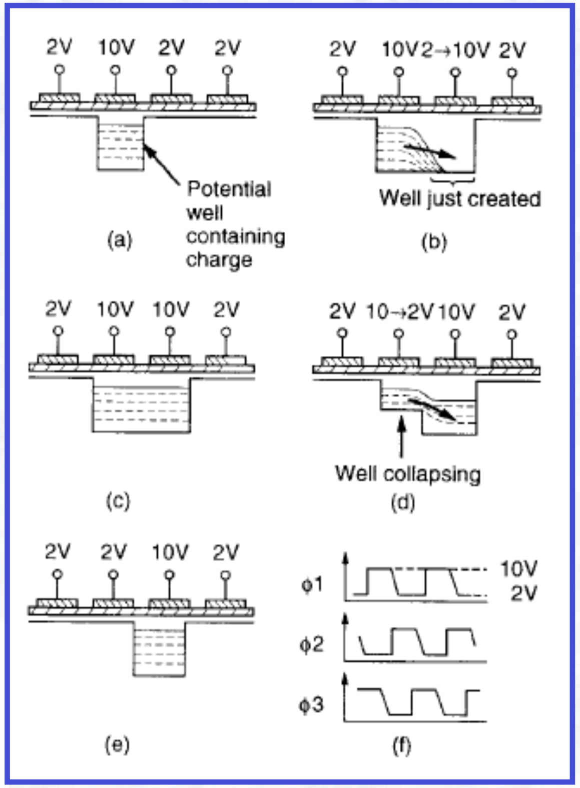
these tracks … with this …. or with this!

C. Damerell, P.Collins

Si-Pixel Detectors: CCD

- First pixel detectors in HEP were CCDs derived from digital cameras
- CCD principle: MIP generates charge which is shifted out sideways to readout
- Very economic as $N_{readout} < N_{pixel}$
- CCDs work - but are slow and do not tolerate out-of-time hits





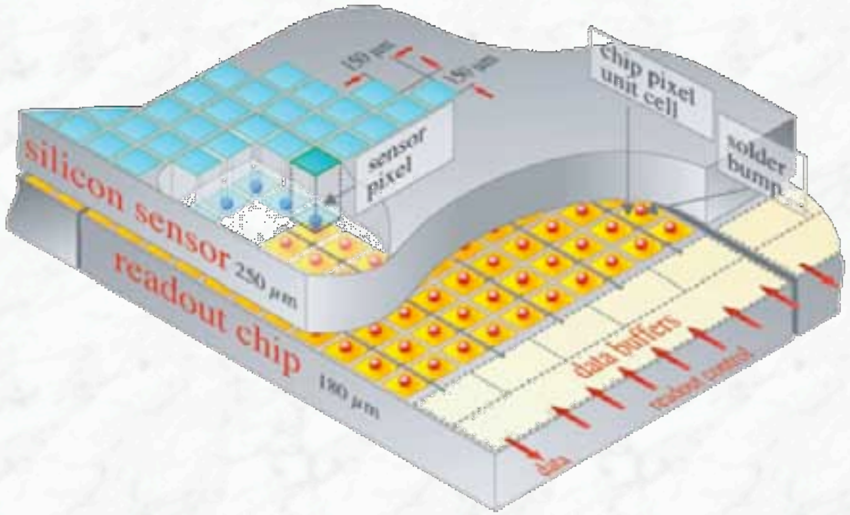
From Paula Collins

Pixel Detector Overview

- Different pixel detector types

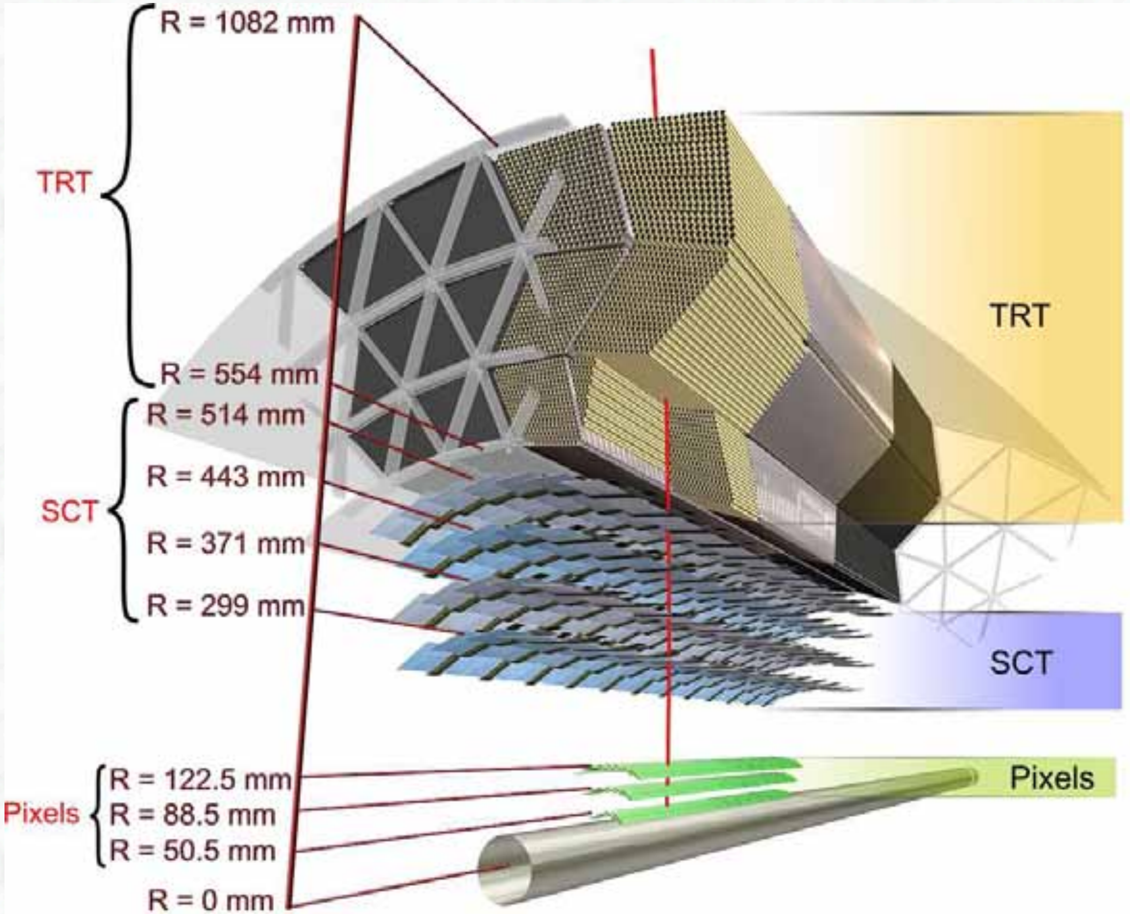
- Hybrid Active Pixel Sensors (HAPS)
  - Detector and readout ASIC are sandwiched together ($N_{readout} = N_{pixel}$)
  - Limitation from readout:
    Pixel size > 120 x 120 µm (2004)
  - Used widely in collider experiments
    - ATLAS: 100M pixels (50x400 μm^2)
    - CMS: 23M pixels (150x150 μm^2)

