Ultra-Fast Timing Detectors

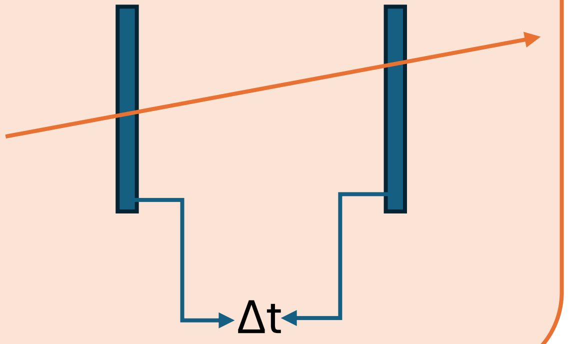
Lorenzo Paolozzi

University of Geneva

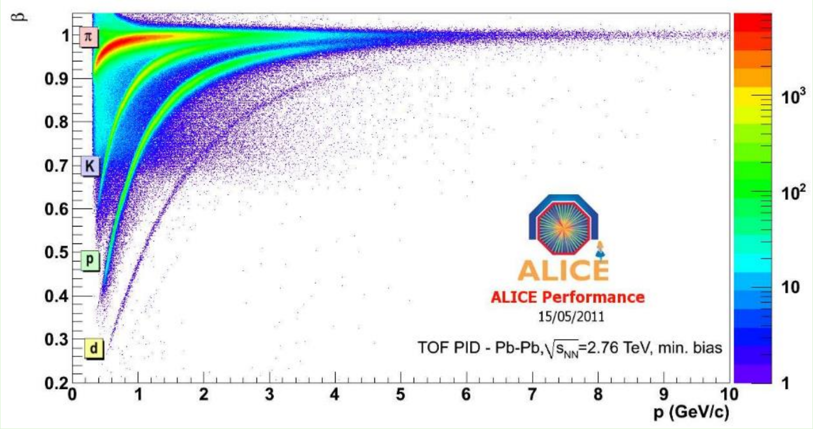
1. Timing detector: applications and technologies
2. Scintillating and Cherenkov detectors in medical imaging
3. Ionization detectors
    1. Signal induction and parallel plate geometry
    2. Time jitter
    3. Gain in gas detectors
    4. Gain in solid state (silicon) detectors
    5. Charge collection noise
4. Front end electronics
    1. Equivalent Noise Charge
    2. Device selection
    3. Gain-Bandwidth product and power consumption
5. Signal treatment: Time-walk and time digitization
6. Readout techniques
    1. Pixel vs Transmission line (strip) readout
    2. Cross talk

Main applications of timing detectors

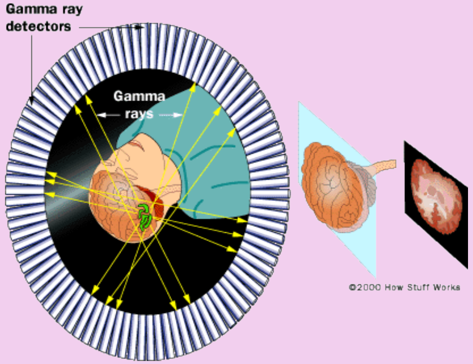
Triggering



Particle identification

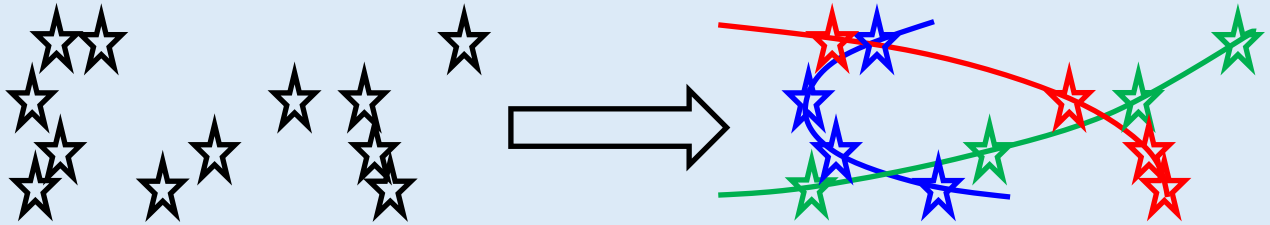


Medical imaging

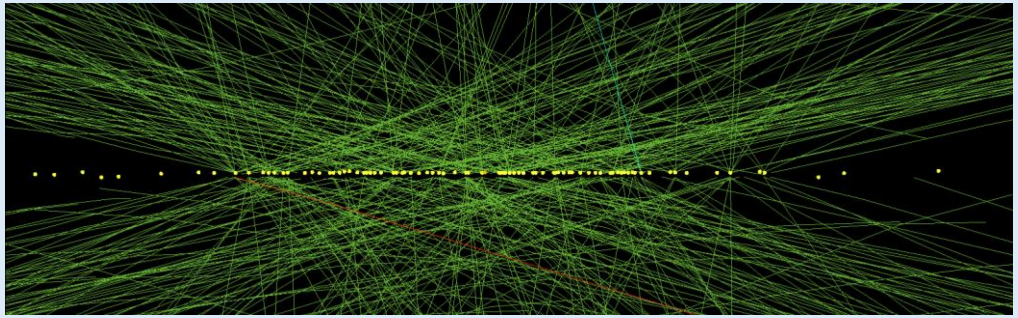


4D tracking

Support to fast tracking

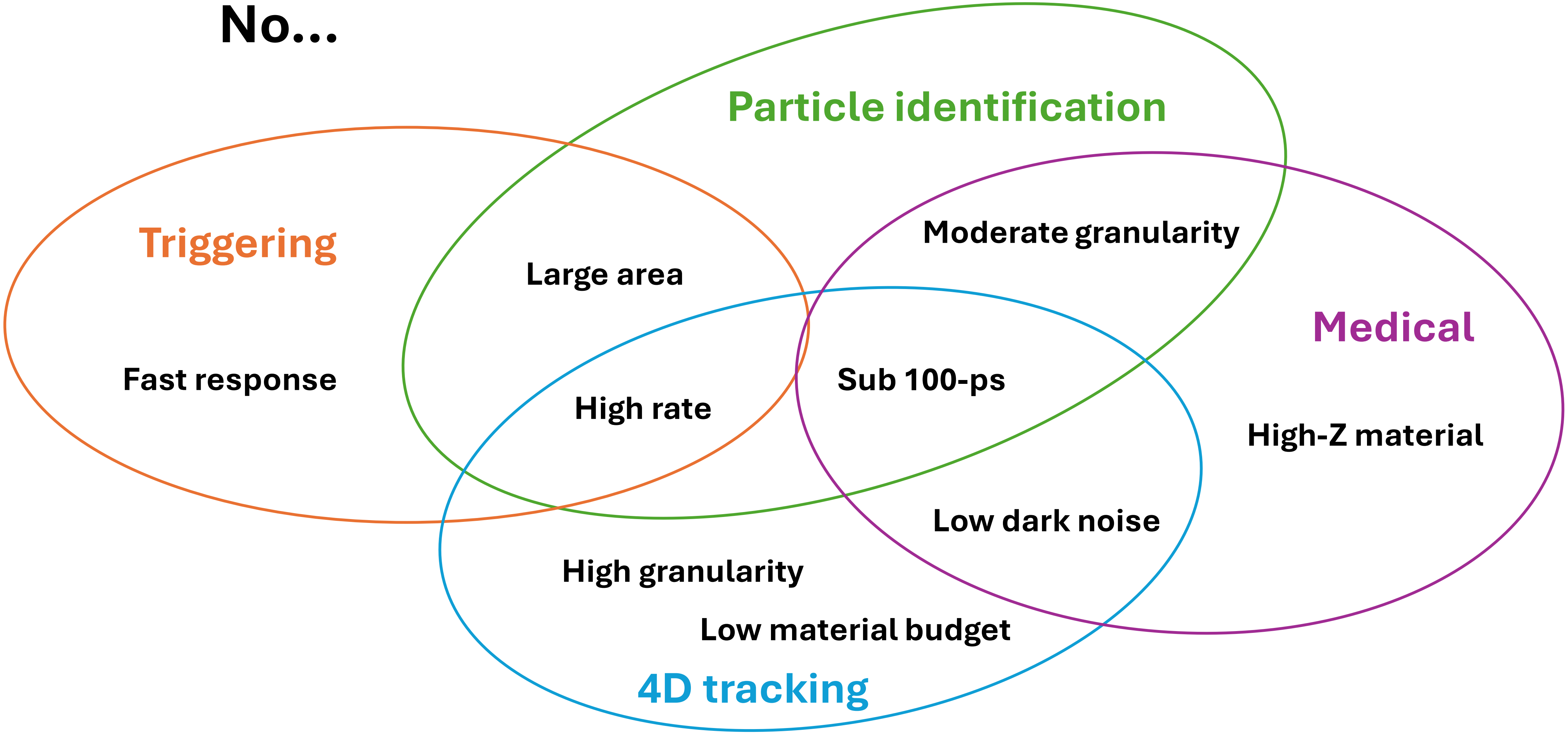


Pile-up suppression



One technology fits them all?

No…



Particle identification

Triggering

Medical

4D tracking

Large area

Moderate granularity

Fast response

Sub 100-ps

High rate

High-Z material

Low dark noise

High granularity

Low material budget

What affects time resolution in a detector?

- **Physical processes**
  - Scintillation
  - Profile of primary ionization
  - Avalanche, streamer, spark formation…
  - Cherenkov emission

- **Signal generation**
  - Signal induction
  - Time walk
  - Signal transmission

- **Electronics**
  - Amplifier noise
  - Discriminator response
  - Time digitization
  - Time synchronization

You cannot fully decouple these effects:

- **You need to have a good understanding of all** to achieve state-of-the-art performance
- The **interface between sensor and electronics** is a key element in your detector design

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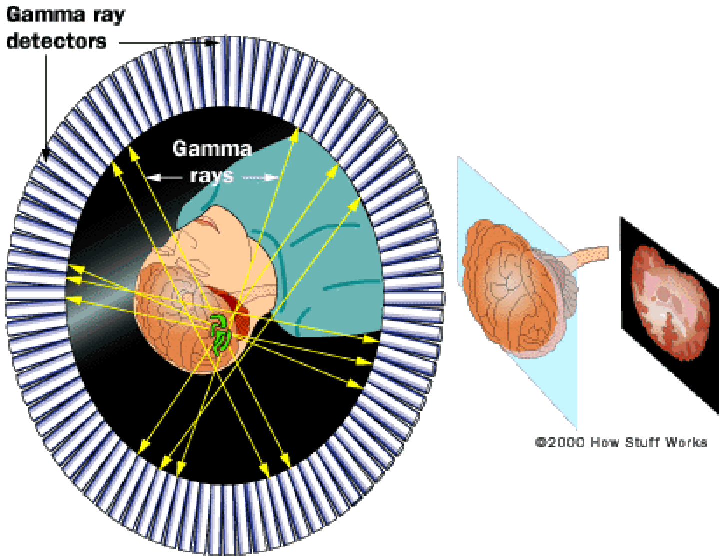
Medical imaging (PET)

Positron Emission Tomography (PET)



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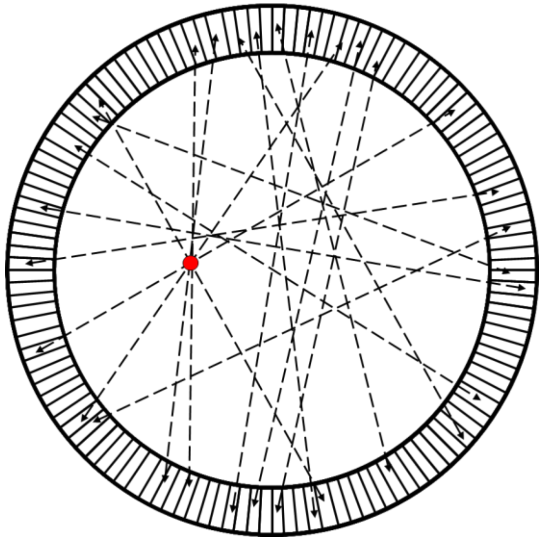
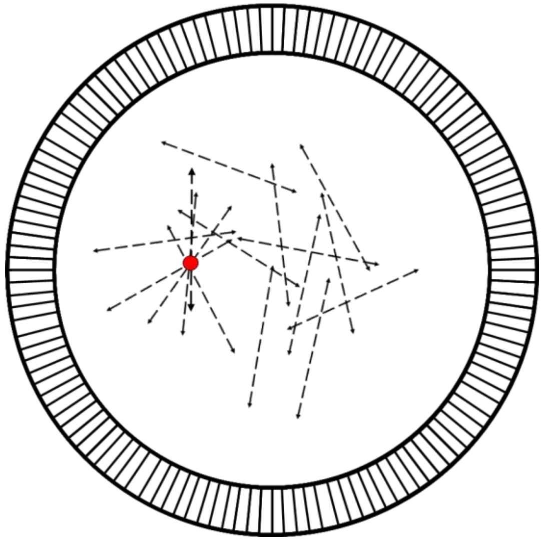
Traditional PET



TOF PET



- Improve signal-to-noise ratio. →

- New possibilities in medical research.
- Greatly reduce radioactive dose in clinical PET.

Scintillating detectors (Medical imaging)

Medical applications require high-Z materials to facilitate the γ conversion:

BGO	**L(Y)SO**	**LaBr3:Ce**
Total Light Yield: 8200 Ph/MeV	Total Light Yield: ~30000 Ph/MeV	Total Light Yield: ~70000 Ph/MeV
Decay constant: ~300 ns	Decay constant: 33-43 ns	Decay constant: 16 ns
Used in clinical PET	Used in clinical TOF-PET	Experimental

No scintillation technology can target ~1 ps time resolution, due the limitations of the physical process.

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A great effort is in introducing Cherenkov light detection in PET.

- Cherenkov light emission is prompt, ideal for timing at 1 ps level.
- Only few (~10) photons are emitted in PET.
- Combined Cherenkov/Scintillation readout are being investigated.

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BGO is back in the picture for TOF-PET

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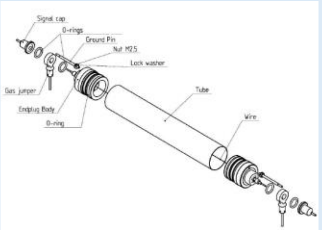
Ionization detectors: gas and solid state

Detectors can be categorized in two main categories based on the type of electric field:

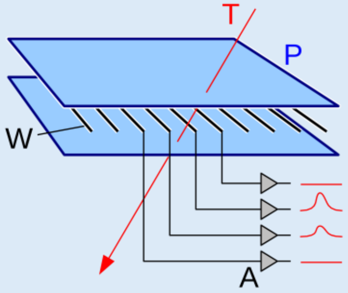
"Non-parallel plate" geometry

Signal formation dominated by drift time

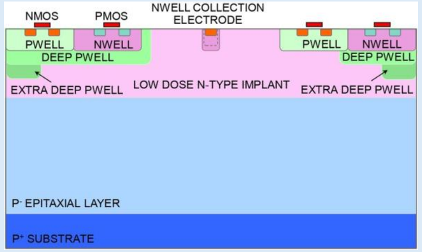
Drift tubes



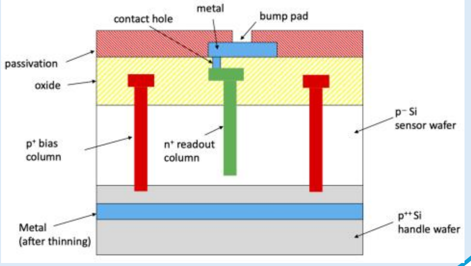
Multi-Wire Chamber



Small electrode planar pixel sensors



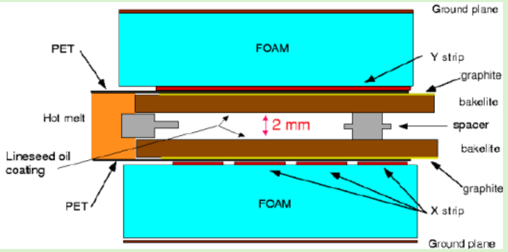
Pillar 3D silicon detectors



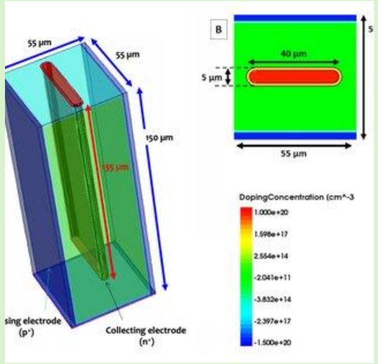
Parallel plate geometry

Immediate induction of signal current

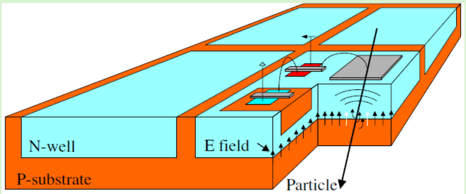
Resistive Plate Chambers



Trench 3D silicon detectors



Large electrode planar pixel sensors



Induced current in a ionization detector

Induced current from the Shockley-Ramo theorem:

$$I_{ind} = \sum_i q_i \bar{v}_{drift,i} \cdot \bar{E}_{w,i}$$

Drifting charge (electron, hole, ion...)

Charge drift velocity

"Weighting" field

- Gives the coupling of the moving charge with the readout electrode
- Obtained with Schockley-Ramo theorem
- In TCAD simulation:
  - Calculate the electric field at HV bias voltage
  - Calculate the electric field at HV+1V bias voltage
  - Make the difference

Precise timing with ionization detectors

What are the main parameters that determine the time resolution of ionization detectors?

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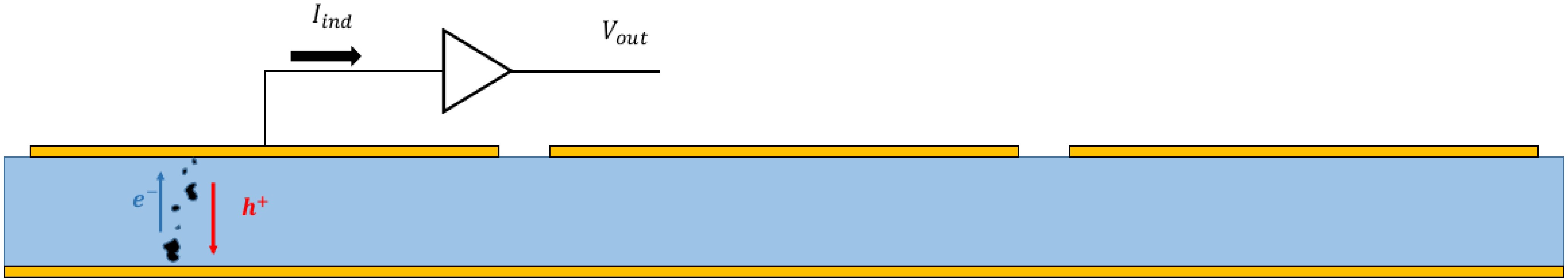

Precise timing with ionization detectors

What are the main parameters that determine the time resolution of ionization detectors?

