A new camera concept for Cherenkov telescopes

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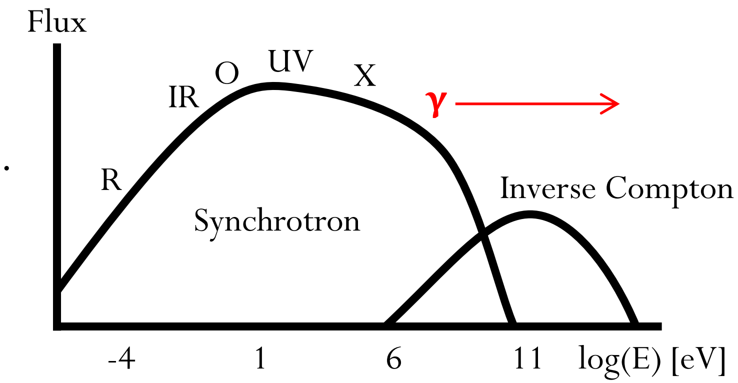
Motivation

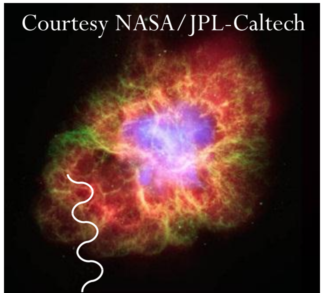
Ground-based very high energy gamma-ray astronomy



- Non-thermal processes generate gamma-rays (keV – PeV).
- Investigation of galactic and extragalactic objects:
  SNR, pulsars, x-binaries, Active Galactic Nuclei etc.
- Improve understanding of processes of high energy gamma-ray production.
- New physics: indirect dark matter searches, test of quantum gravity models
- Ground-based high energy gamma-ray astronomy uses atmosphere as calorimeter and thus profits of a very large collection area.
- **I**maging **A**tmospheric **C**herenkov **T**elescopes cover energy range of 10 GeV – 100 TeV.

Current and future ground-based telescopes:
MAGIC, H.E.S.S., VERITAS, FACT **C**herenkov **T**elescope **A**rray (under development)