HAPS design principle



- Monolithic Active Pixel Sensors (MAPS)
  - Preamplifier integrated into detector, ASIC nearby
  - Pixel size > 15 x 15 µm (2005)
  - Current research topic in many groups, (MIMOSA, IReS Strasbourg)

2.4 The ATLAS and CMS central tracking detectors



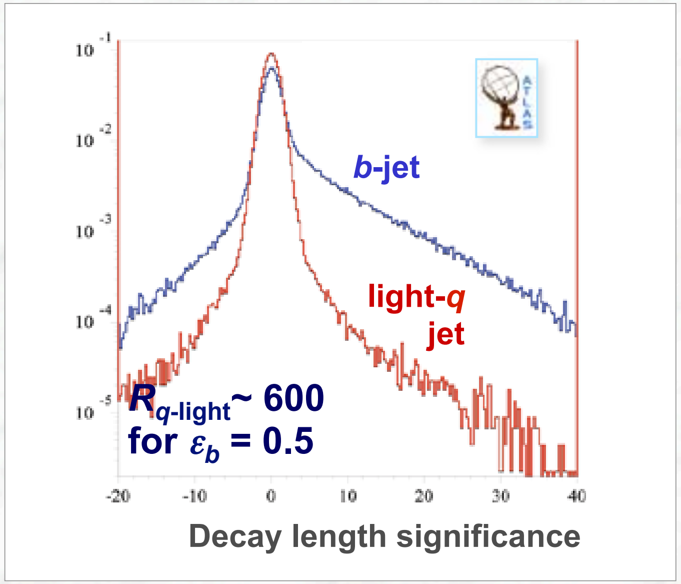
Vertexing and *b*-jet tagging

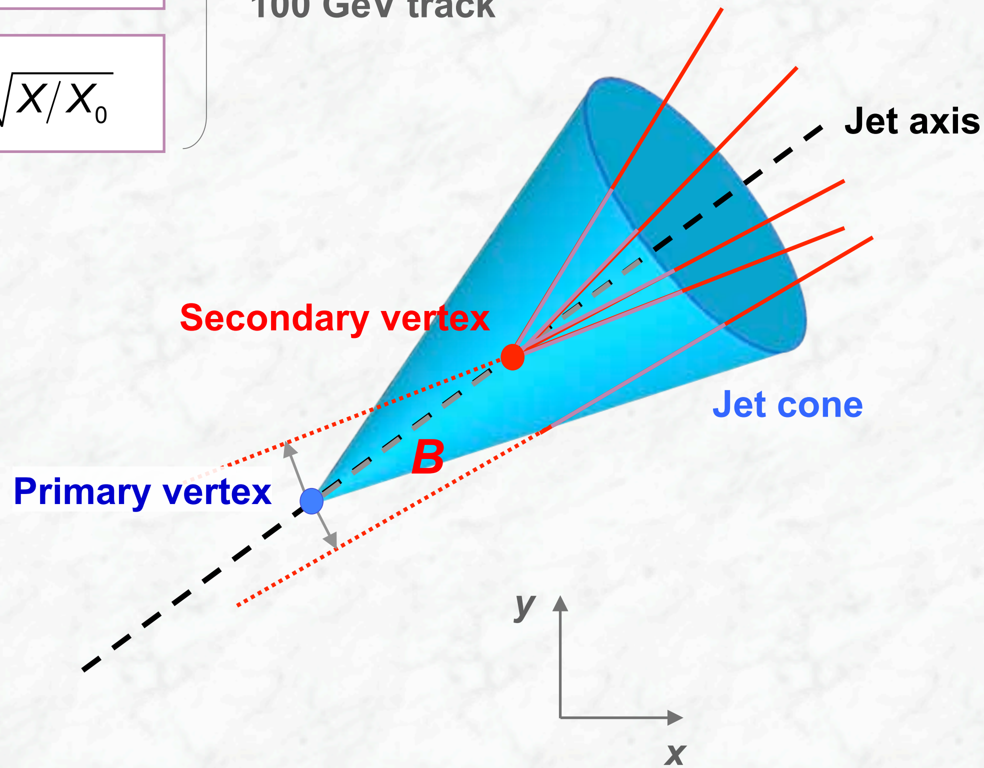
- The innermost silicon detector must provide the required *b*-tagging efficiency

Good vertex resolution is achieved by placing the **innermost (*B*) layer close to the beam pipe**, and **the next layer farer to it** (lever arm), and by an excellent *B*-layer resolution

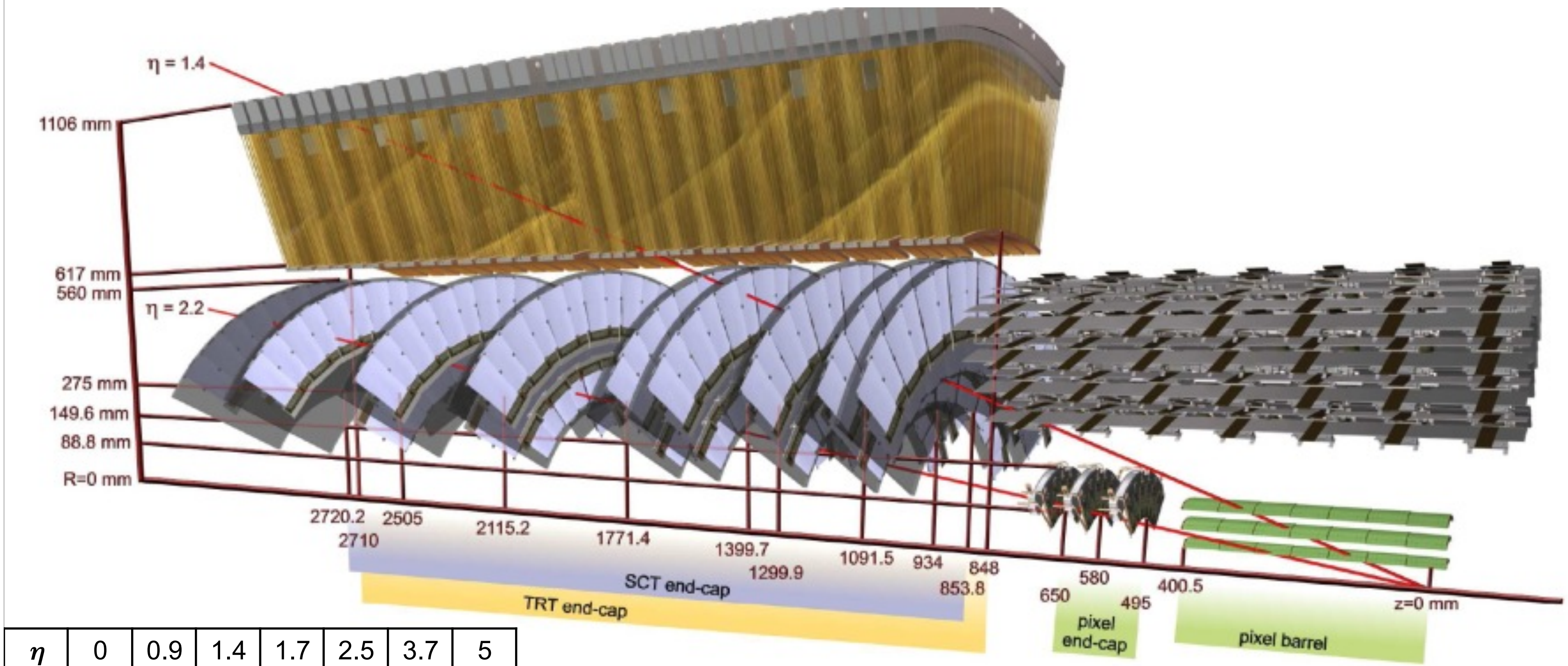
Small multiple scattering term: $\sigma_{MS} \sim \frac{1}{p}\sqrt{X/X_0}$