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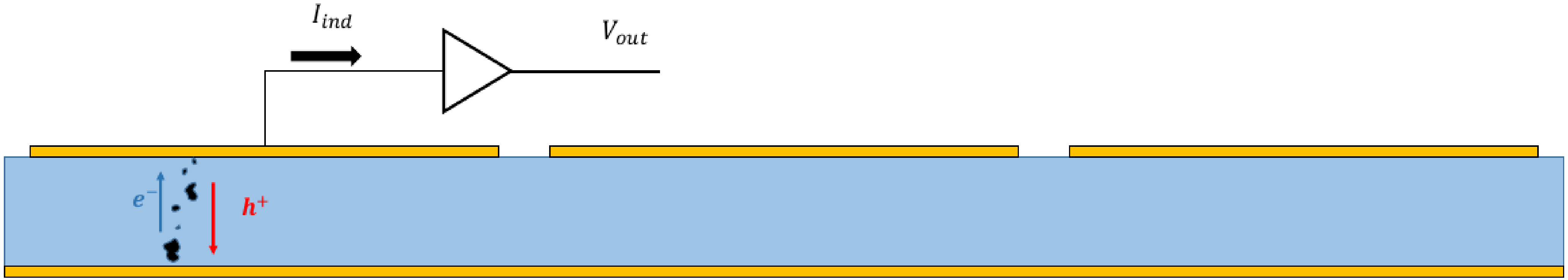

Precise timing with ionization detectors

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- Geometry and fields
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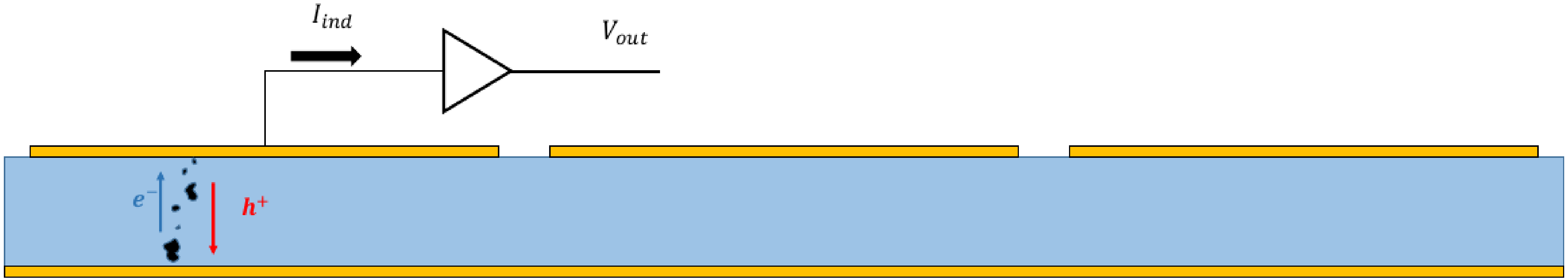

Precise timing with ionization detectors

What are the main parameters that determine the time resolution of ionization detectors?

- Geometry and fields
- Charge collection noise
- Electronic noise

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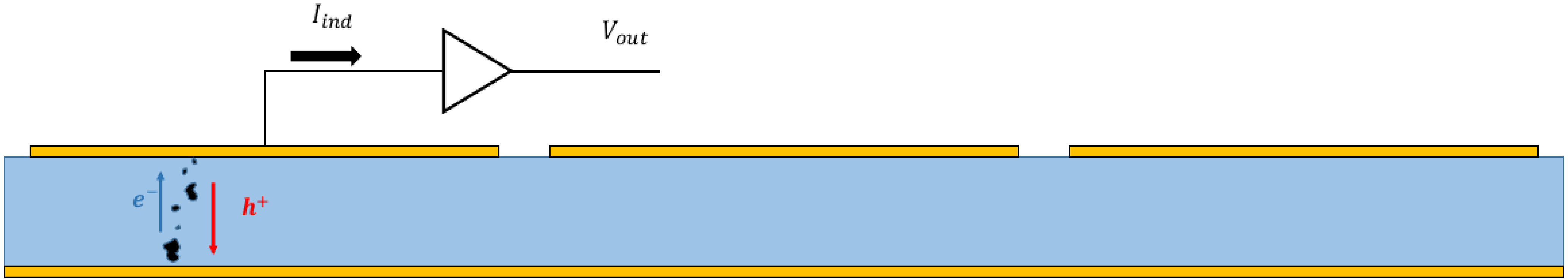

Precise timing with ionization detectors

What are the main parameters that determine the time resolution of semiconductor detectors?

- Geometry and fields
- Charge collection noise
- Electronic noise
- Gain

Induced current from the Shockley-Ramo theorem:

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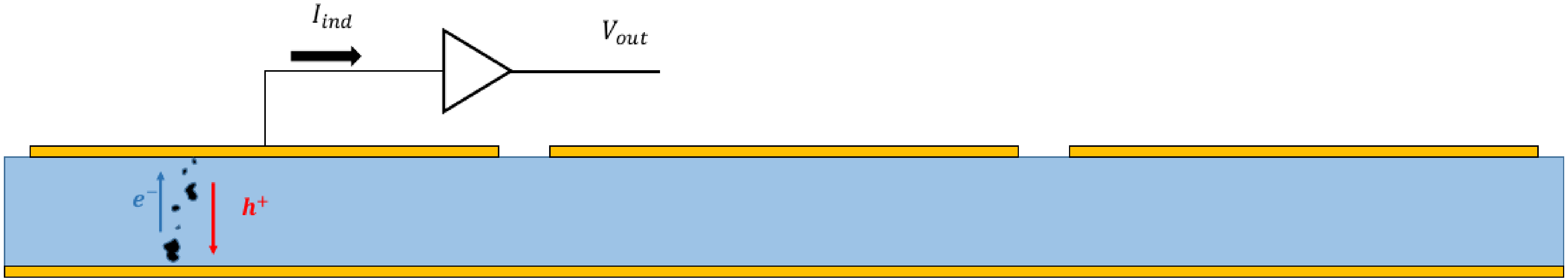
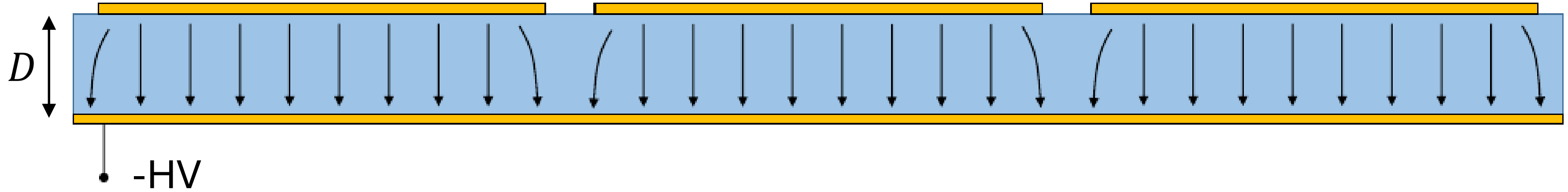


Sensor geometry and fields

Sensor optimization for time measurement means:
Sensor time response **independent** from the particle trajectory



→ **"Parallel plate"** read out: wide pixels w.r.t. depletion region

$$I_{ind} = \sum_i q_i \bar{v}_{drift,i} \cdot \bar{E}_{w,i} \cong \boxed{v_{drift}}\boxed{\frac{1}{D}}\sum_i q_i$$

Scalar, saturated

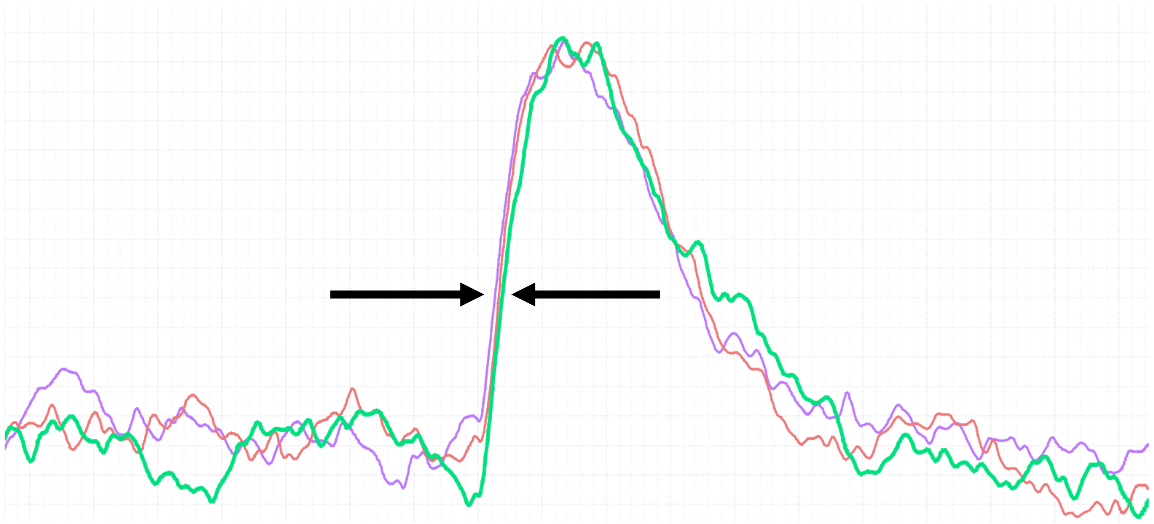
Scalar, uniform

Desired features:

- Uniform **weighting field** (signal induction)
- Uniform **electric field** (charge transport)
- Saturated charge **drift velocity** (signal speed)

Time jitter

Once the geometry has been fixed, the time resolution depends mostly on the **signal to noise ratio**.



Time jitter

Fast integration

$$\sigma_t = \frac{\sigma_V}{\frac{dV}{dt}} \simeq \frac{t_{rise}}{\frac{Signal}{Noise}} \simeq \frac{ENC}{I_{ind}}$$

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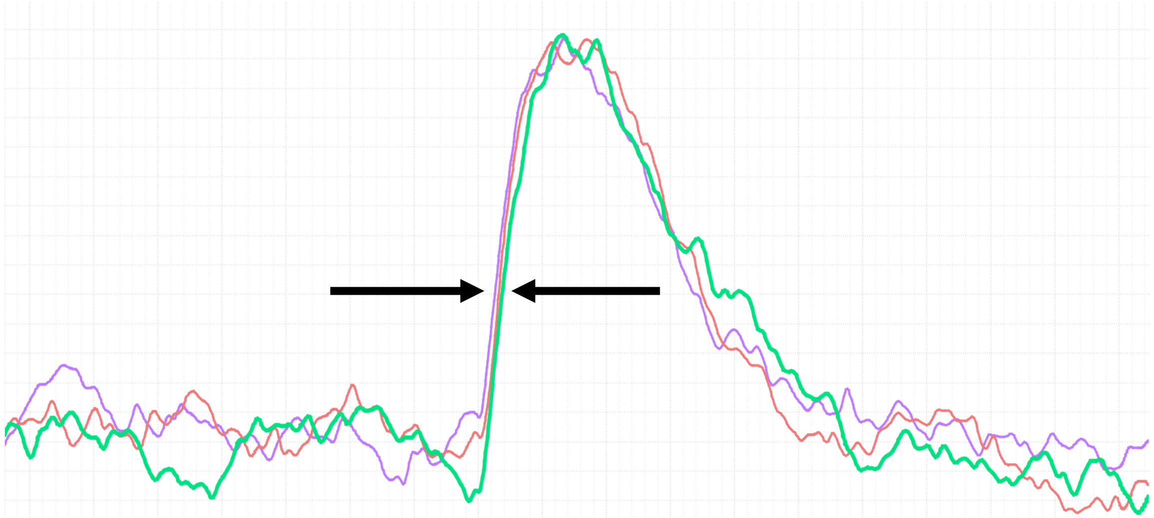

Fast integration

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Note also that **for sensors without gain**:

$$\boldsymbol{I_{ind} = v_{drift}\frac{1}{D}\sum_i q_i = v_{drift}\frac{dq}{dx}}$$

Time resolution is independent from the sensor thickness!

Time jitter

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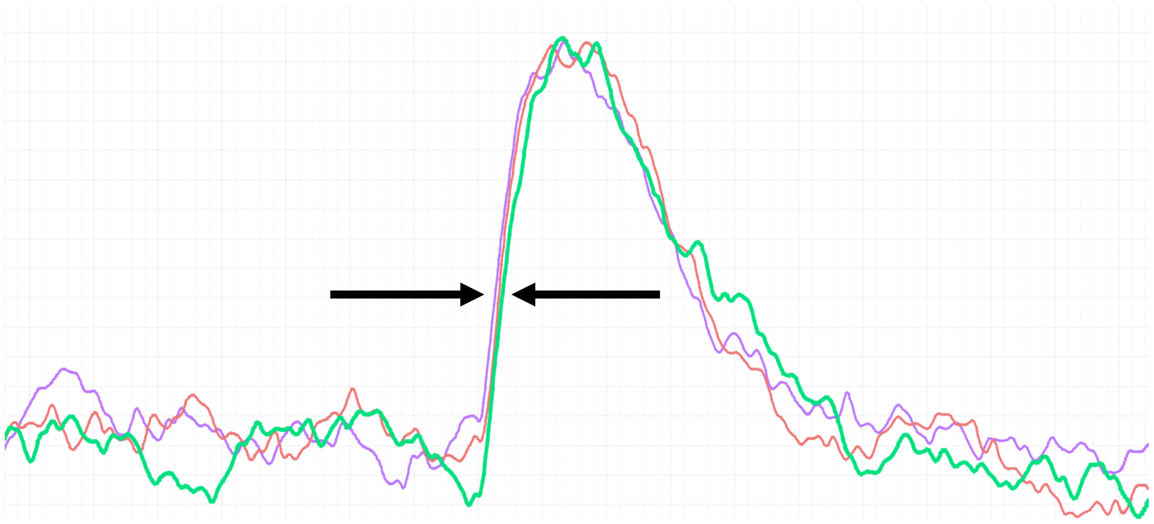
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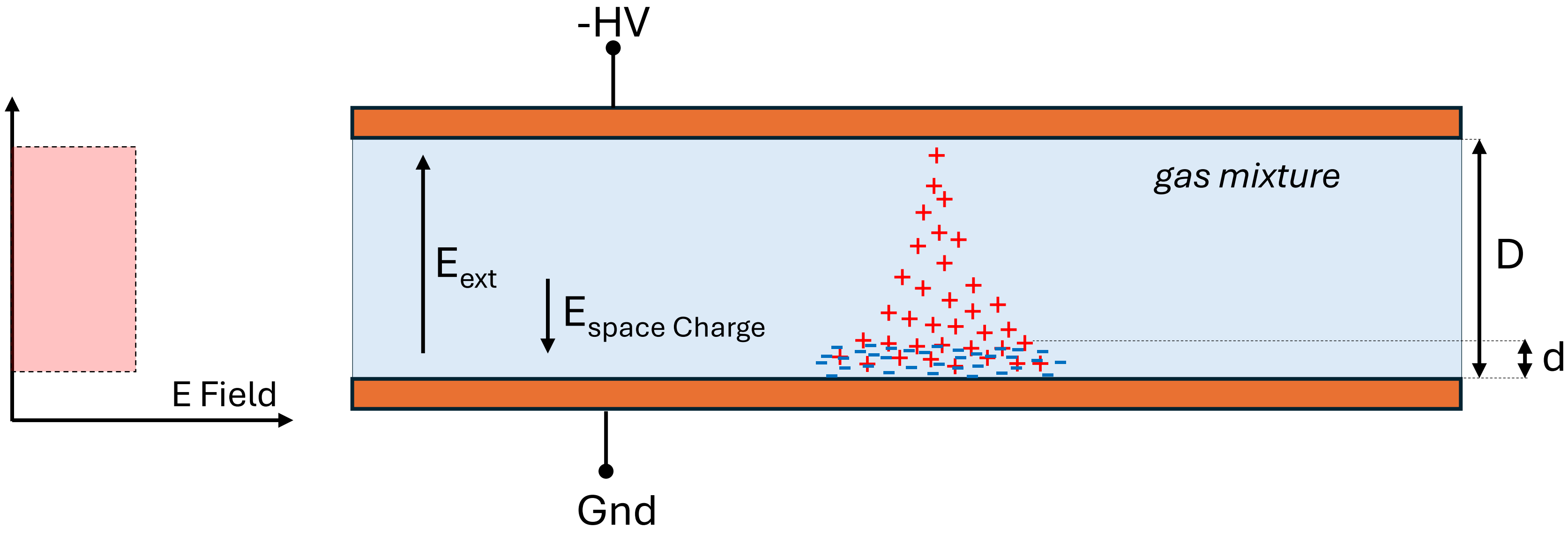
Boost signal (gain)

Gain: case for gas detector (RPC)



- Exponential avalanche growth
- Gain limited by space charge saturation ⟹ logistic model

- Positive charges (Ions) do not contribute to the prompt signal, not to new e/I pair production
- The electrons are produced mostly at the end of the gas gap

$$Q_{ind,prompt} = \sum_e \int_{x_i}^{D} \frac{1}{D} q_i v_{drift} = Q_{tot} \frac{d}{D}$$

d: the average path of the electrons from the generation point to the bottom electrode