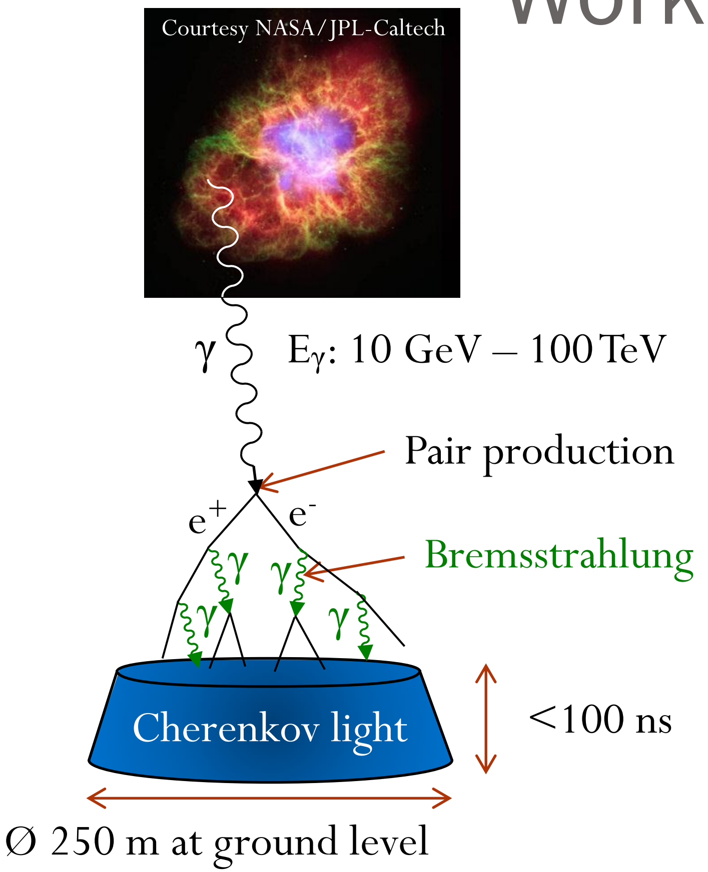
Working principle

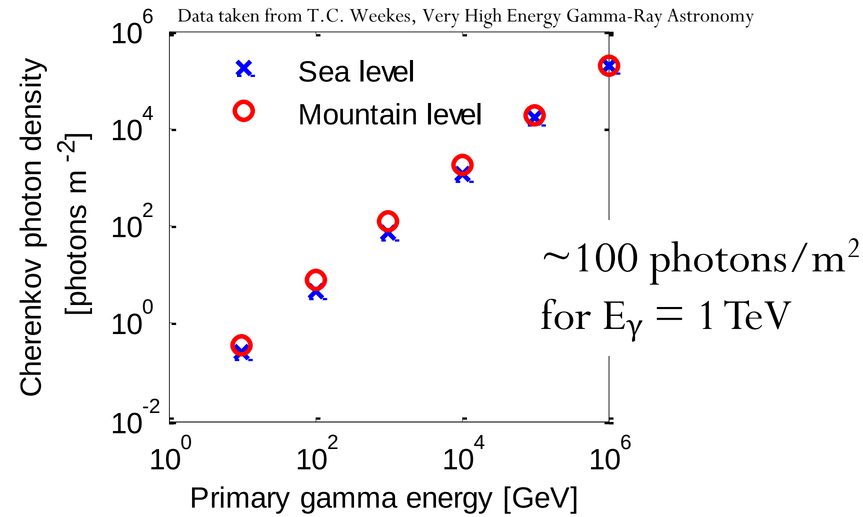


γ

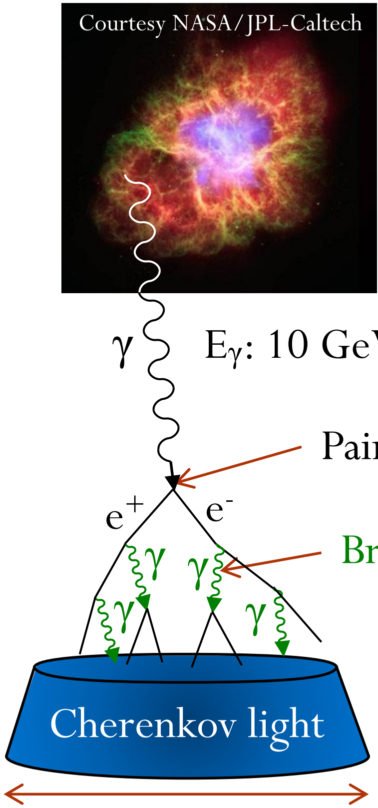
E_γ: 10 GeV – 100 TeV

Working principle





Working principle



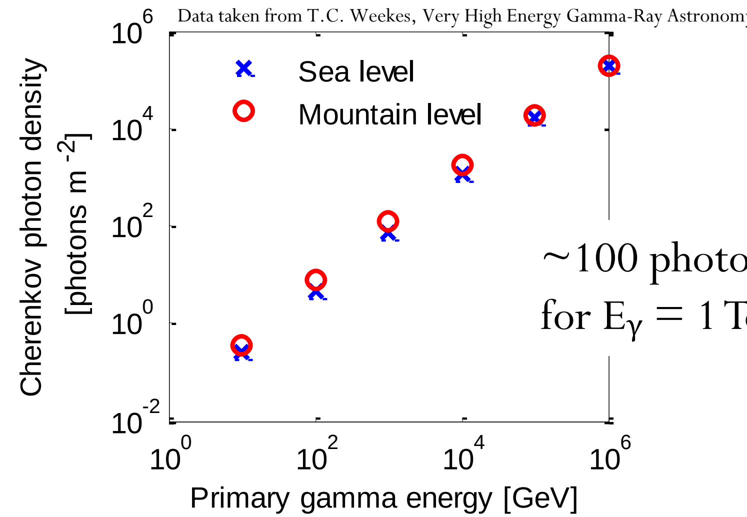
E_γ: 10 GeV – 100 TeV