Expected transverse IP resolution ~13 μm for 100 GeV track



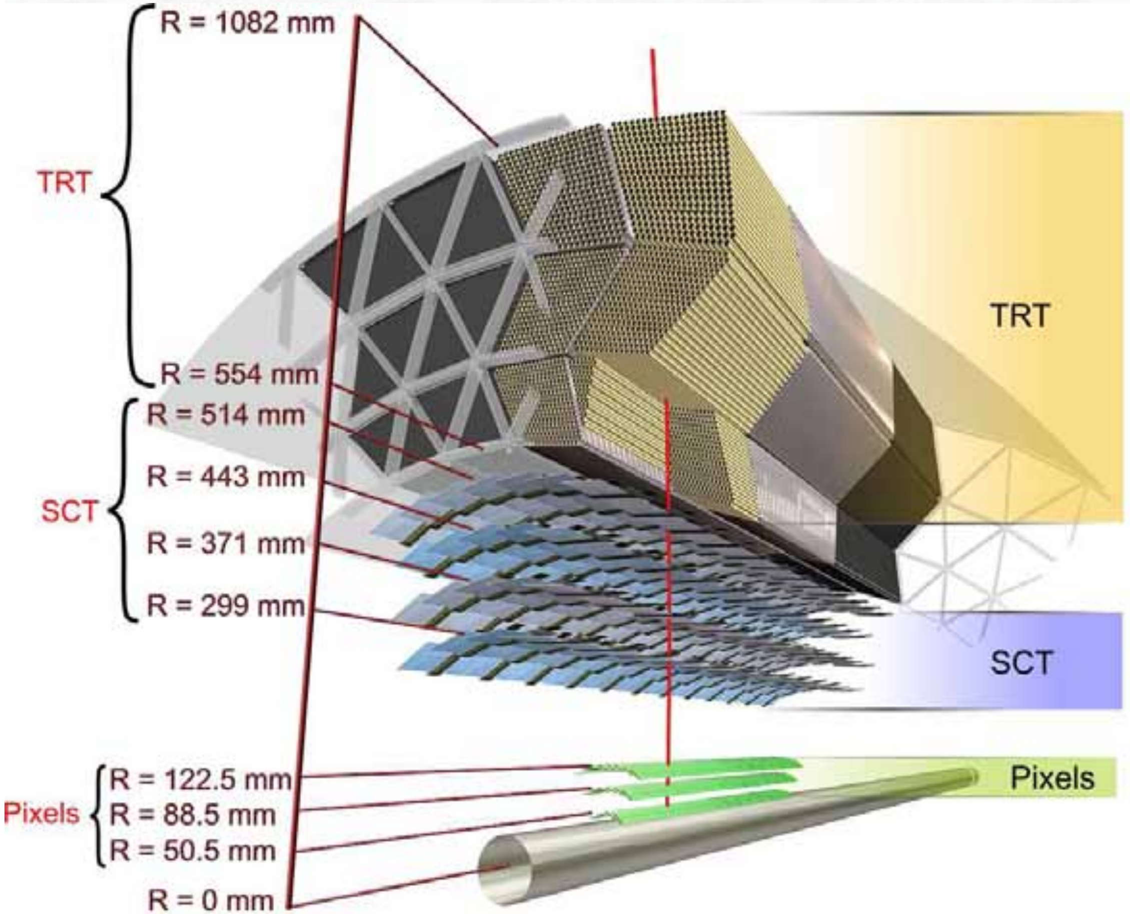


The ATLAS Inner Detector (one end-cap)