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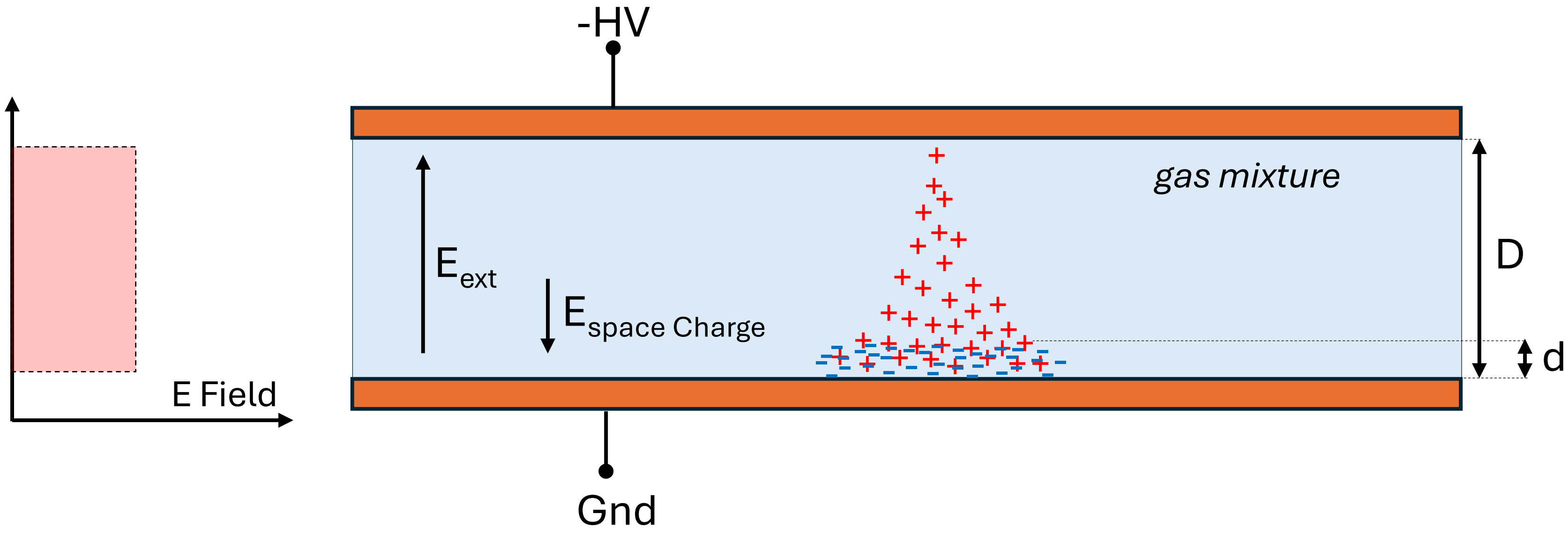

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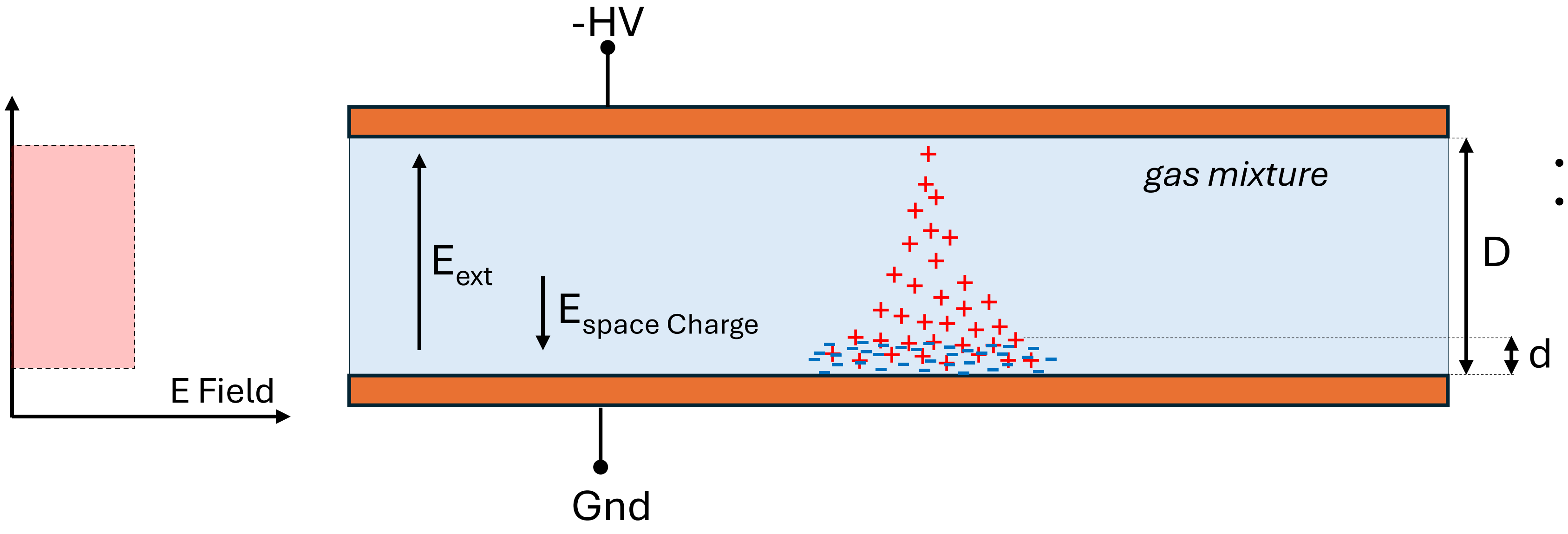

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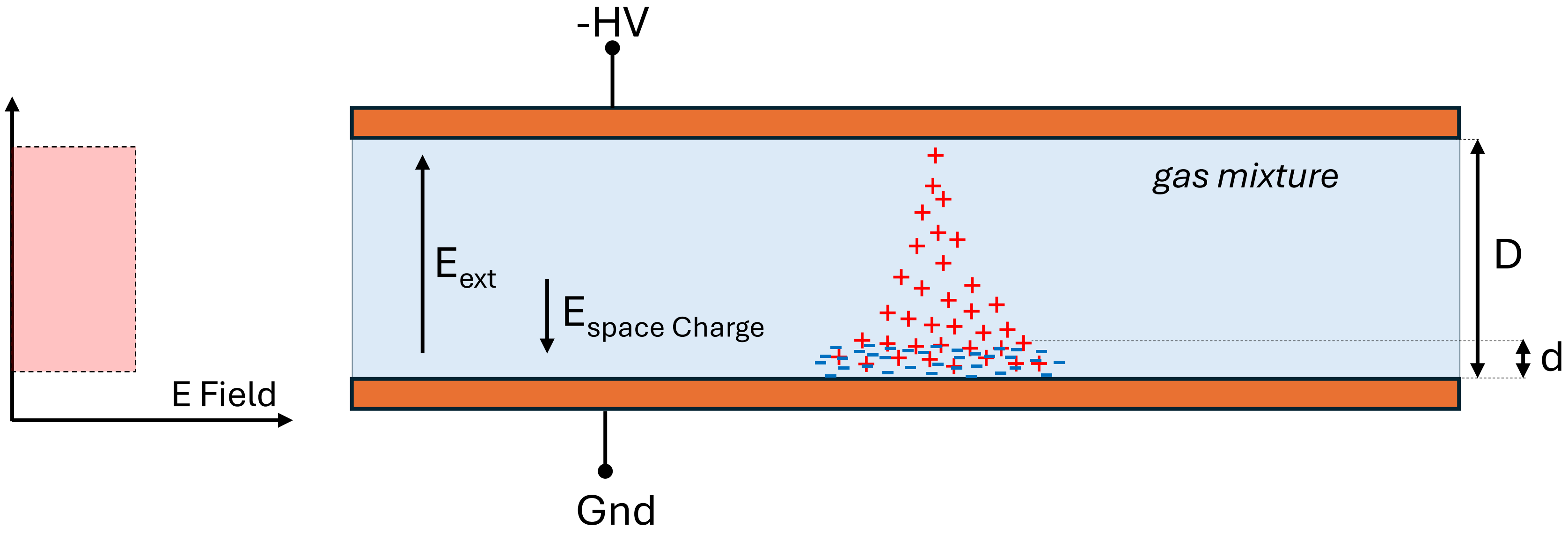
⟹ Only a small fraction (~5%) of the total charge is induced on the electrode as prompt signal usable for timing measurement ⟹ Large gain ($\gtrsim 10^5$) is needed

Gain: case for gas detector (RPC)



$$\sigma_t \sim 400\ ps$$

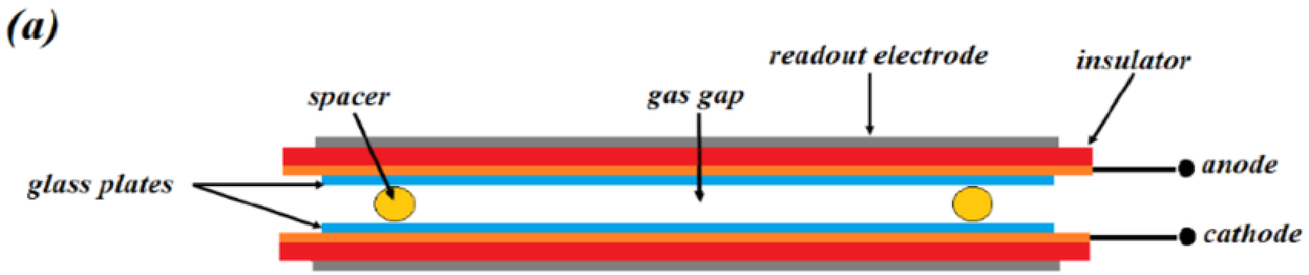
Time resolution is dominated by:

- Gas gap thickness
- Point of first e/I pair production
- Avalanche development
- Avalanche saturation

The contribution of the front-end electronics **to the time resolution** is small compared to these effects (if proper front-end is adopted)

Gain: case for gas detector (RPC)

Improvement is possible by adopting different detector geometries:



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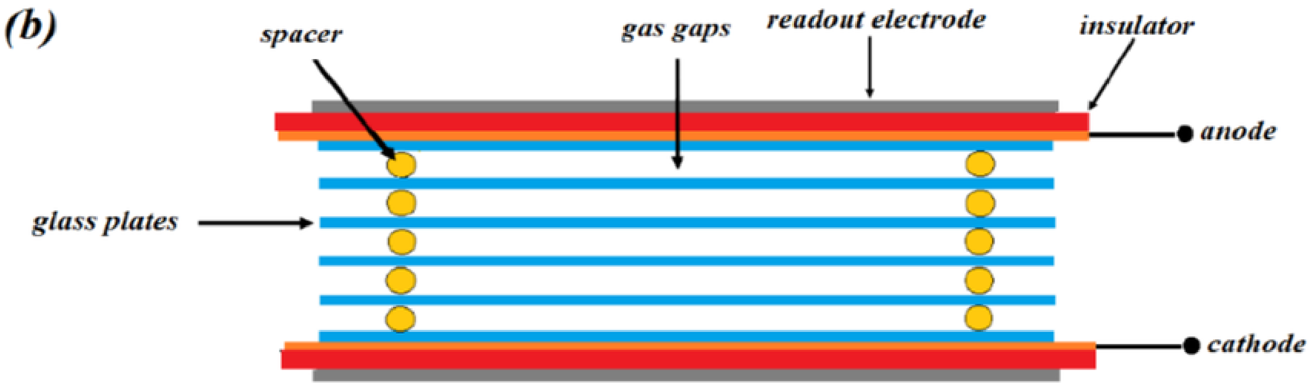
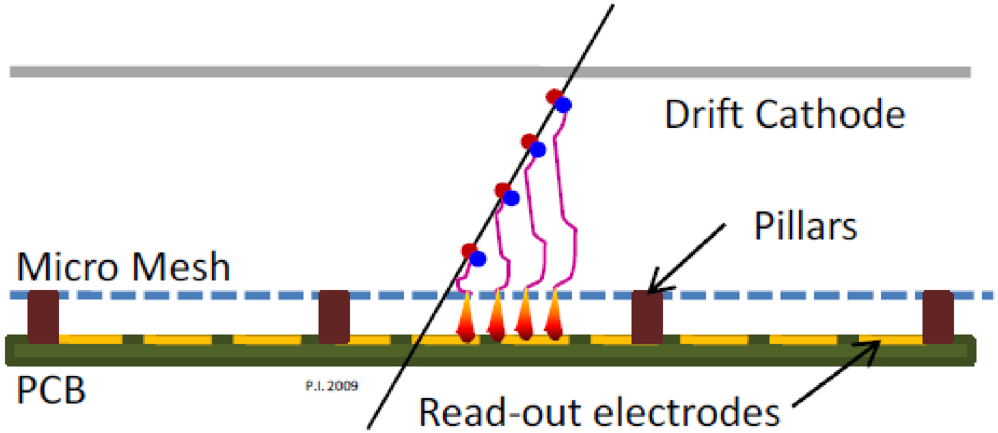


$\sigma_t \sim 50\ ps$

Gain: Micropattern Gas Detectors

Micromegas detector



- Tackles the problem of small prompt signal generation by **decoupling absorption region and gain region** in the detector
- Signal dominated by drift: **poor time resolution** despite the parallel-plate geometry

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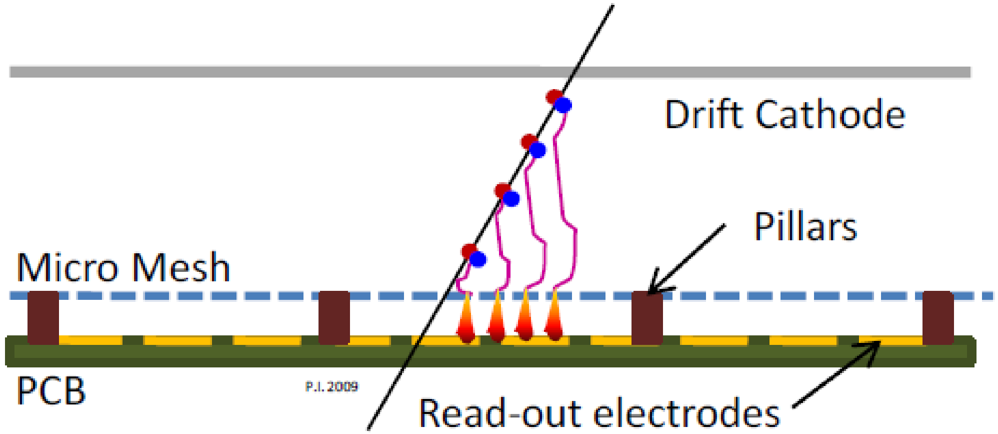

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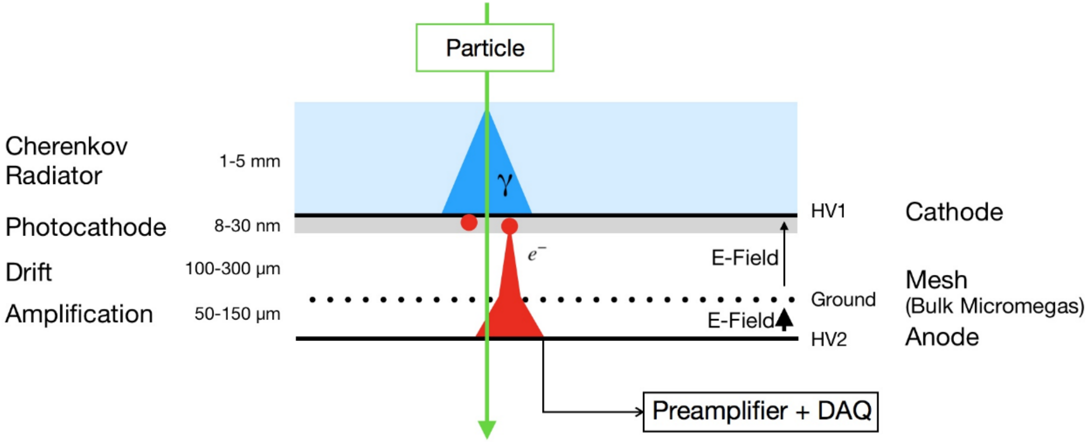
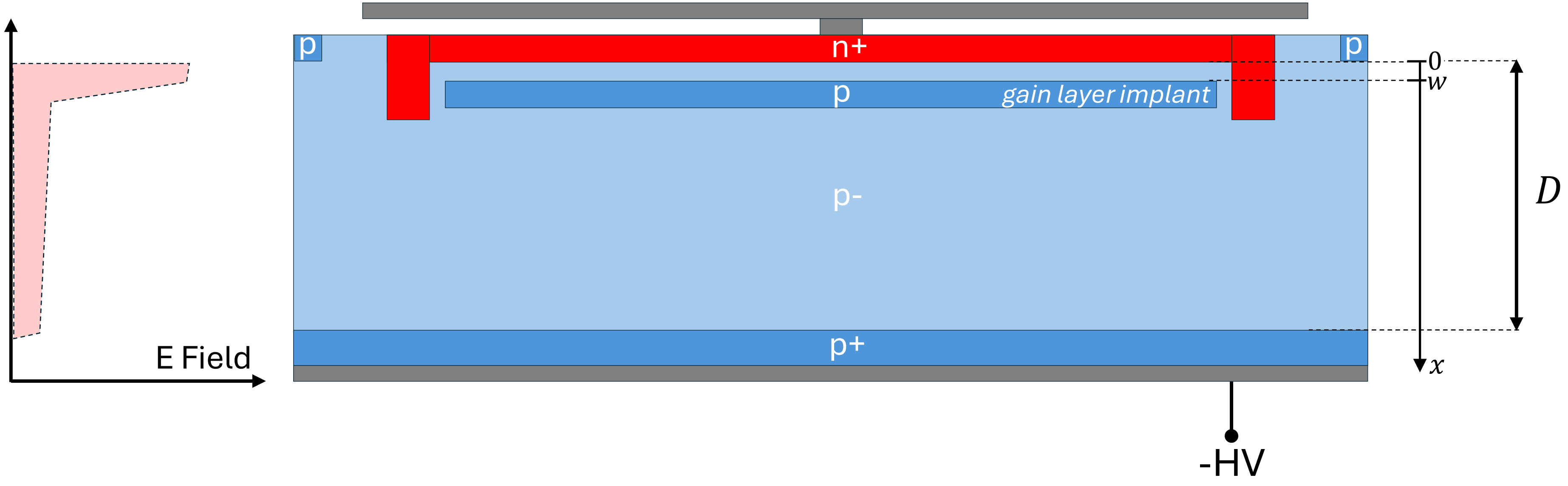
PICOSEC Micromegas



- The Micromegas is used as an electron multiplier coupled to a Cherenkov radiator

Gain: case for a solid state (silicon) detector

- In silicon **PIN detectors** the time resolution is limited by the **Signal to Noise ratio.**
- A gain layer allows larger signals, and thus better time resolution.
- This is achieved in the **reach through avalanche diodes (APD)** with a gain layer under the pixel.



$$Gain(x) = \frac{e^{-\int_x^w (\alpha-\beta)dx'}}{1 - \int_0^w \alpha(x) e^{-\int_x^w (\alpha-\beta)dx'}\, dx}$$

Note: local McIntyre model

- Both electrons and holes participate to the gain.
- Impact parameter (α, β) depend on the choice of semiconductor.
- Highest achievable gain depends on the **ratio** $\boldsymbol{\frac{\alpha}{\beta}}$**.**