Pair production

Bremsstrahlung

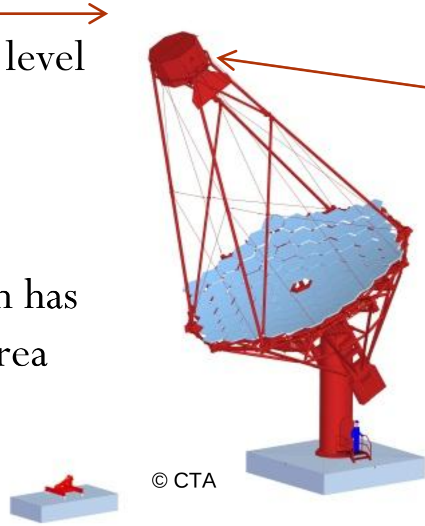
<100 ns

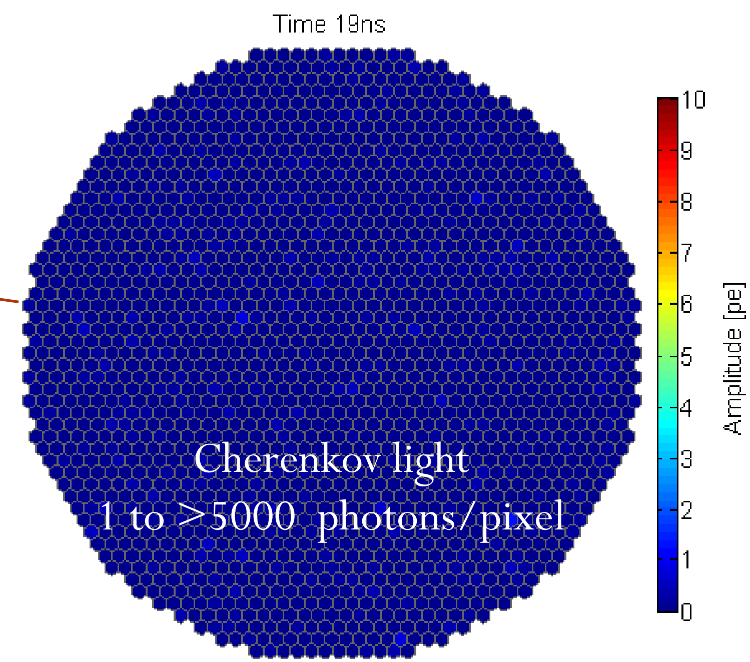
Ø 250 m at ground level



~100 photons/m^2 for E_γ = 1 TeV

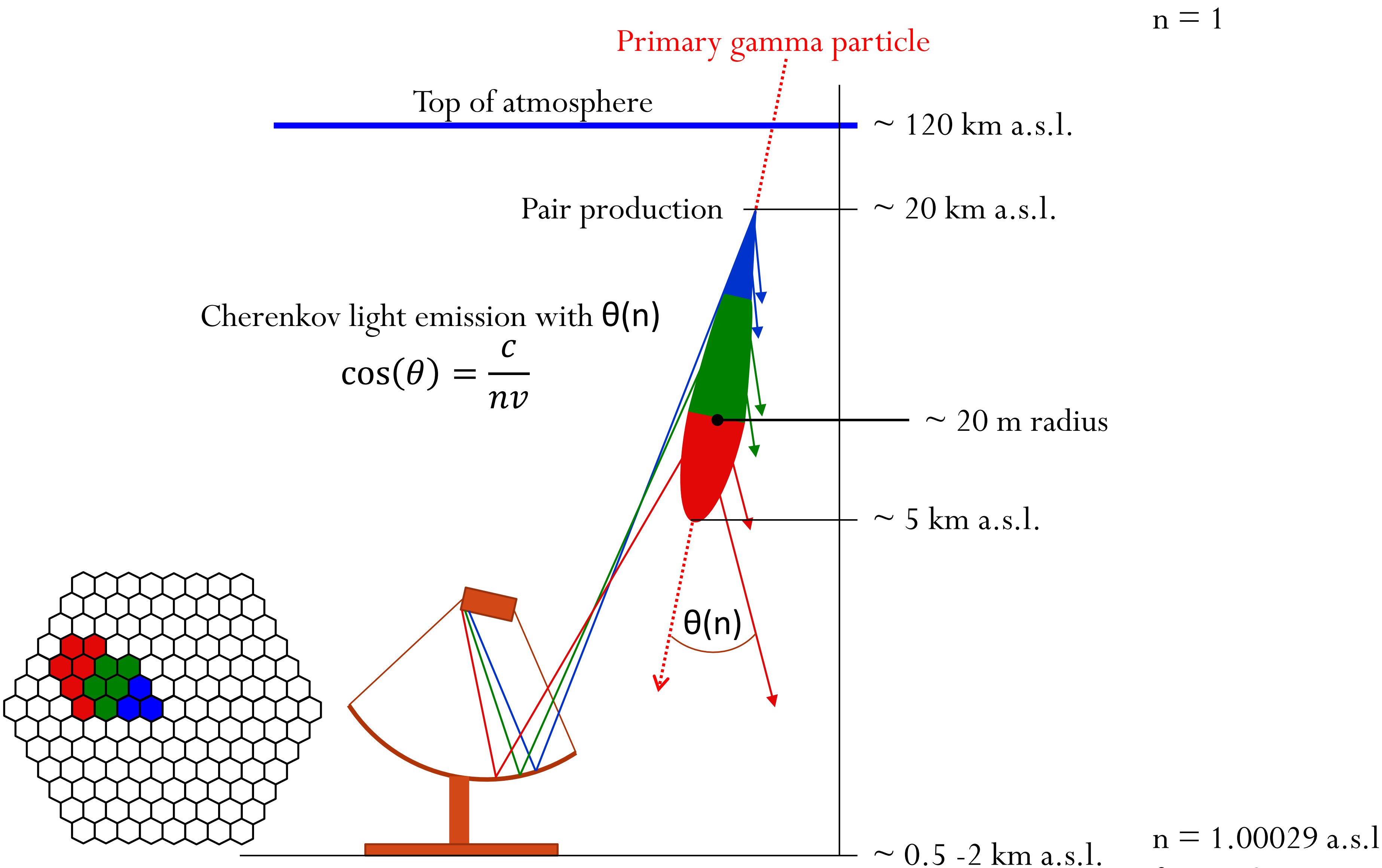
Mirror with Ø 12 m has 100 m^2 collection area