η	0	0.9	1.4	1.7	2.5	3.7	5
θ	90°	44°	28°	21°	9.4°	2.8°	0.8°

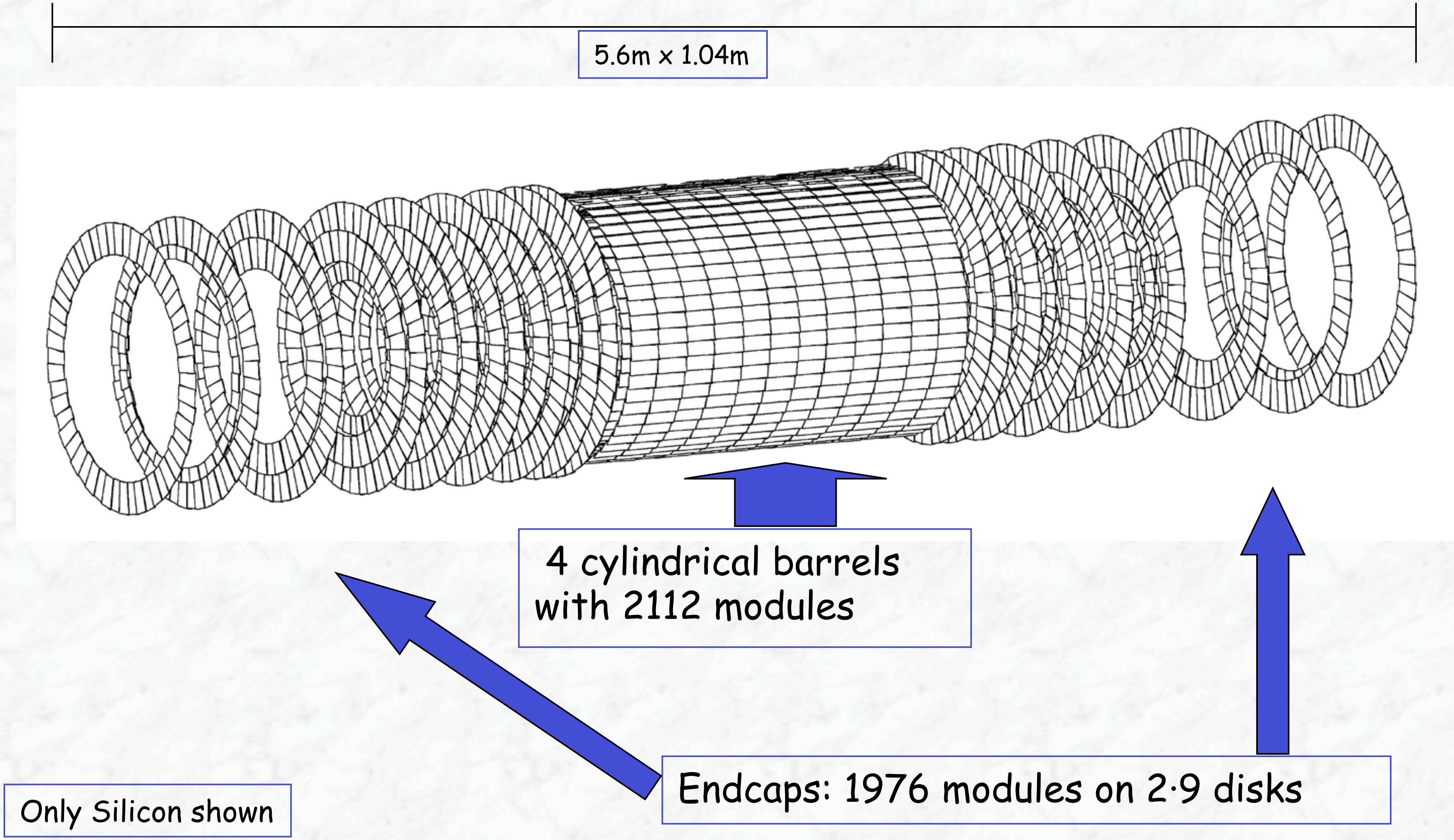
The ATLAS Inner Detector



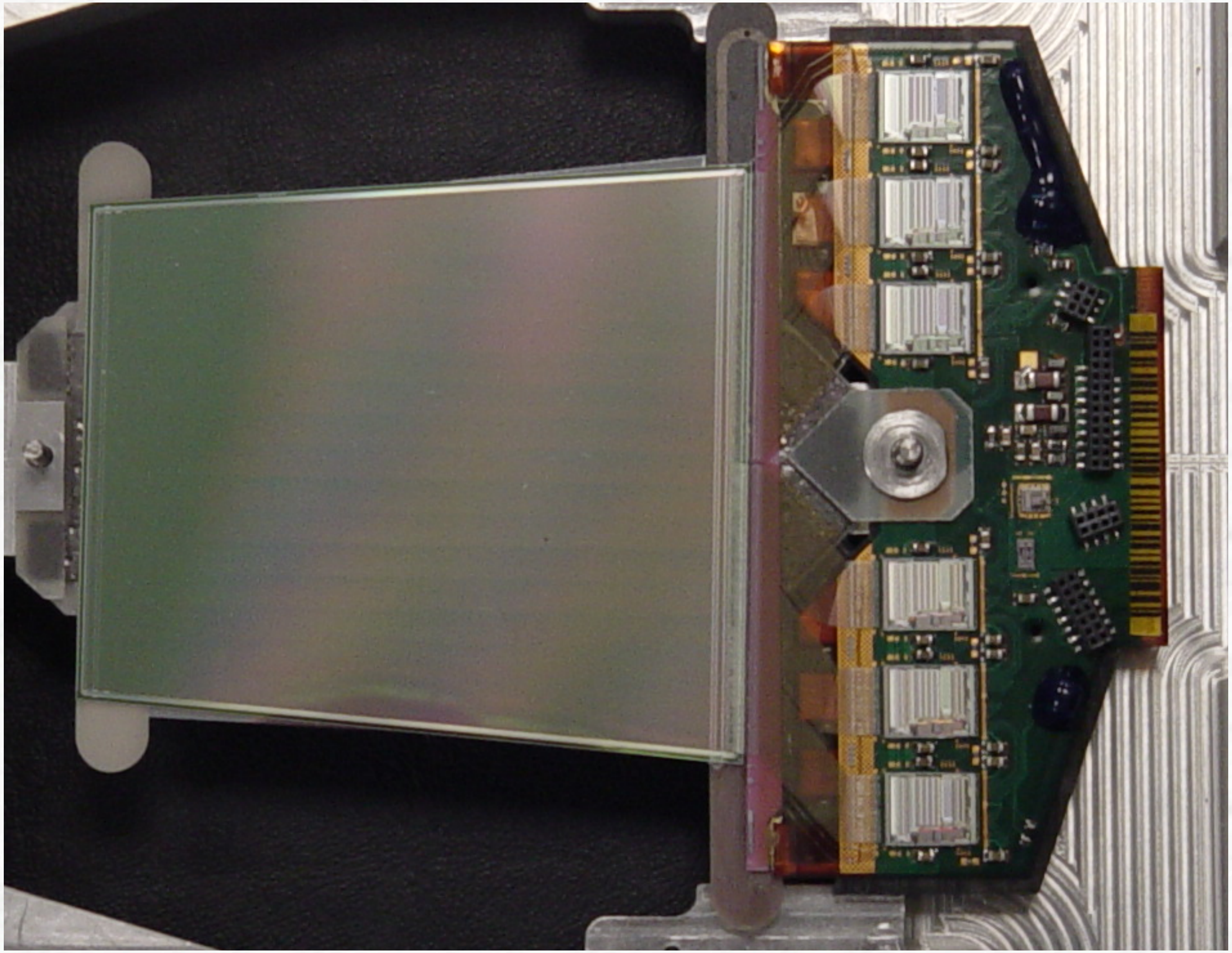
	R- ϕ accuracy	R or z accuracy	# channels
Pixel	**10 μm**	**115 μm**	**80.4M**
SCT	**17 μm**	**580 μm**	**6.3M**
TRT	**130 μm**		**351k**