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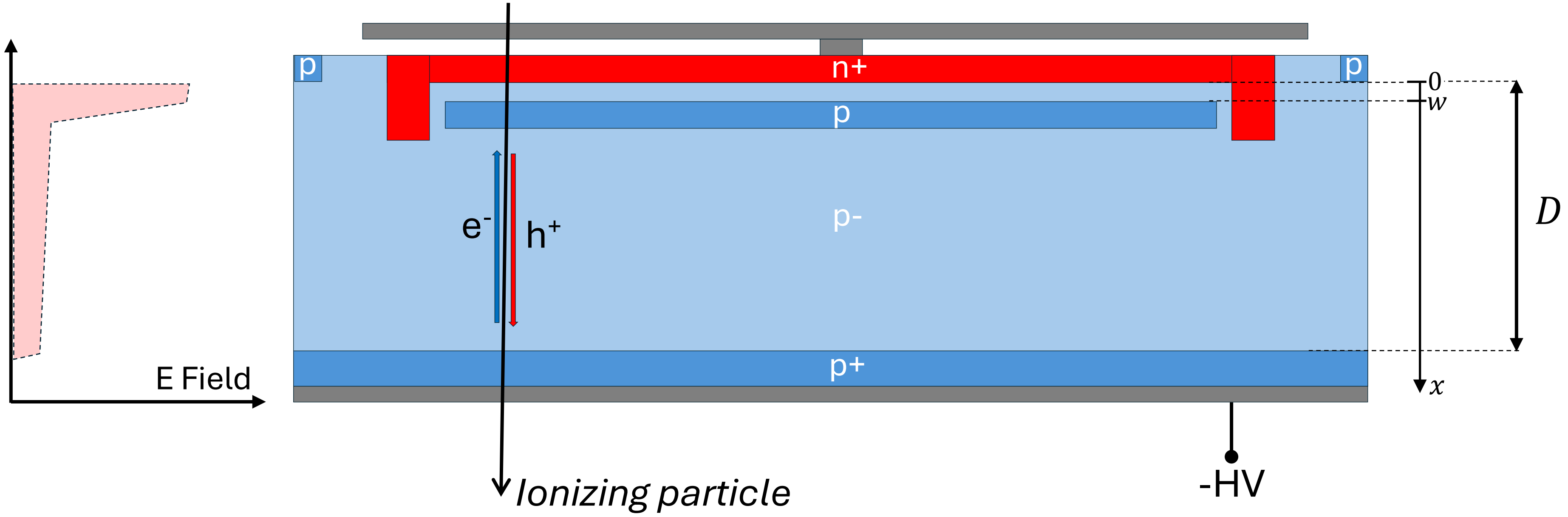

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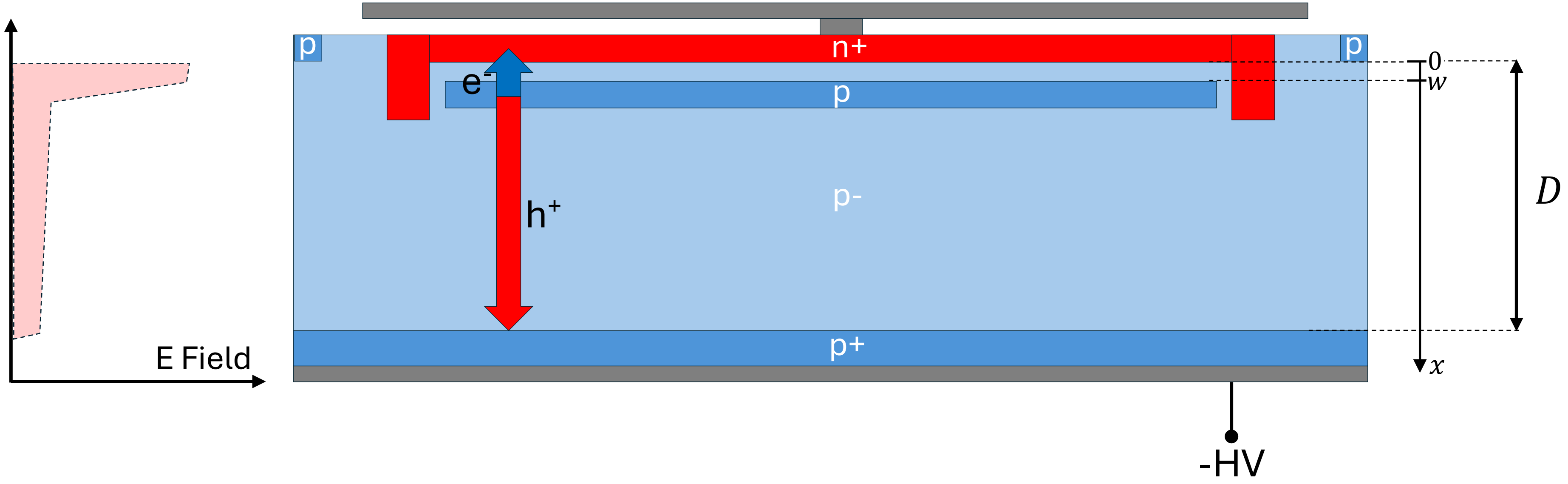

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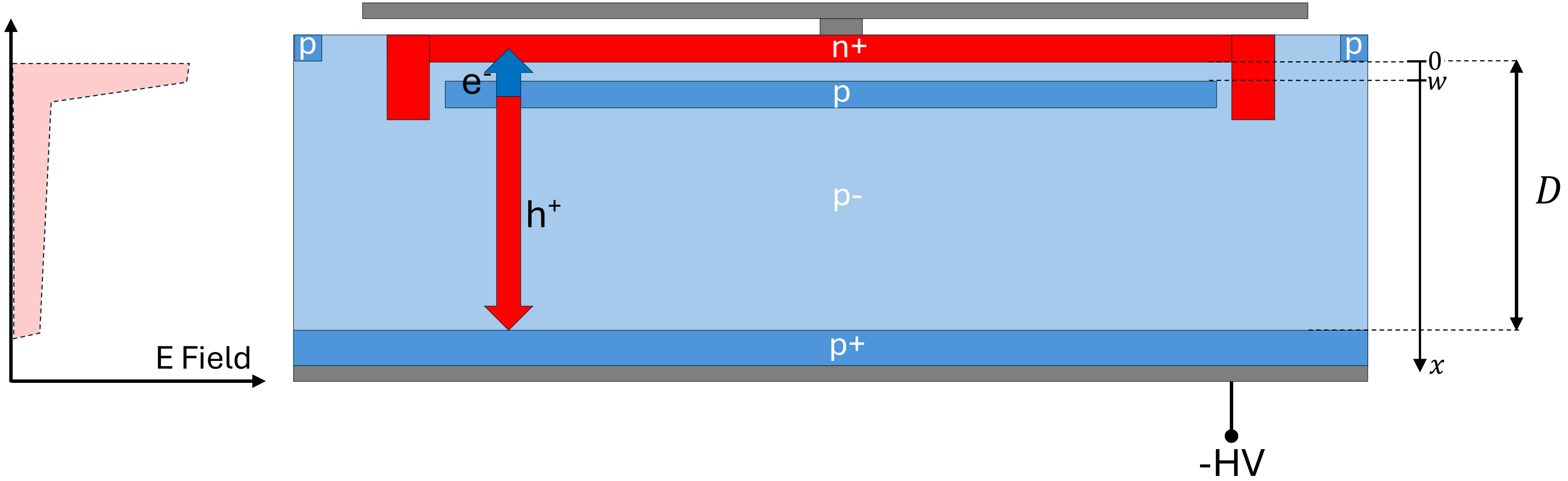


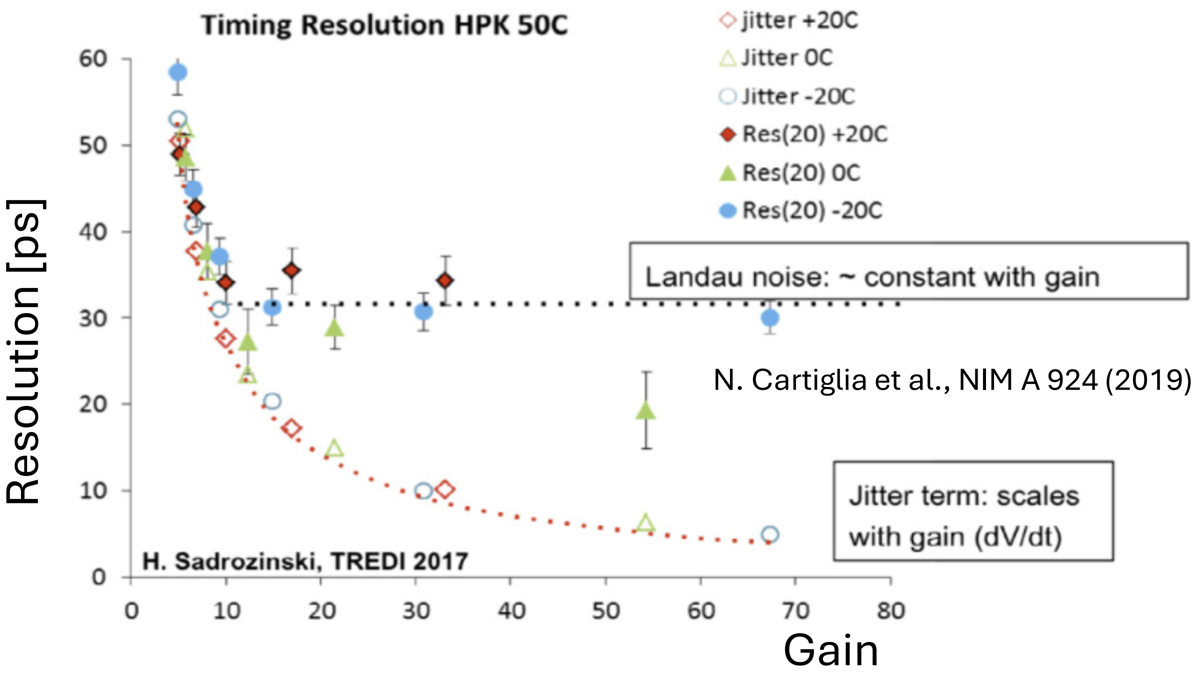
$$I_{ind} = \sum_{e,h} \frac{1}{D} q_i v_{drift}$$

Larger current for a thinner sensor: the **time resolution improves for thinner APDs**!

$$Q_{ind} = \sum_{e,h} \int_{x_i}^{D} \frac{1}{D} q_i v_{drift} = Q_{tot,e} \frac{w}{D} + Q_{tot,h} \frac{D-w}{D}$$

Most of the **signal is induced by the holes** drifting back to the sensor backside

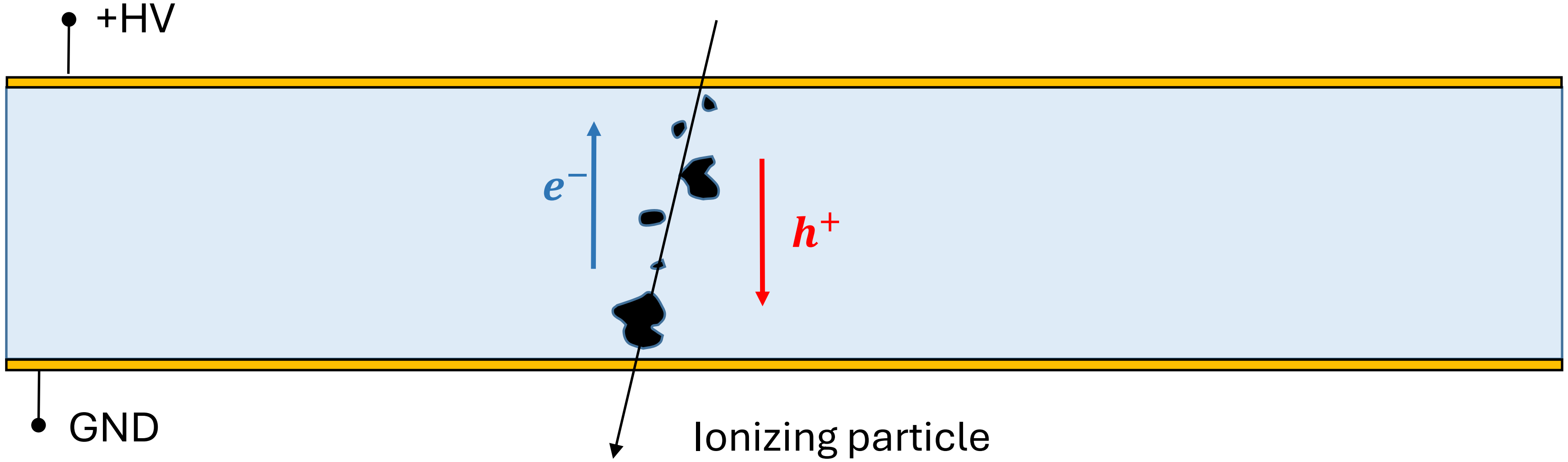
LGAD time jitter and time resolution



N. Cartiglia et al., NIM A 924 (2019) 350-354

$\sigma_t \sim 30\ ps$ achieve by 50-μm-thick "Low-Gain" Avalanche Diodes (LGADs)

Charge collection noise



is produced by the non uniformity of the charge deposition **profile** in the sensor:

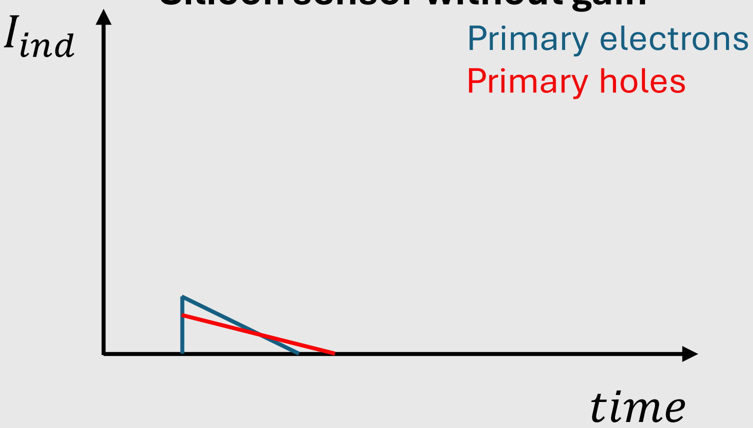
$$I_{ind} \cong v_{drift} \frac{1}{D} \boxed{\sum_i q_i}$$

When **larger clusters** are absorbed at the electrodes, their contribution is removed from the induced current. The **statistical origin** of this variability of I_{ind} makes this **effect irreducible in PN-junction sensors.**

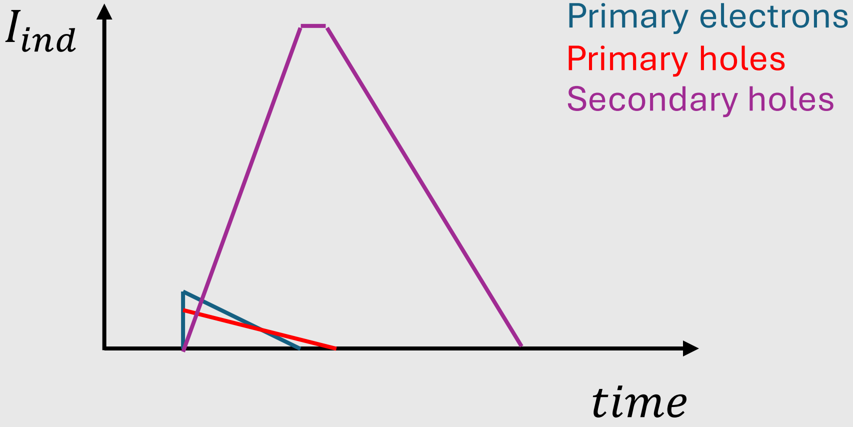
Charge collection noise: case for a solid state (silicon) detector

Noiseless induced current

Silicon sensor without gain



Avalanche diode



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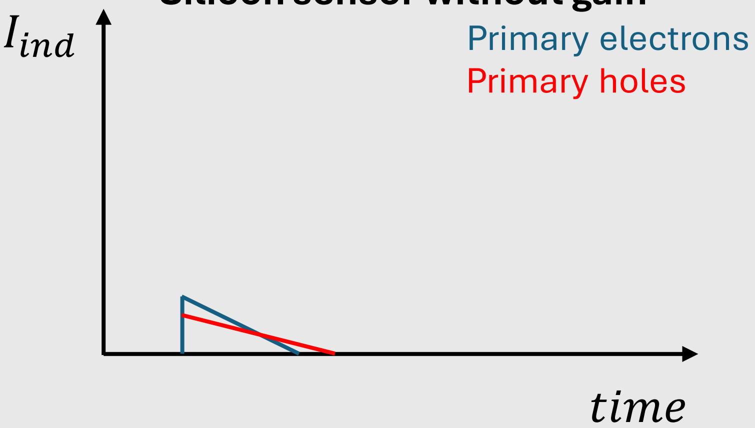
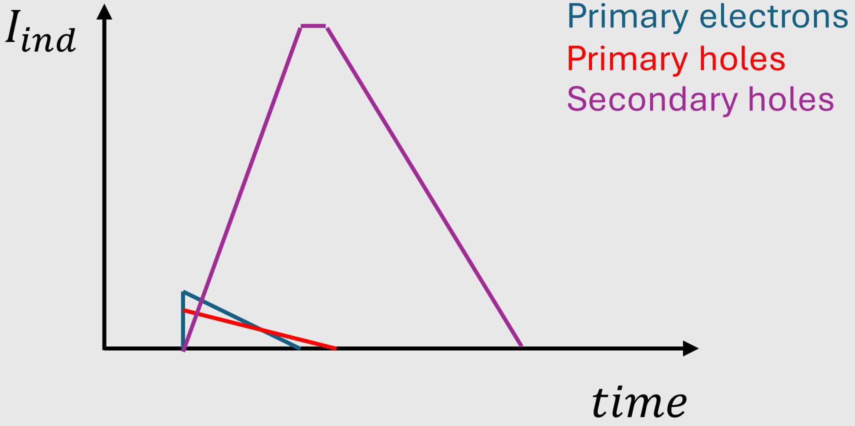
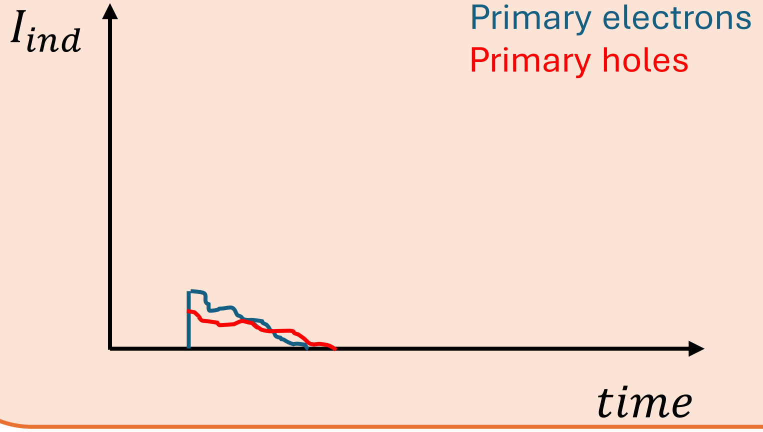