$$\sigma/p_T \sim 0.05\%\ p_T \oplus 1\%$$

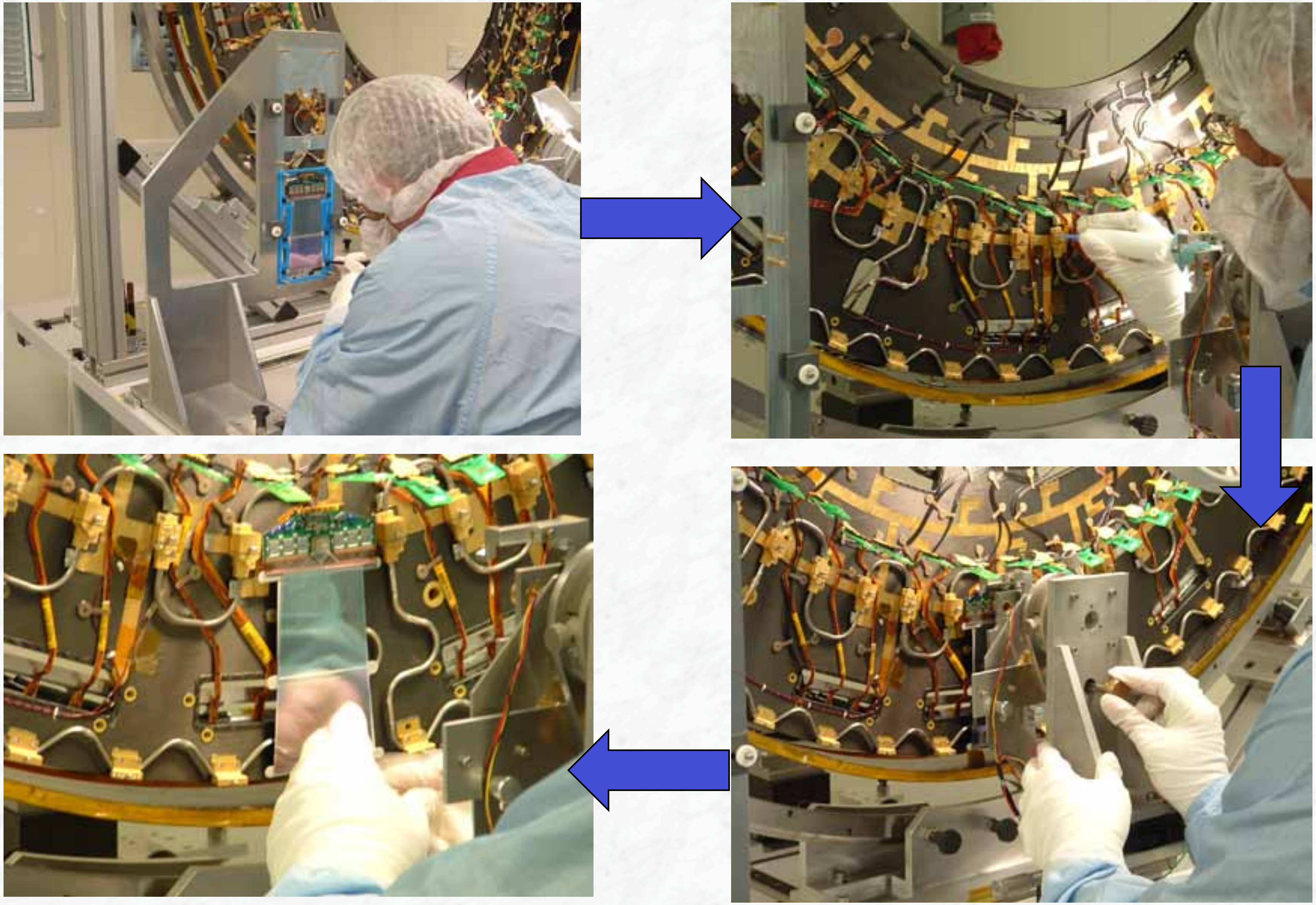
Example: ATLAS Si-Tracker SCT



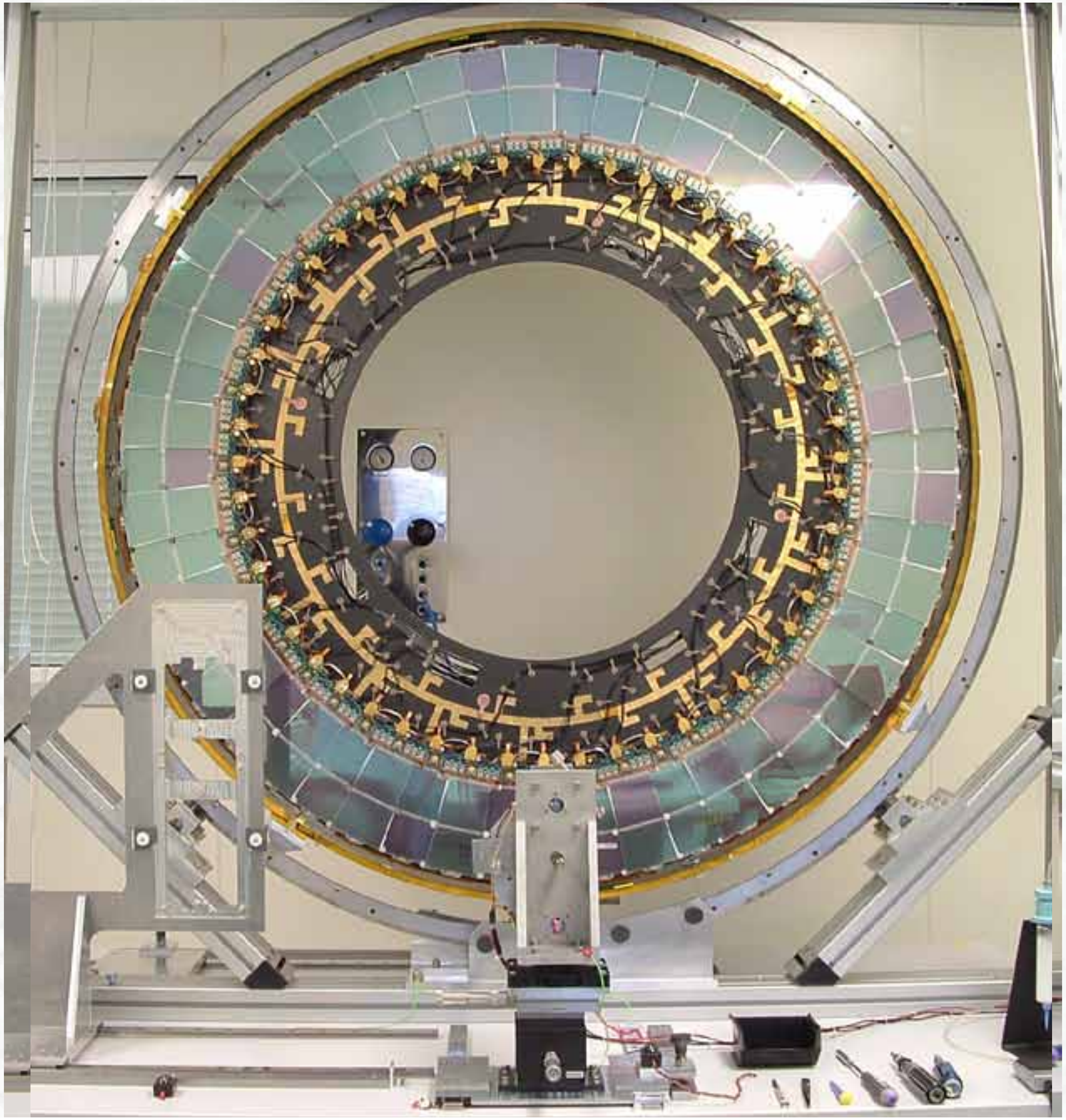
Example: ATLAS SCT Module



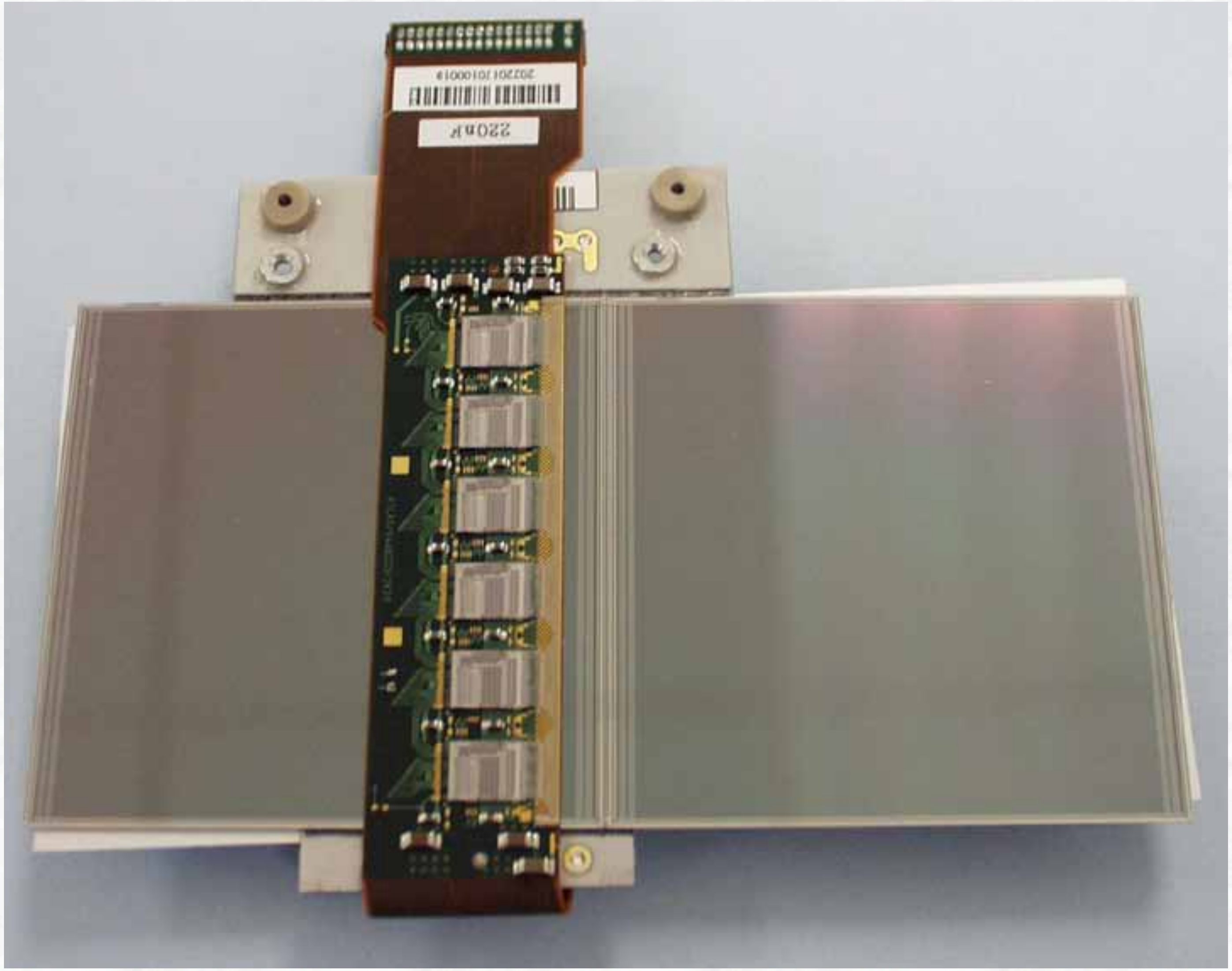