Avalanche diode

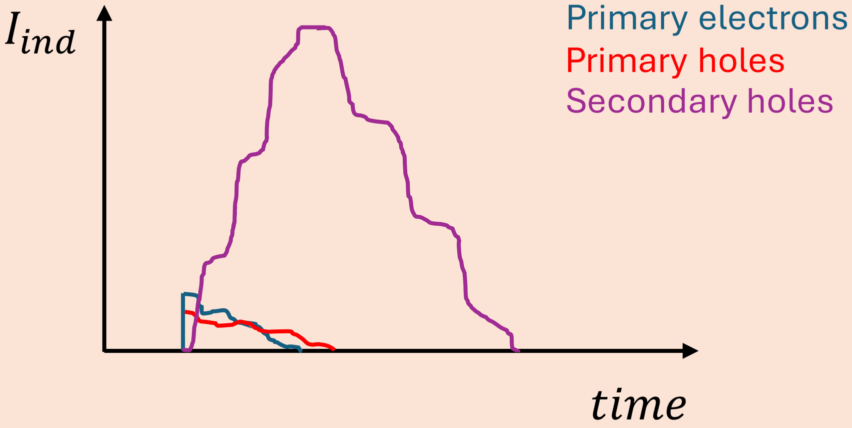


With charge collection noise

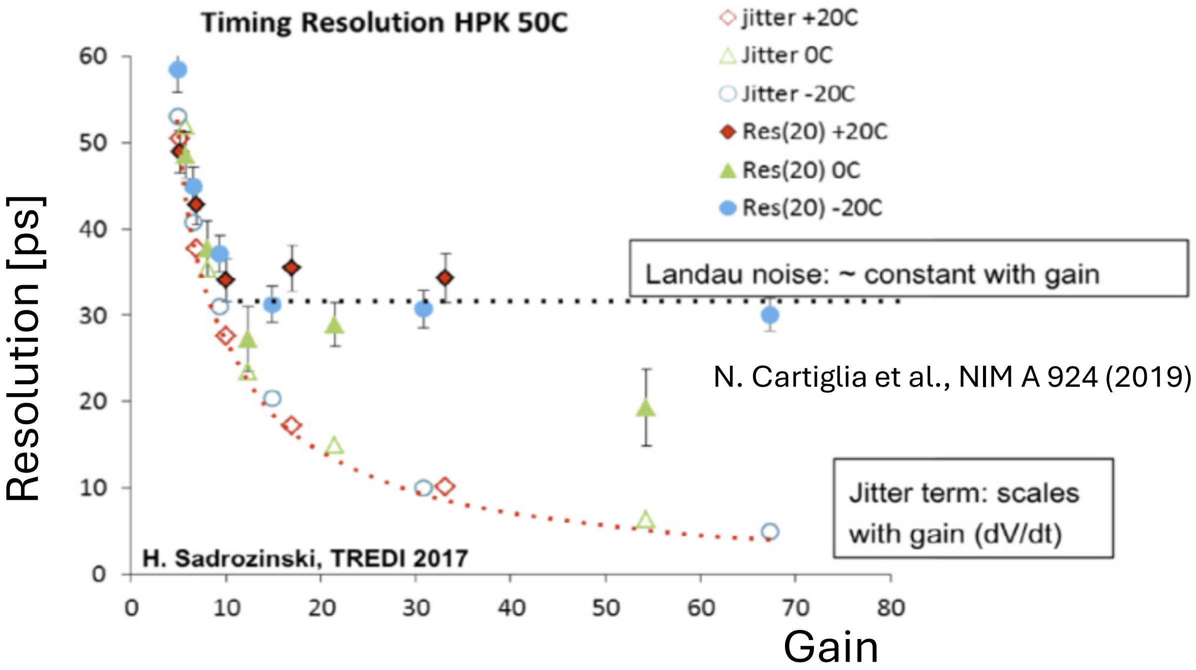
Silicon sensor without gain



Avalanche diode



Charge collection noise: case for a solid state (silicon) detector



N. Cartiglia et al., NIM A 924 (2019) 350-354

Charge collection noise represents an intrinsic limit to the time resolution for a semiconductor PN-junction detector.

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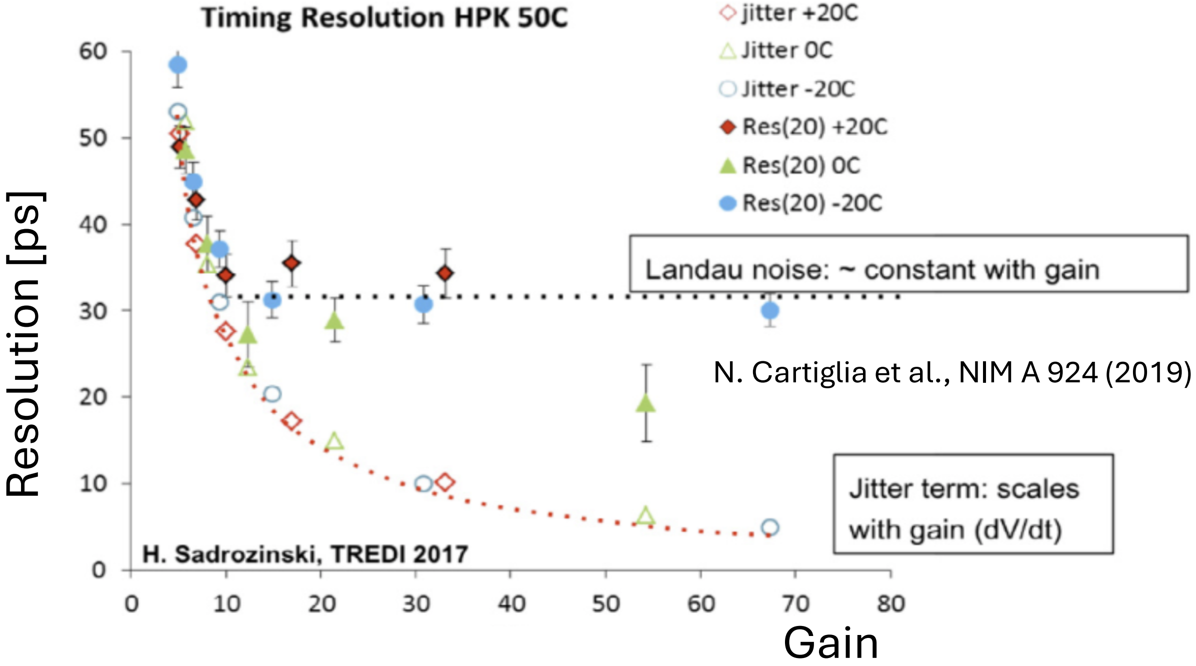
Charge collection noise: case for a solid state (silicon) detector



N. Cartiglia et al., NIM A 924 (2019) 350-354

Charge collection noise represents an intrinsic limit to the time resolution for a semiconductor PN-junction detector.

$\sigma_t \sim 30\ ps$ achieve by 50-μm-thick “Low-Gain” Avalanche Diodes (LGADs)

Lower contribution from sensors wihtout internal gain

→ $\sigma_t \sim 20\ ps$ achieved by 50-μm-thick PIN Diodes

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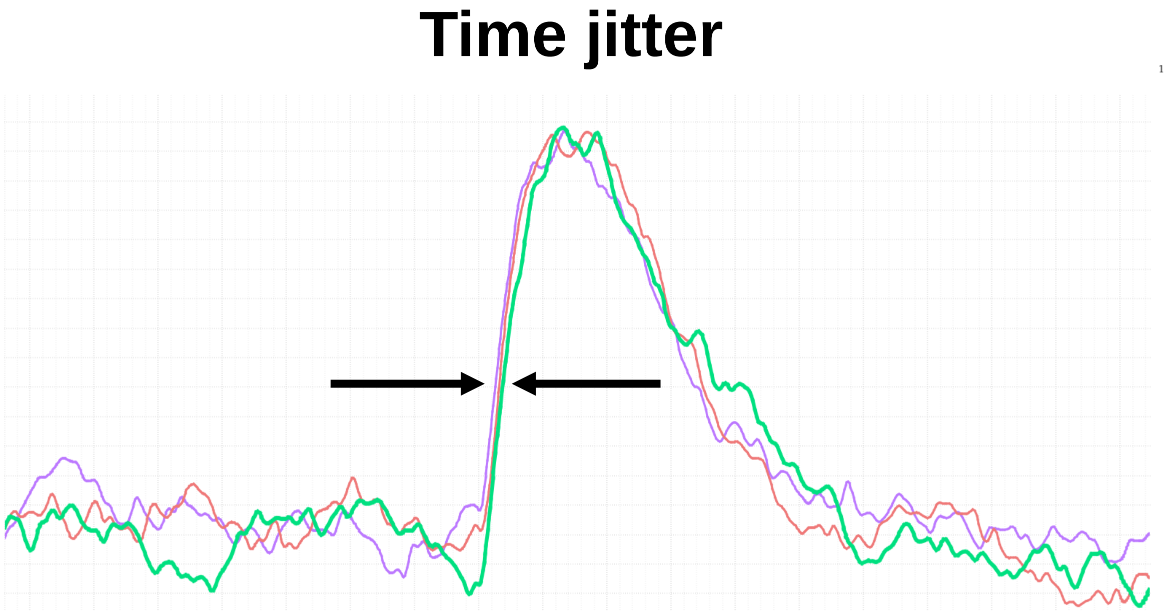
Time jitter

Once the geometry has been fixed, the time resolution depends mostly on the **signal to noise ratio**.

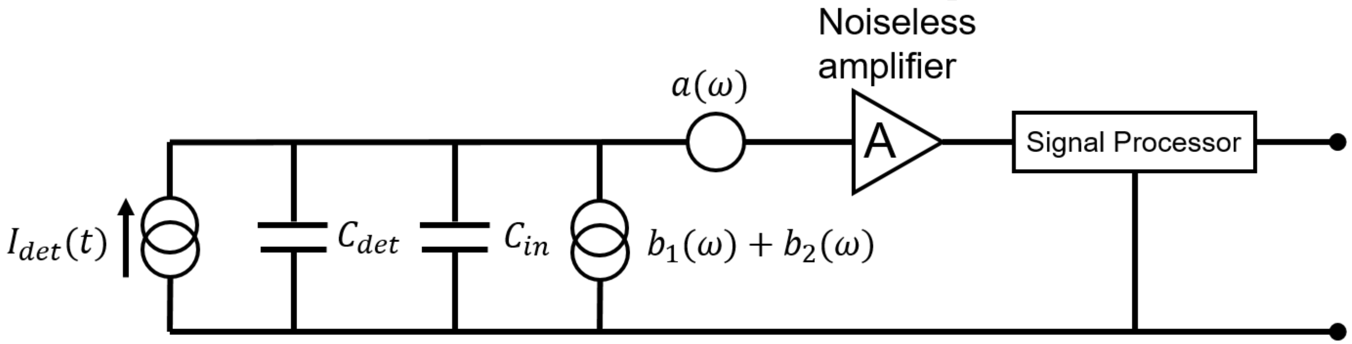


Fast integration

Reduce noise (front-end performance and electrode design)

$$\sigma_t = \frac{\sigma_V}{\frac{dV}{dt}} \simeq \frac{t_{rise}}{\frac{Signal}{Noise}} \simeq \frac{\boxed{ENC}}{I_{ind}}$$

Electronic noise: device comparison

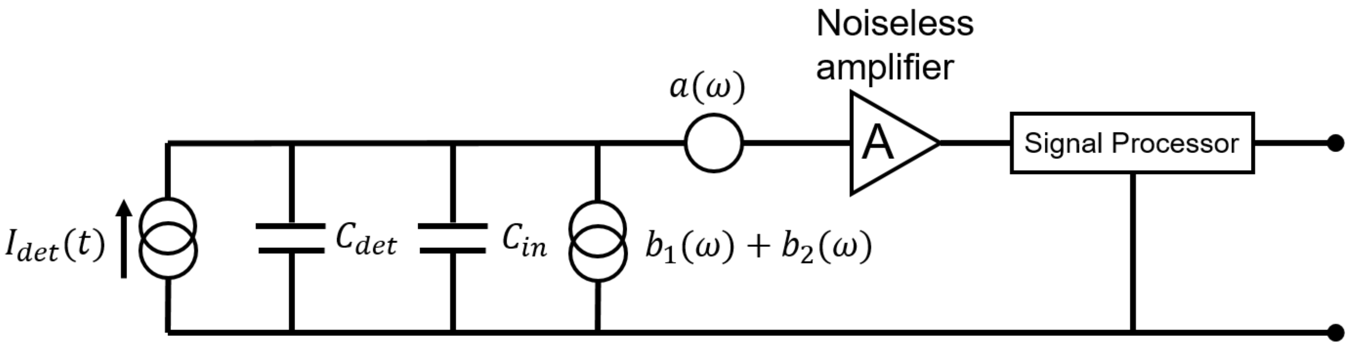


$$ENC^2 = A_1 \frac{a_W}{\boldsymbol{\tau_M}}(C_{det} + C_{in})^2 + A_2 \frac{ln2}{\pi} c(C_{det} + C_{in})^2 + \cancel{A_3(b_1 + b_2)\boldsymbol{\tau_M}}$$

$$\boldsymbol{\tau_M \sim 1\, ns}$$

We can neglect the parallel noise, which makes the BJT technology a good candidate to make an amplifier for timing detector

Electronic noise: BJT



$$ENC^2 = \boxed{A_1 \frac{a_W}{\boldsymbol{\tau_M}} (C_{det} + C_{in})^2} + \cancel{A_2 \frac{ln2}{\pi} c(C_{det} + C_{in})^2} + \cancel{A_3(b_1 + b_2)\boldsymbol{\tau_M}}$$

BJT based amplifier

$$ENC_{\text{series noise}} \propto \sqrt{k_1 \cdot \frac{C_{tot}^2}{\beta} + k_2 \cdot R_b C_{tot}^2}$$

Goal: maximize the current gain β at high frequencies while keeping a low base resistance R_b

Electronic noise: BJT

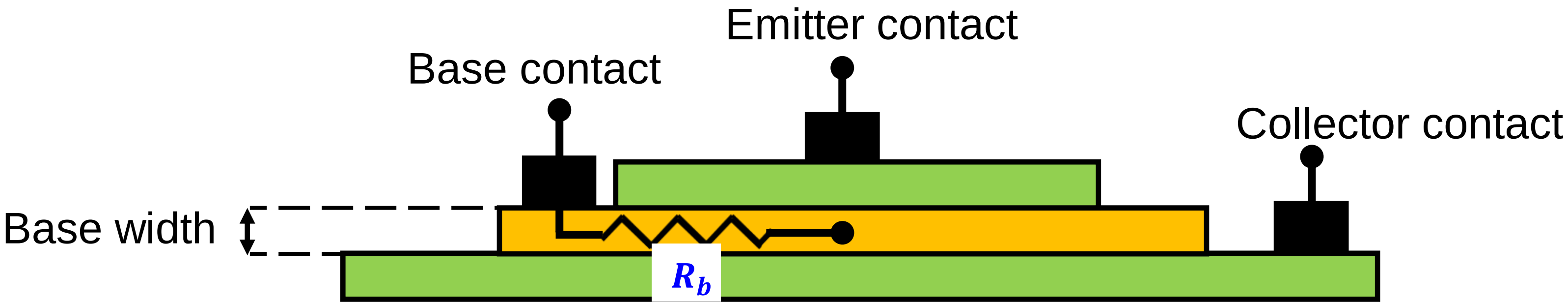
For a NPN BJT, the amplifier current gain β can be expressed as:

$$\beta = \frac{i_C}{i_B} = \frac{\tau_p}{\tau_t}$$

τ_p = hole recombination time in Base

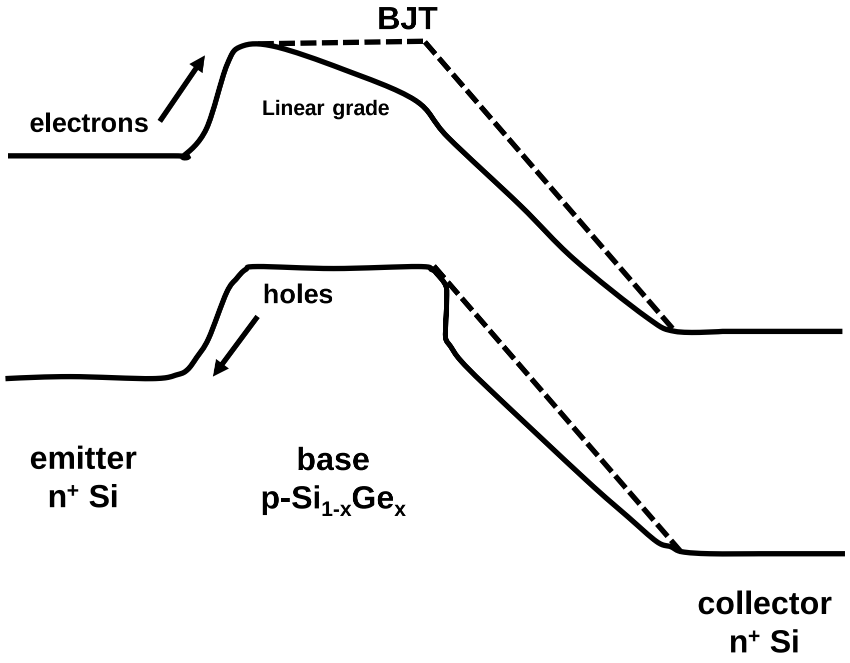
τ_t = electron transit time (Emitter to Collector)

Large $\beta \Longrightarrow$ Minimize the electron transit time



Electronic noise: SiGe HBT

In SiGe Heterojunction Bipolar Transistors (HBT) the **grading** of the bandgap in the Base changes the **charge-transport mechanism** in the Base **from diffusion to drift**:



Grading of germanium in the base:

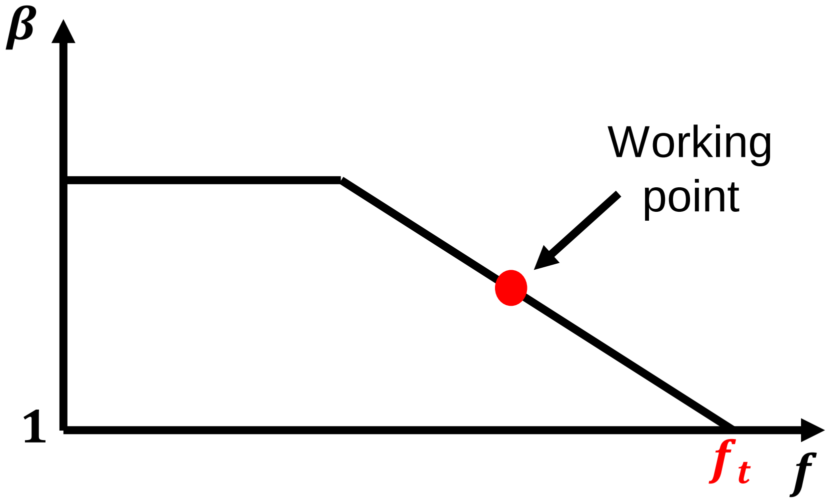
field-assisted charge transport in the Base,
equivalent to introducing an electric field in the Base

$\Longrightarrow$ short e^- transit time in Base $\Longrightarrow$ very high β

$\Longrightarrow$ smaller size $\Longrightarrow$ reduction of R_b and very high f_t

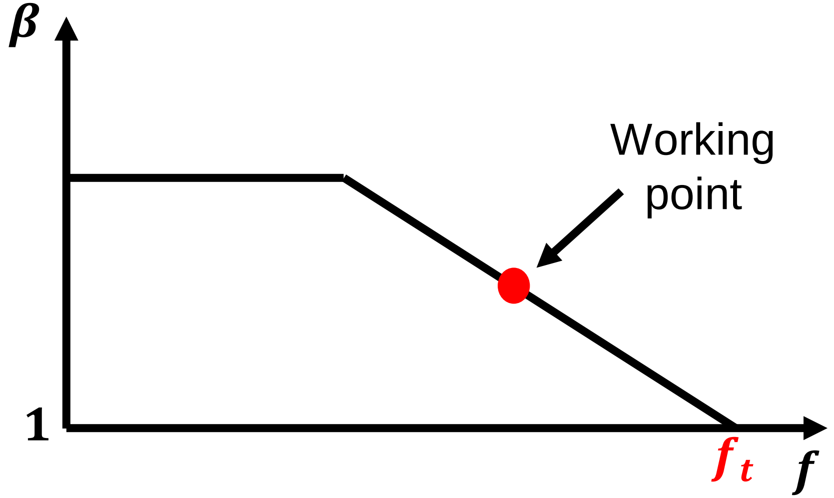
Hundreds of GHz

Current gain and power consumption



	$f_t = 10\ GHz$	$f_t = 100\ GHz$
β_{max} at $200\ MHz$	50	500
β_{max} at $1\ GHz$	10	100
β_{max} at $5\ GHz$	2	20

Current gain and power consumption



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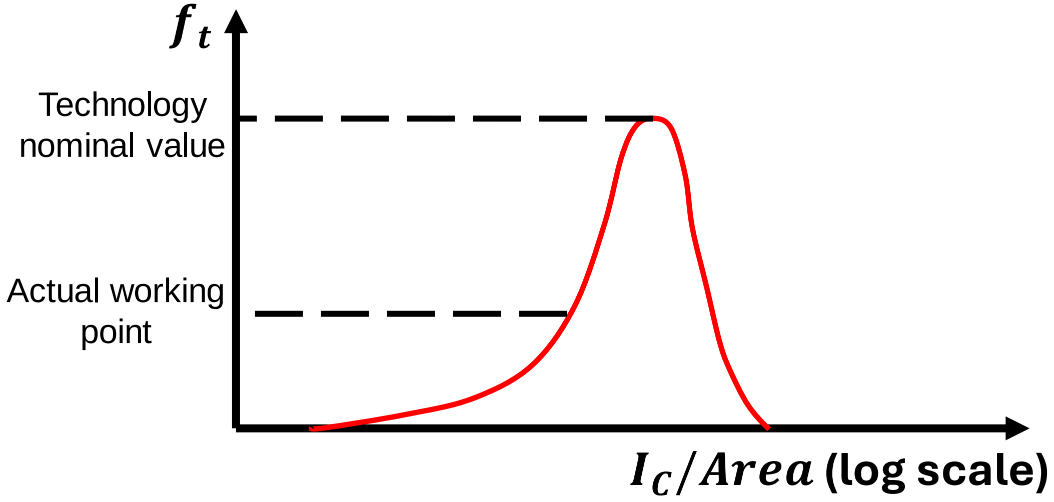
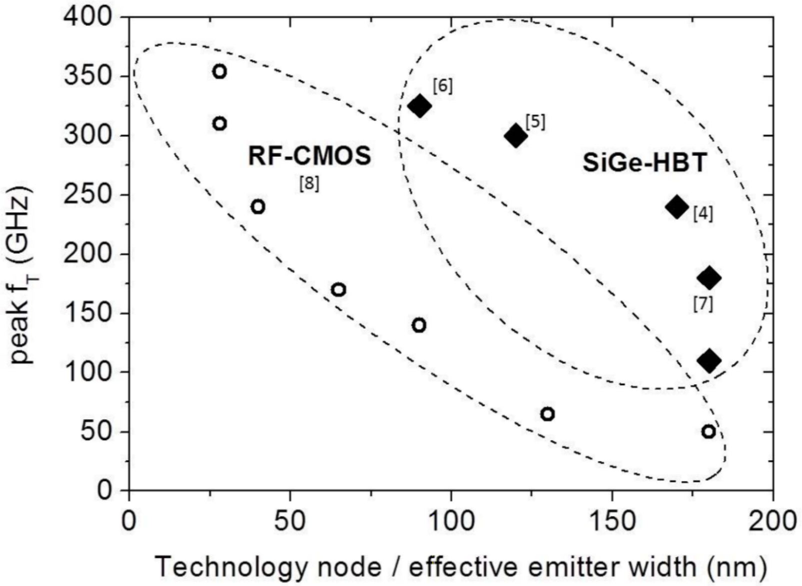


Trade-off: **σ_t** ⇔ **Power Consumption**

$f_t > 100\ GHz$ technologies are necessary for fast, low-power amplification.

A comparison with CMOS technologies

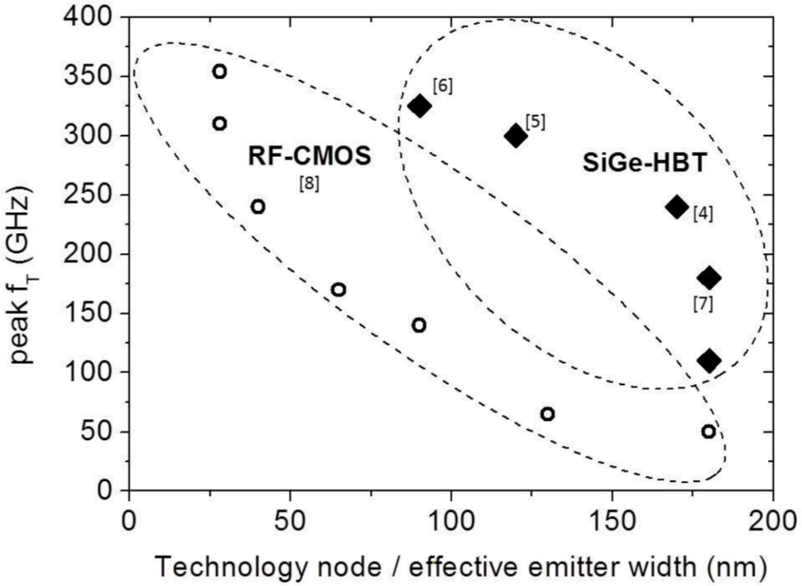
Intrinsic performance



A. Mai and M. Kaynak, SiGe-BiCMOS based technology platforms for mm-wave and radar applications.
DOI: 10.1109/MIKON.2016.7492062

A comparison with CMOS technologies

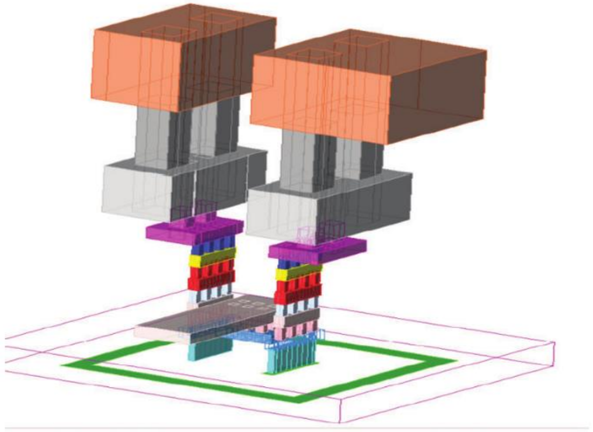
Intrinsic performance

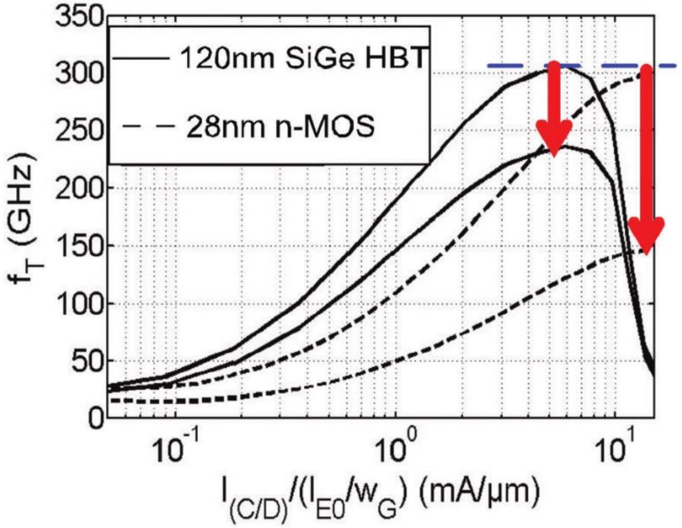


A. Mai and M. Kaynak, SiGe-BiCMOS based technology platforms for mm-wave and radar applications.
DOI: 10.1109/MIKON.2016.7492062

Robustness to parasitics

M. Schröter, U. Pfeiffer and R. Jain, Silicon-Germanium Heterojunction Bipolar Transistors for mm-Wave Systems: Technology, Modeling and Circuit Applications.





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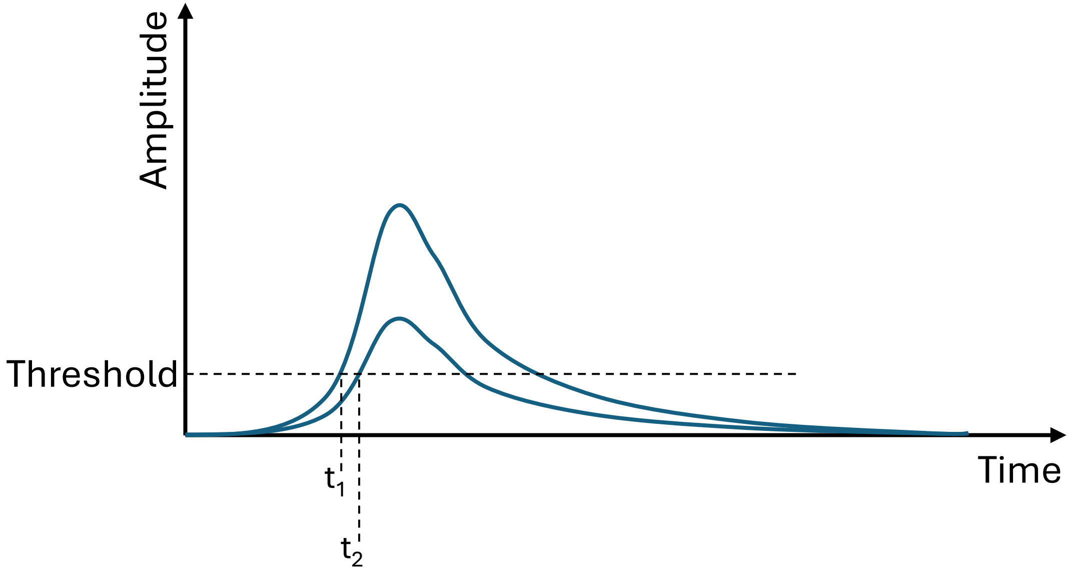
Time walk



Larger signals cross the discrimination threshold earlier than smaller ones, introducing extra time error

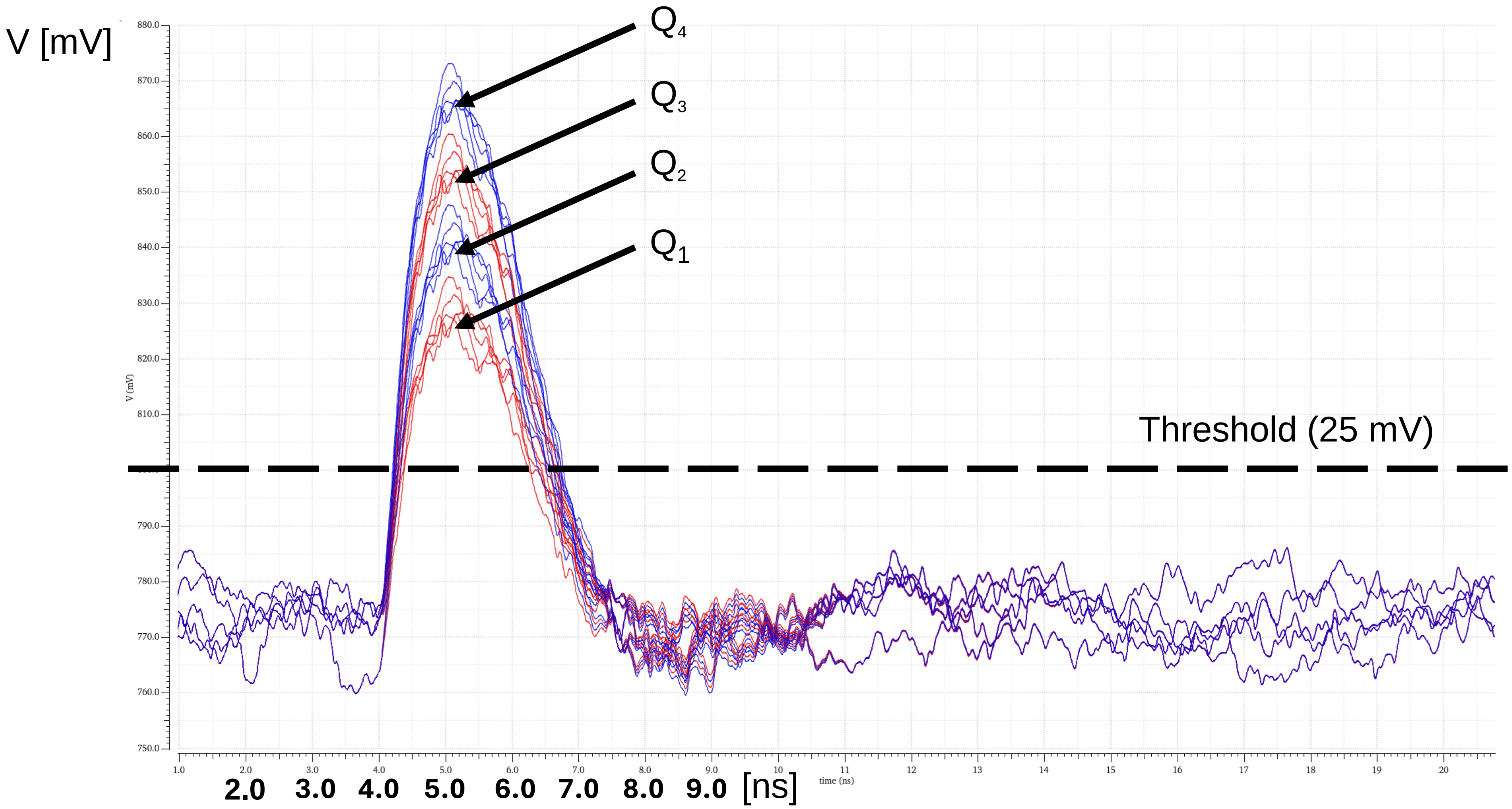
$$V(t) = V_0(t_0) + \frac{dV}{dT}(t - t_0)$$

→ We can **partially** correct for time walk by measuring the signal slope → The choice of the designer is **how to measure this slope**

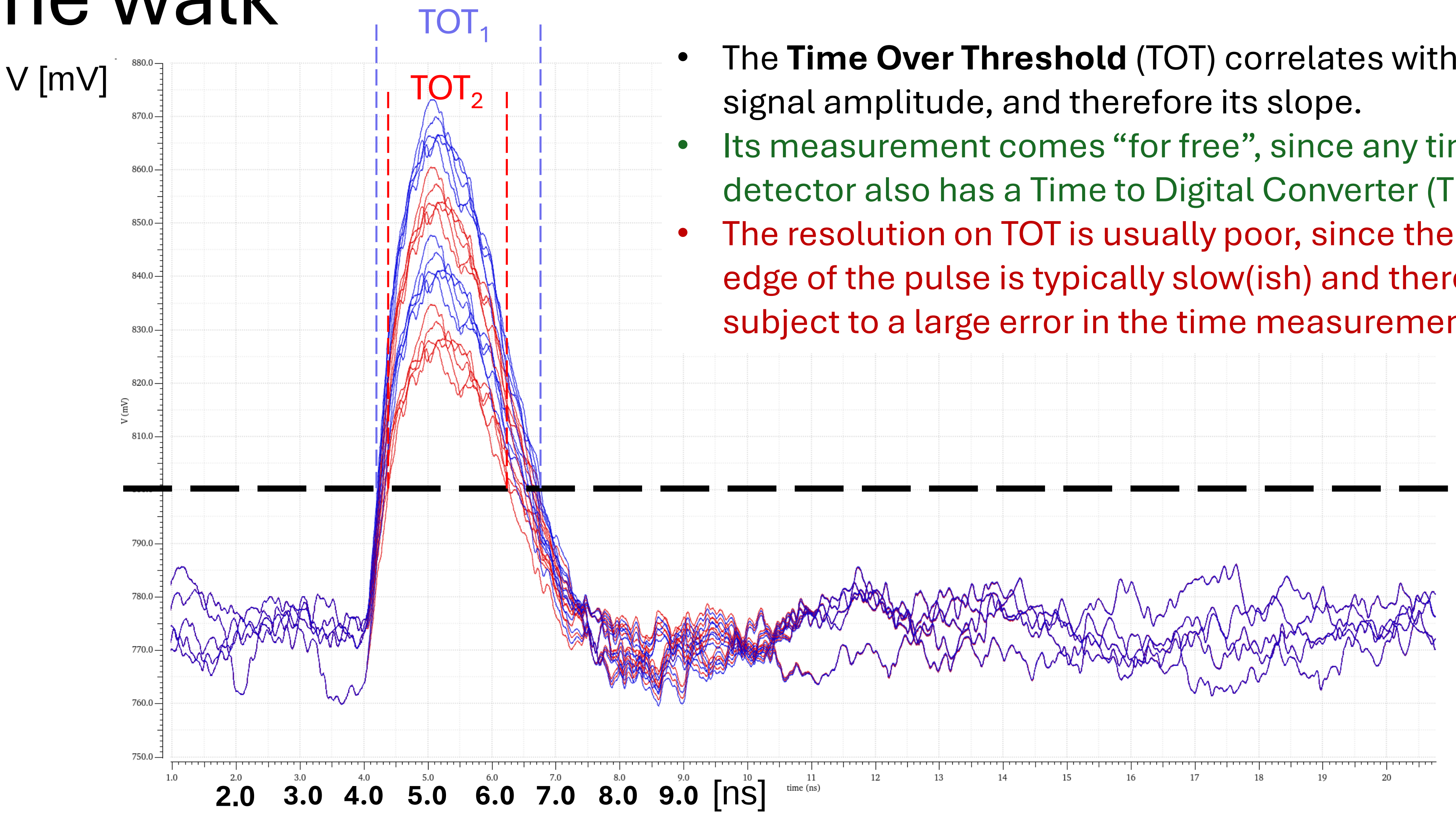
Note 1: In some devices, like silicon pixel detectors, a linear correction yields good results. When the physical process plays a crucial role in time resolution a more complex correction may be necessary

Note 2: In silicon detectors the Landau fluctuations of deposited charge are responsible for time walk. Not to be confused with charge collection noise, which is sometimes erroneously called Landau noise.

Time walk

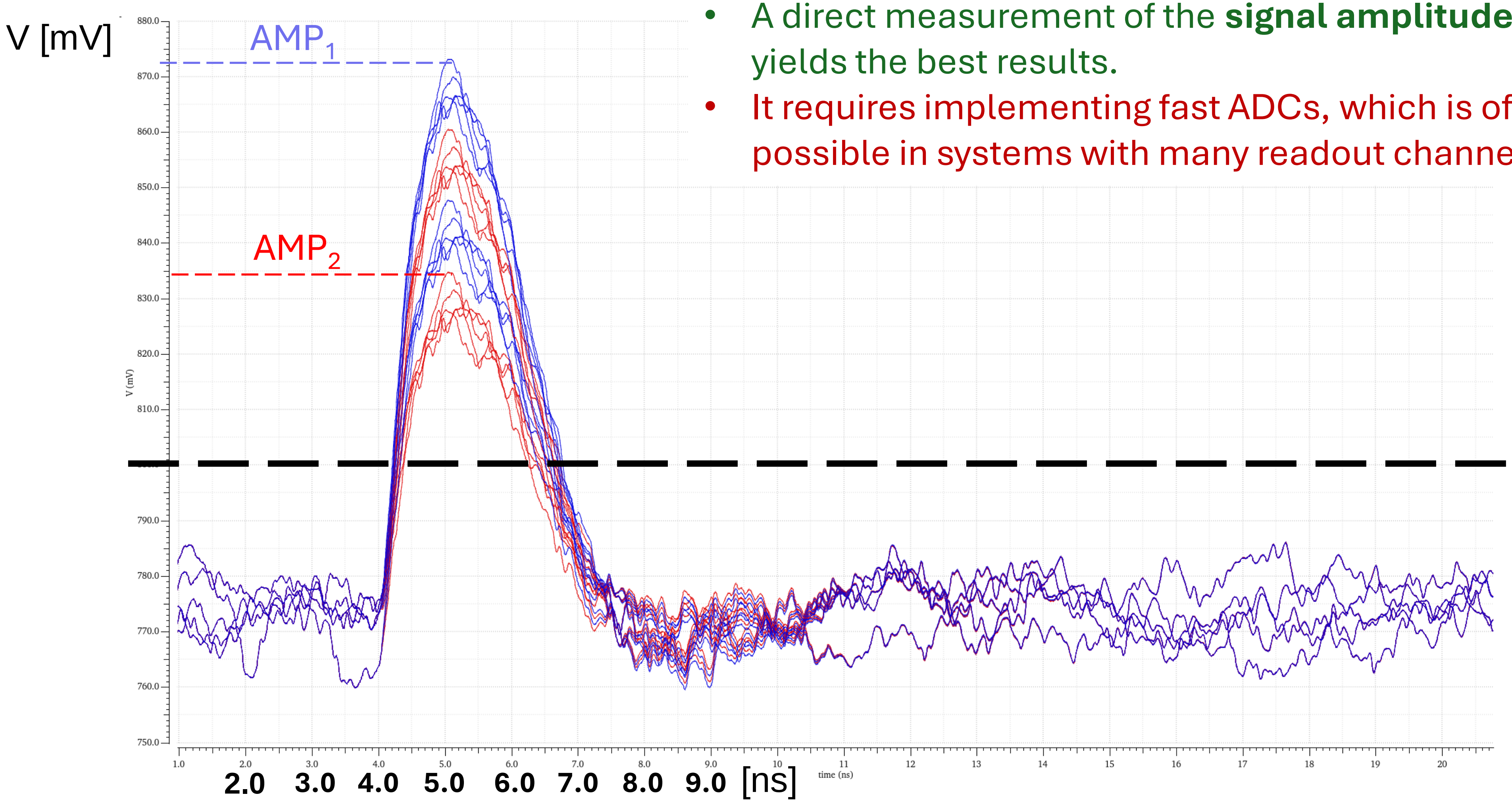

V [mV]
Q4
Q3
Q2
Q1
Threshold (25 mV)
880.0
870.0
860.0
850.0
840.0
830.0
820.0
810.0
790.0
780.0
770.0
760.0
750.0
V (mV)
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10
11
12
13
14
15
16
17
18
19
20
time (ns)
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
[ns]

Time walk



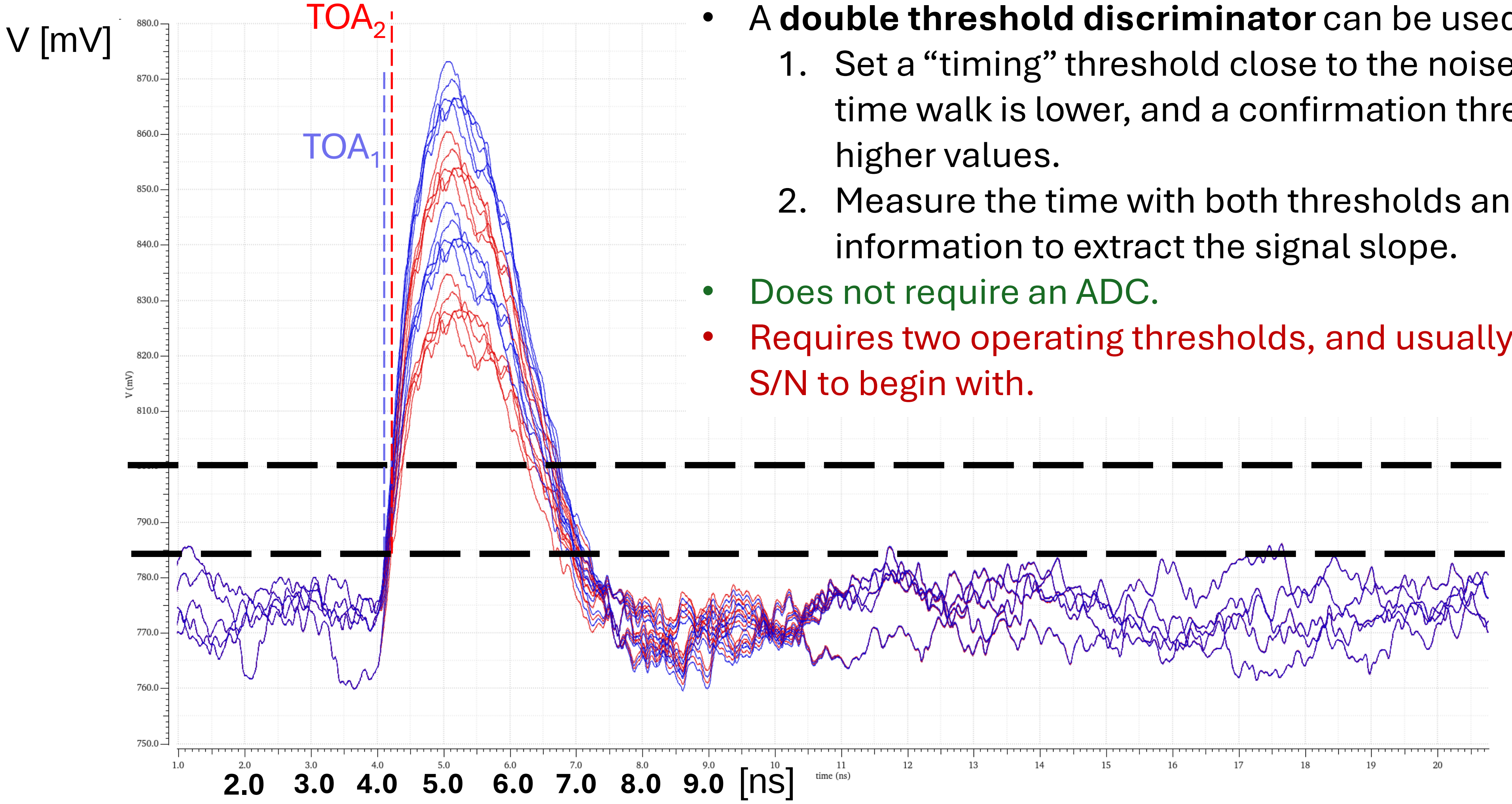
- The **Time Over Threshold** (TOT) correlates with the signal amplitude, and therefore its slope.
- Its measurement comes “for free”, since any timing detector also has a Time to Digital Converter (TDC).
- The resolution on TOT is usually poor, since the falling edge of the pulse is typically slow(ish) and therefore subject to a large error in the time measurement.

Time walk



- A direct measurement of the **signal amplitude** often yields the best results.
- It requires implementing fast ADCs, which is often not possible in systems with many readout channels.

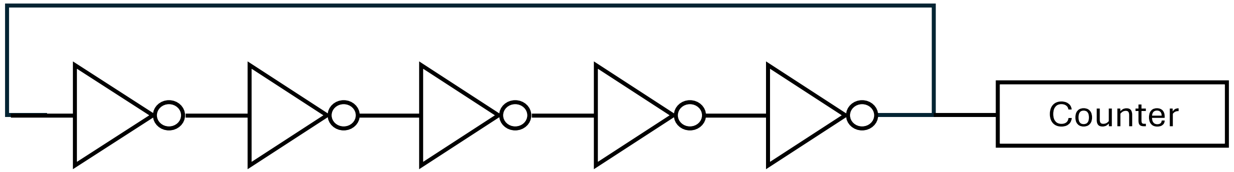
Time walk



- A **double threshold discriminator** can be used to either:
    1. Set a “timing” threshold close to the noise, where time walk is lower, and a confirmation threshold at higher values.
    2. Measure the time with both thresholds and use the information to extract the signal slope.
- Does not require an ADC.
- Requires two operating thresholds, and usually a good S/N to begin with.

Time digitization

Ring oscillator based TDC



- Time information is promptly available.
- High readout rate.
- Dynamic range can be extended with a counter.
- Good (bot not excellent) time resolution. → Can be improved with Vernier line.

Controlled in phase

- Simpler synchronization at system level.
- Worse performance.
- Start and stop to save power…
  - …at the cost of further degrading performance.

Free running

- More robust wrt noise.
- Better timing performance.
- More complex calibration with a precise clock distribution.
- Larger power consumption.

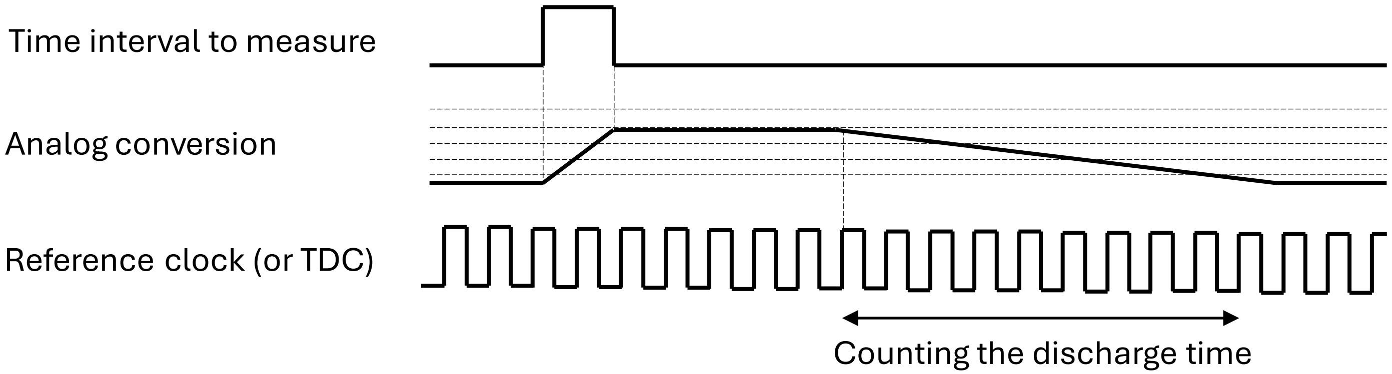
Time digitization

Conversion TDC

Time to amplitude converter → ADC

- Requires an ADC. ➡ Can be an amplitude to time converter. ☺
- Low readout rate.
- Limited dynamic range.
- Complex calibration.
- Excellent time resolution: 1ps achievable in the 80s of last century.

A typical implementation is charging a capacitor with a constant current for a duration equal to the time interval that you want to measure.



Time synchronization

Flash slide

In large experimental setups

- Synchronization at 10ps level in large setups is complex, but it is an engineering problem that can has been already addressed.

In ASIC

- More complex is the issue of synchronizing different regions of an ASIC.

Time synchronization

Flash slide

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↓

More about it later…

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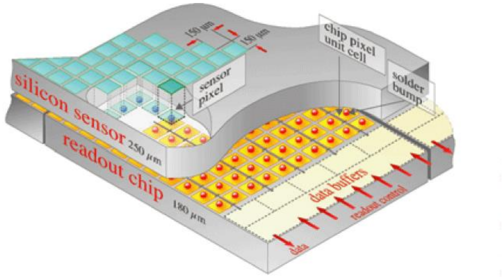
Readout technique: pixel vs transmission line

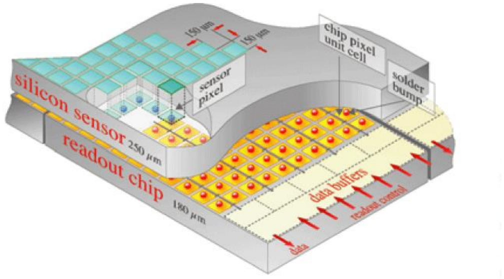
Pixel readout



- Front end performance **dominated by the pixel capacitance**.
- In ASIC, signal **transmission depends on the RC of the interconnections**:
  - A few 100 µm routing can introduce skew between the lines and disrupt the time synchronization between the signals.
  - Tools used for digital design are not meant for 10ps-level synchronization: full-custom design is usually needed.

Readout technique: pixel vs transmission line

Pixel readout



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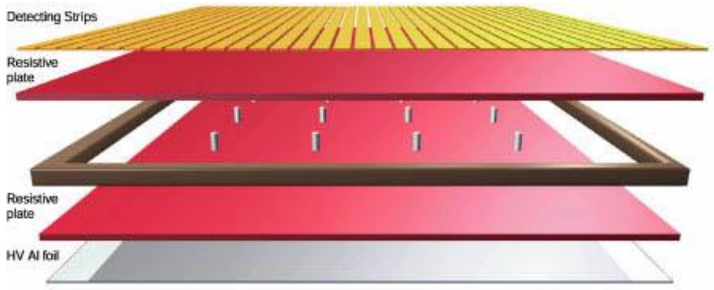
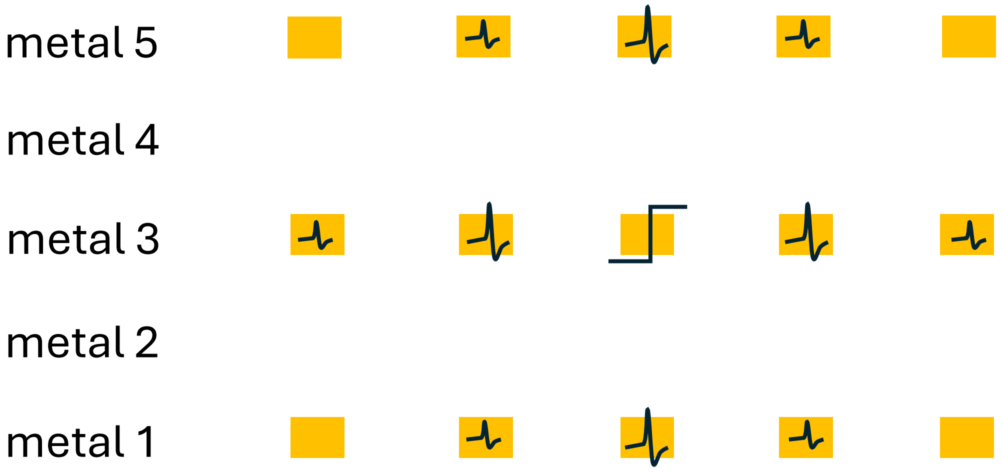
Transmission line readout



- Front end performance **depend on the impedance** of the transmission line: the reactive component of the strip compensate its capacitance.
  - A ground plane behind the strips can be used to control the impedance and decouple the strip from the backplane.
  - Low density materials (foams) are useful dielectrics to keep the impedance high.
- **Half of the signal will be lost** due to the initial splitting!
- Impedance **matching is critical**, and it can be complex at higher frequencies.