From Module to Detector



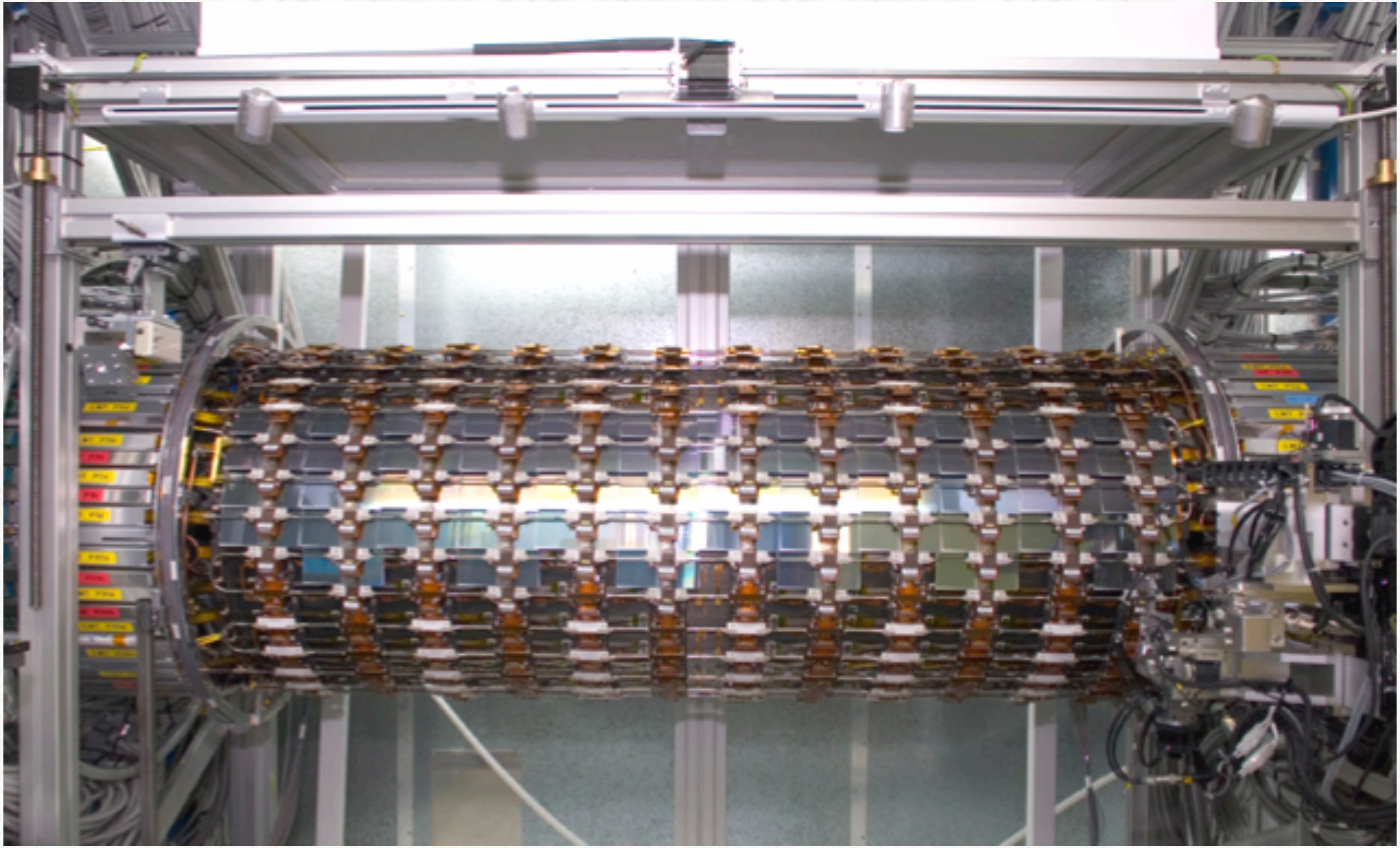
SCT Endcap



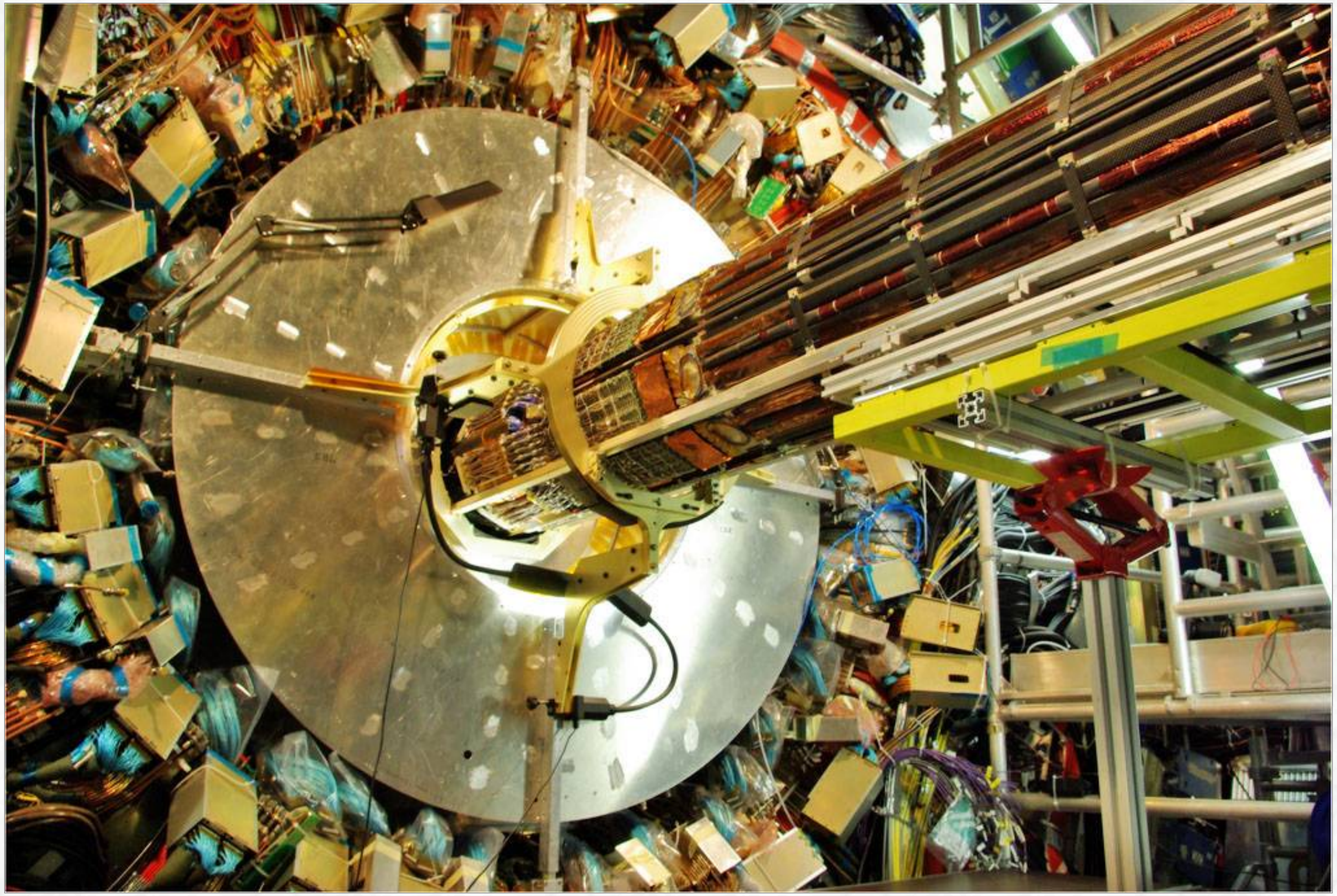
Example: ATLAS SCT Module



SCT Barrel

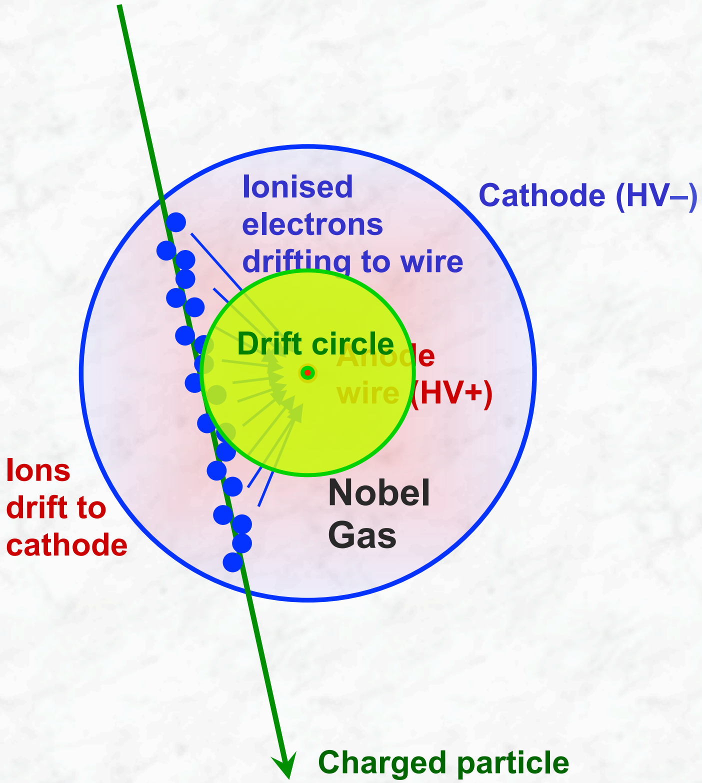


ATLAS pixel detector



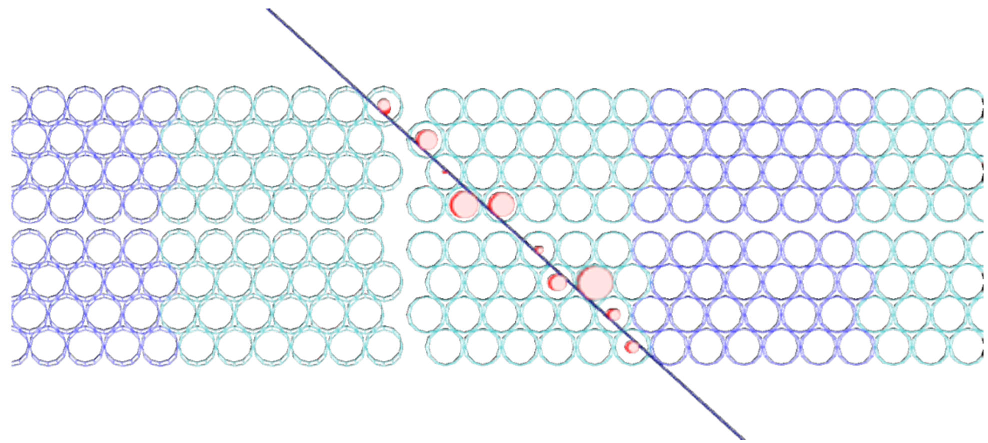
Drift Tubes (DT) in ATLAS: inner detector and muon spectrometer

- Classical detection technique for charged particles based on gas ionisation and drift time measurement