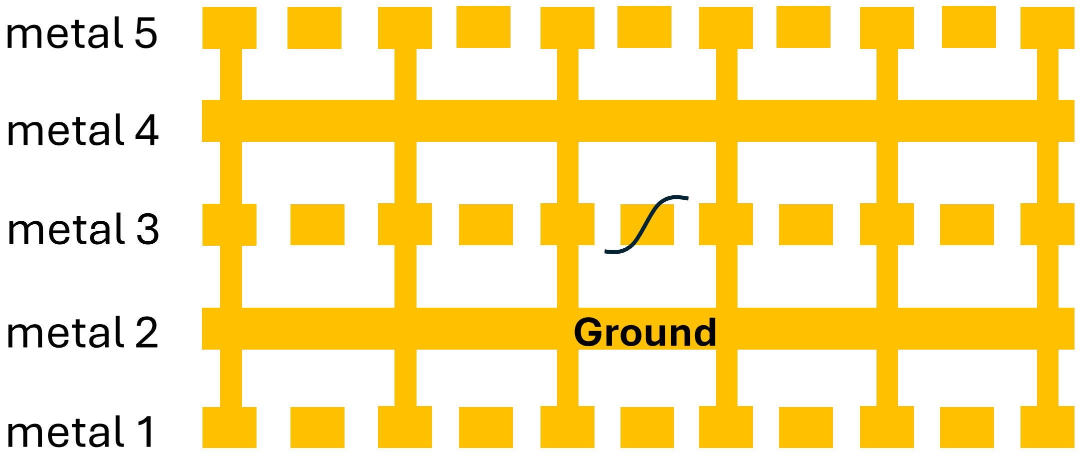
Cross talk

In ASIC



Cross talk

In ASIC



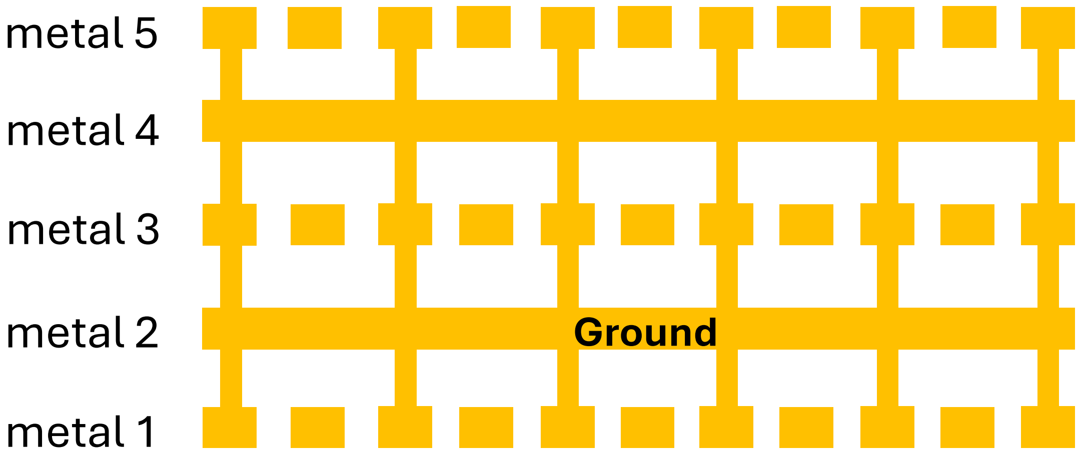
Line shielding is a must, but it increases significantly the line capacitance, increasing the RC.

⇩

High density routing is prohibitive, and the architecture of the ASIC should be designed to avoid it at all costs.

Cross talk

In ASIC



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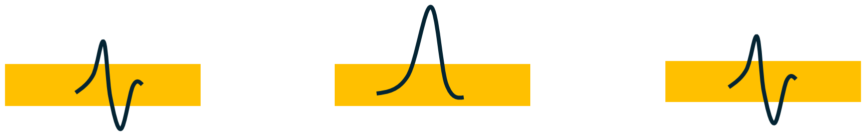
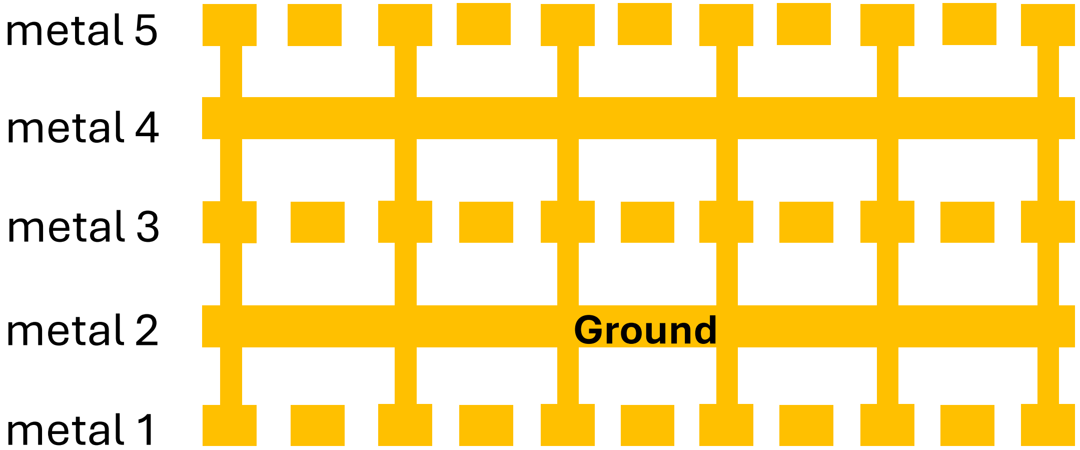
On strips



- The use of a transmission line makes the shielding simpler: the impact on the impedance does not scale with the strip length.
- The absence of cross talk shielding is devastating: the signal.
- Self induced noise is the most complex issue to address.

Cross talk

In ASIC



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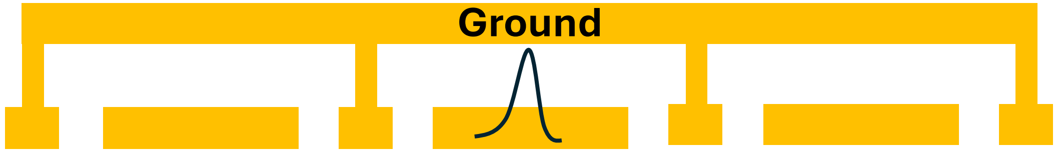
On strips



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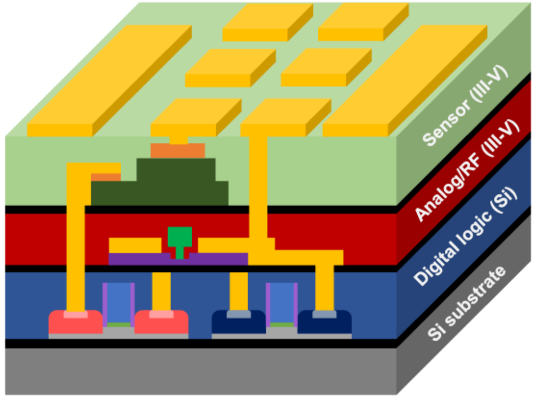
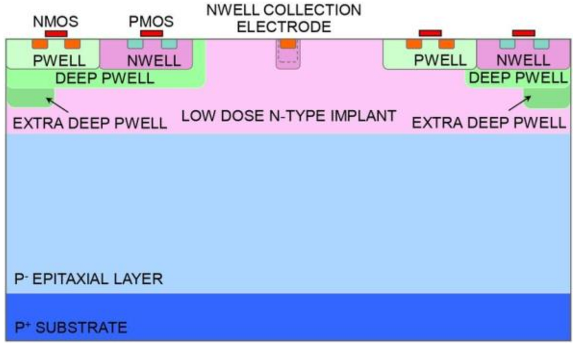
Note for the future on pixel detectors

Bonus slide



3D integration allows addressing most of the challenges in timing pixel design, by decoupling the sensitive nodes from the fast electronics without significantly increasing the pixel capacitance.



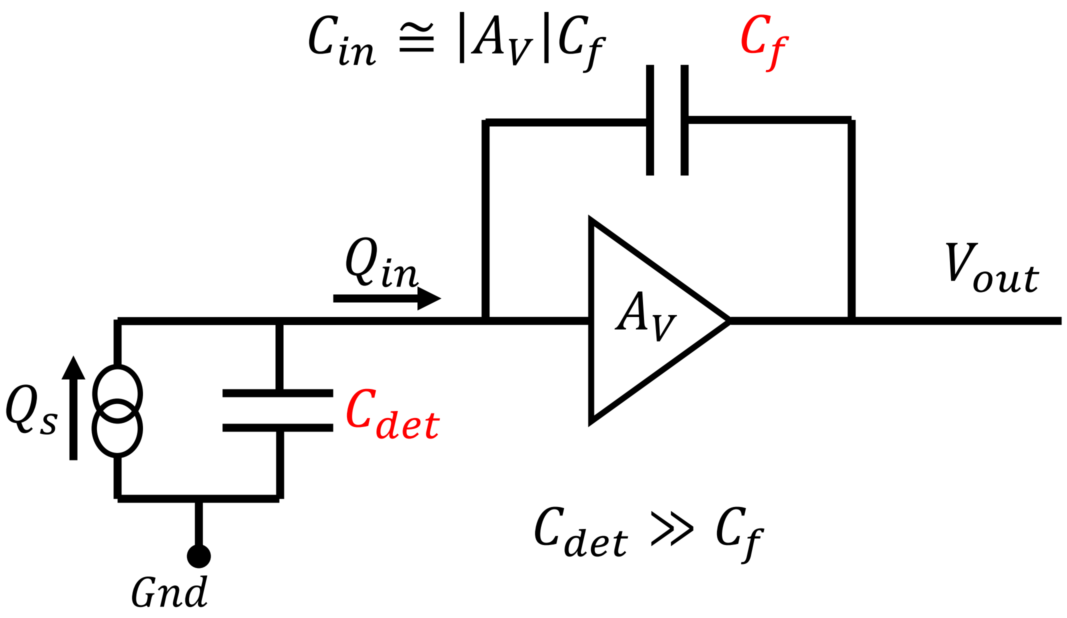
Pixel pitch reduction ($\lesssim 10\ \mu m$) and 3D interconnections can **enable the small-electrode (non-parallel-plate) readout as a timing technology**.

→

- The miniaturization of the pixel size will require also a reduction of the depletion volume, and hence the signal, making it challenging for the performance of present front-end electronics.

Extra

Front end electronics



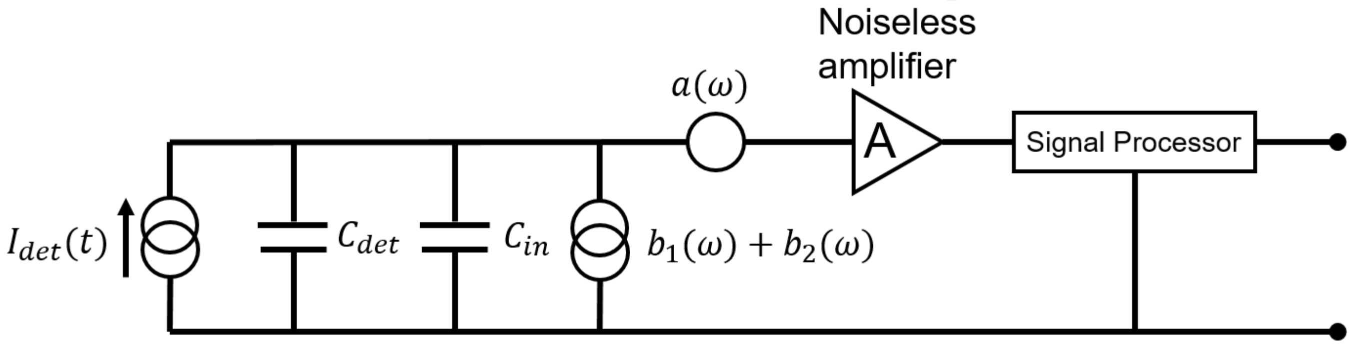
$$\frac{dV_{out}}{dQ_{in}} = \frac{A_V V_{in}}{C_{in} V_{in}} \cong -\frac{1}{C_f}$$

$$\frac{Q_{in}}{Q_S} = \frac{C_{in}}{C_{in} + C_{det}} \approx \frac{|A_V| C_f}{|A_V| C_f + C_{det}} = \frac{C_f}{C_f + \frac{C_{det}}{|A_V|}}$$

$$A_Q = \frac{dV_{out}}{dQ_S} = \frac{Q_{in}}{Q_S}\frac{dV_{out}}{dQ_{in}} \cong \frac{1}{C_f + \frac{C_{det}}{|A_V|}}$$

The voltage gain **at high frequencies** is used to compensate the detector capacitance

Electronic noise: device comparison



$$ENC^2 = A_1 \frac{\boxed{a_W}}{\boldsymbol{\tau_M}}(C_{det} + C_{in})^2 + \boxed{A_2 \frac{ln2}{\pi} c(C_{det} + C_{in})^2} + \cancel{A_3(b_1 + b_2)\boldsymbol{\tau_M}}$$

CMOS based amplifier

$$2kT\frac{\boldsymbol{h}}{g_m}$$

Large ${}^{1}/_{f}$ contribution

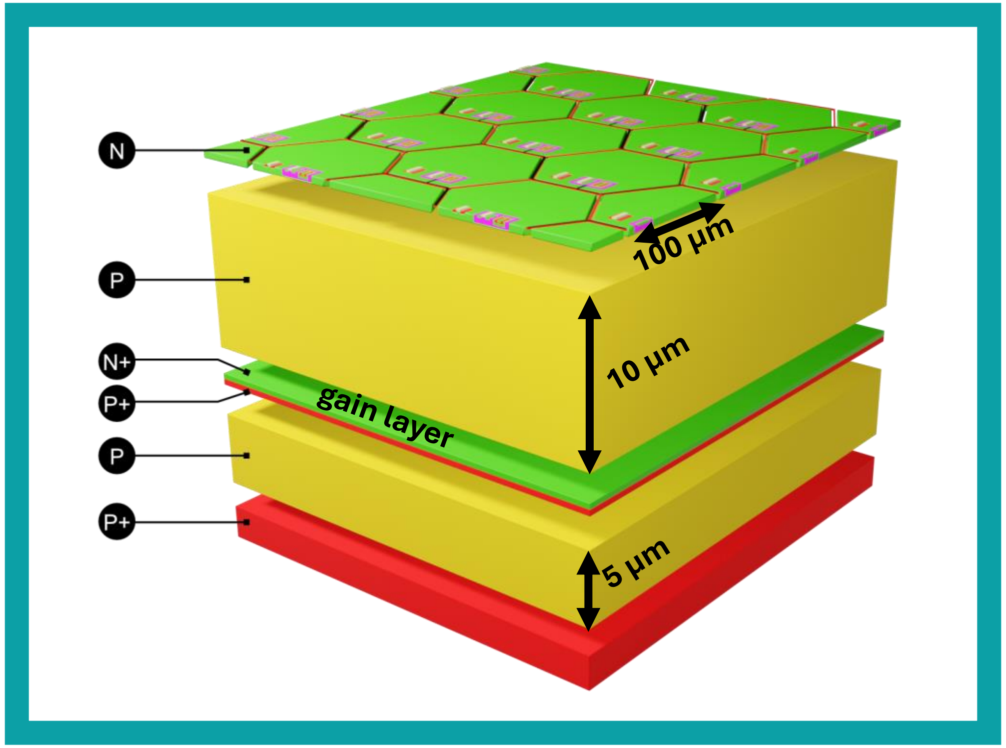
New sensor concept: PicoAD

Multi-Junction Picosecond-Avalanche Detector

with continuous and deep gain layer:

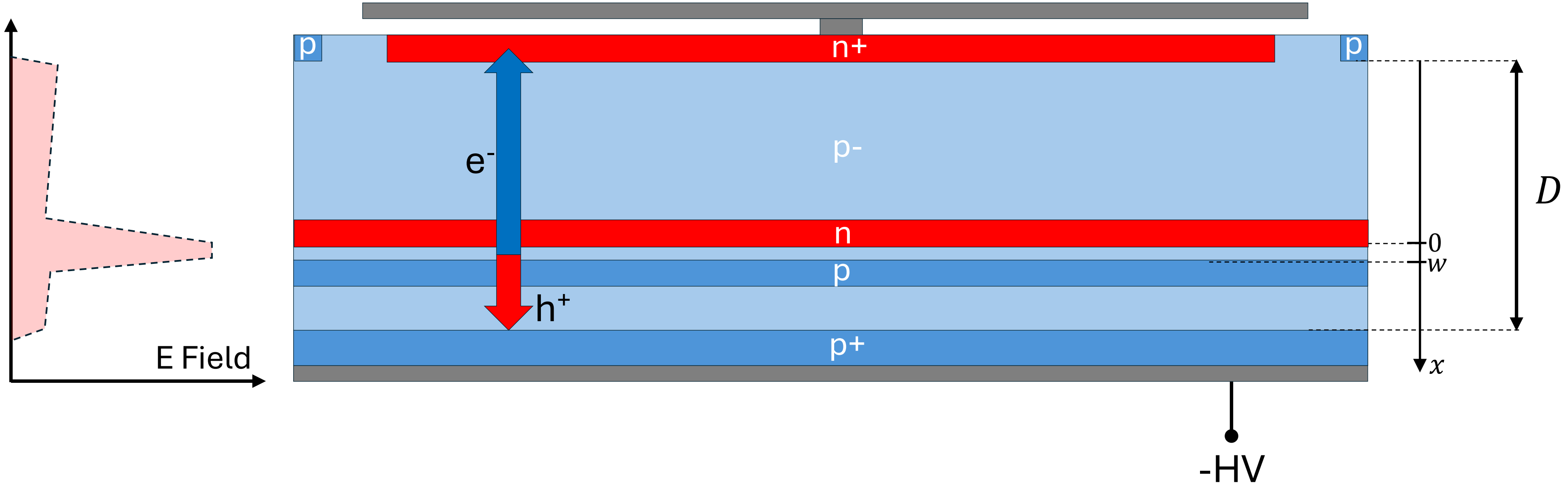
- De-correlation from implant size/geometry
  → **high pixel granularity and full fill factor**
  (high spatial resolution)
- Only small fraction of charge gets amplified
  → **reduced charge-collection noise**
  (enhance timing resolution)

$$\sigma_T \cong \frac{t_{rise}}{Signal/_{Noise}} \cong \frac{\boxed{ENC}}{\boxed{I_{Ind}}}$$



New sensor concept: PicoAD

- Thinner absorption region without increasing pixel capacitance
- Full gain fill-factor
- Smaller signal: requires high-performance front-end electronics



$\sigma_t = 10\ ps$ achieve by 20-μm-thick PicoAD