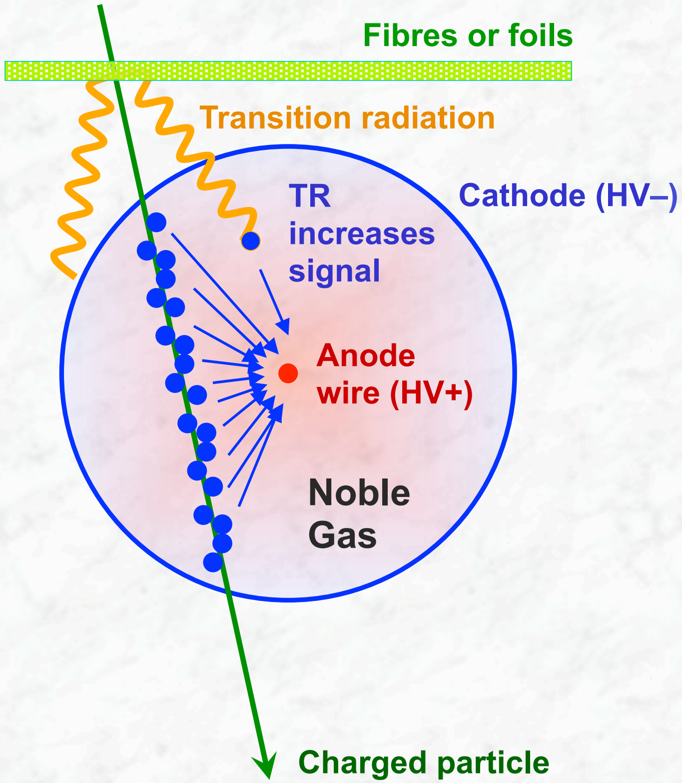
TRT: Kapton tubes, ∅ = 4 mm
Muon chambers: Aluminium tubes, ∅ = 30 mm

Example: muon in MDTs **(aligned !)**

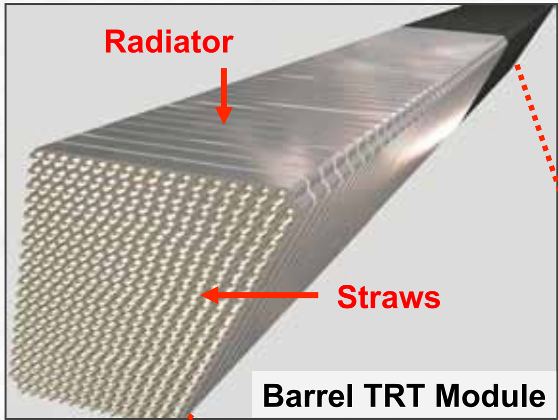


Combining Tracking with particle ID: ATLAS TRT

- e/π separation via transition radiation: polymer (PP) fibres/foils interleaved with DTs



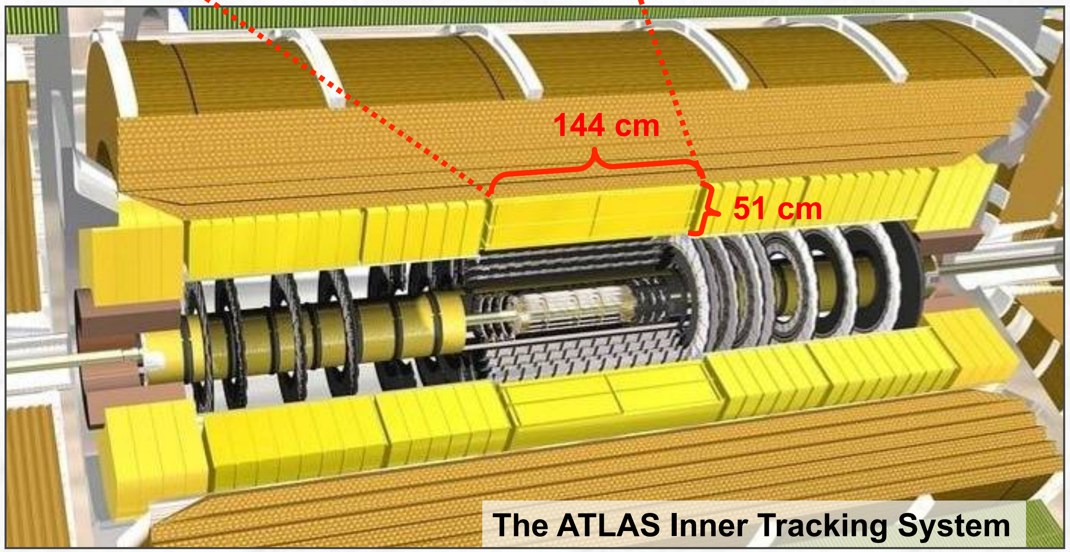
Electrons radiate → higher signal
Particle Identification by counting the number of high-threshold hits



Total: 370000 straws

Barrel ($|\eta| < 0.7$): 36 r-ϕ measurements / track
Resolution ~130 μm / straw

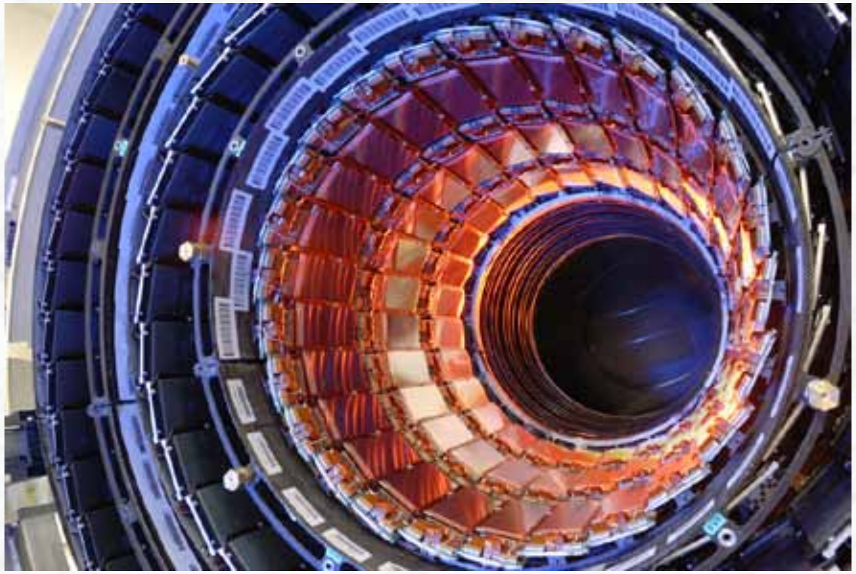
18 end-cap wheels ($|\eta| < 2.5$): 40 or less z-ϕ points



Comparison between the ATLAS and CMS tracking systems

Both use solenoidal fields

CMS tracking detector



- CMS: full silicon strip and pixel detectors
  - high resolution, high granularity

- ATLAS: Silicon (strips and pixels)
  + Transition Radiation Tracker
  - high granularity and resolution close to interaction region
  - “continuous” tracking at large radii

	ATLAS	CMS
Magnetic field	2 T solenoid + independent muon + toroid: 0.5 T (barrel), 1 T (endcap)	4 T solenoid + return yoke
Tracker	Silicon pixels and strips + transition radiation tracker $\sigma/p_T \approx 5 \cdot 10^{-4}\, p_T + 0.01$	Silicon pixels and strips (full silicon tracker) $\sigma/p_T \approx 1.5 \cdot 10^{-4}\, p_T + 0.005$