Cherenkov light
1 to >5000 photons/pixel

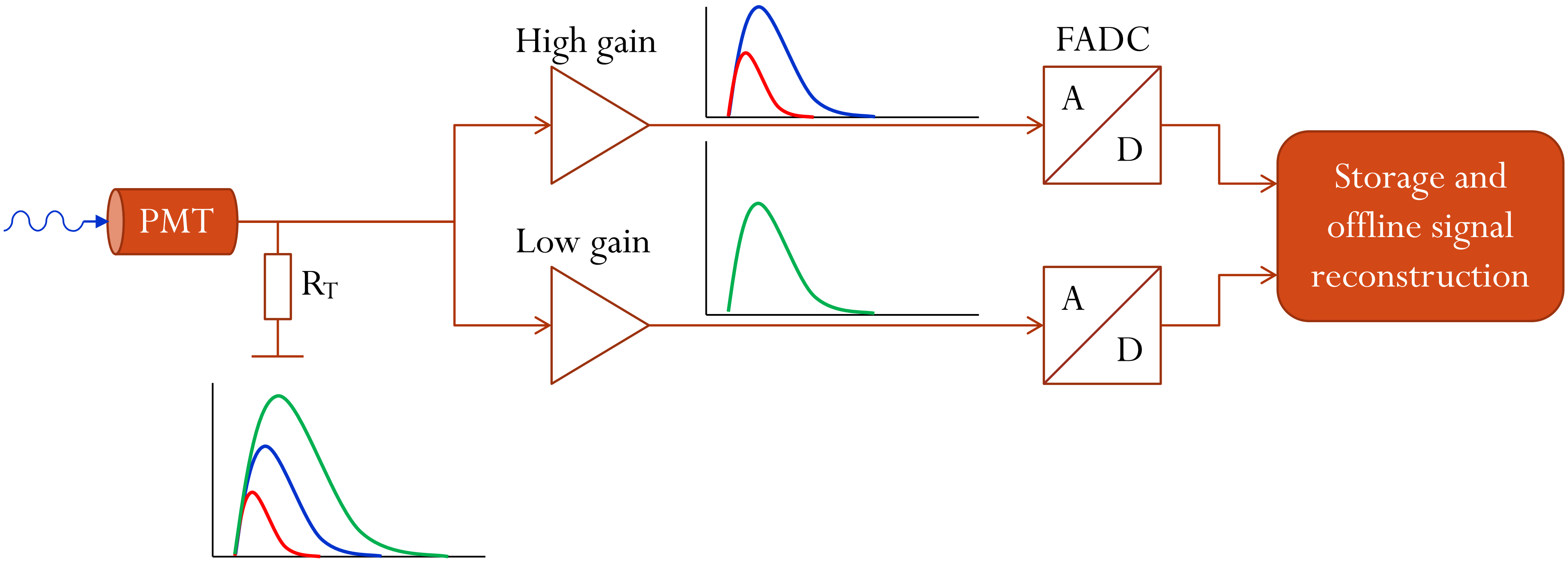
Working principle



Handling large dynamic signals

Large dynamic amplitude range can be treated in two ways:

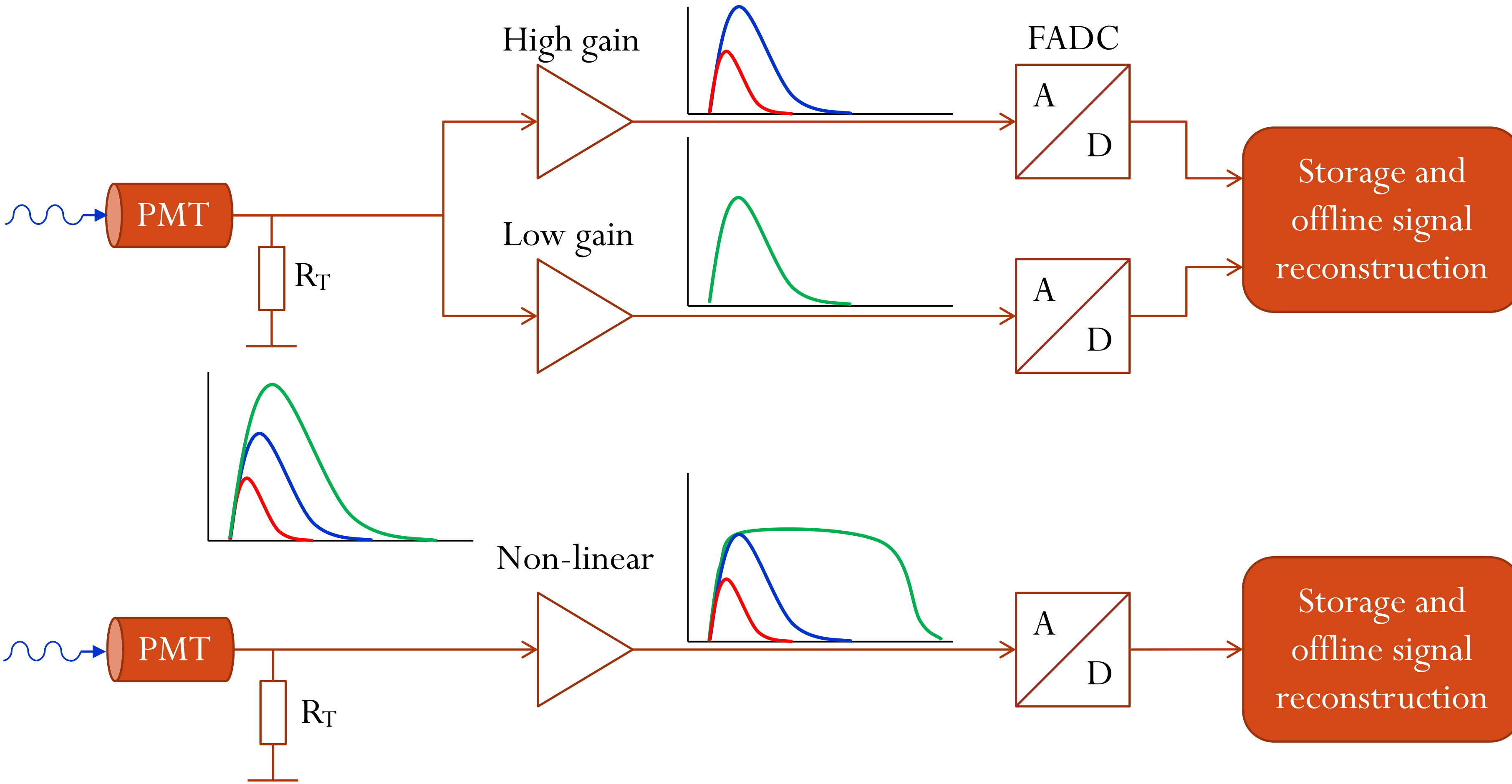
- dual signal path with
  - a high gain covering the low amplitude range (e.g. 0.2 – 200 pe) and
  - a low gain covering the high amplitude range (e.g. 20 – 5000 pe)



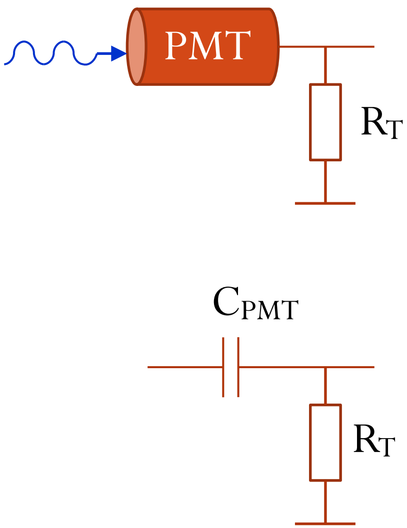
Handling large dynamic signals

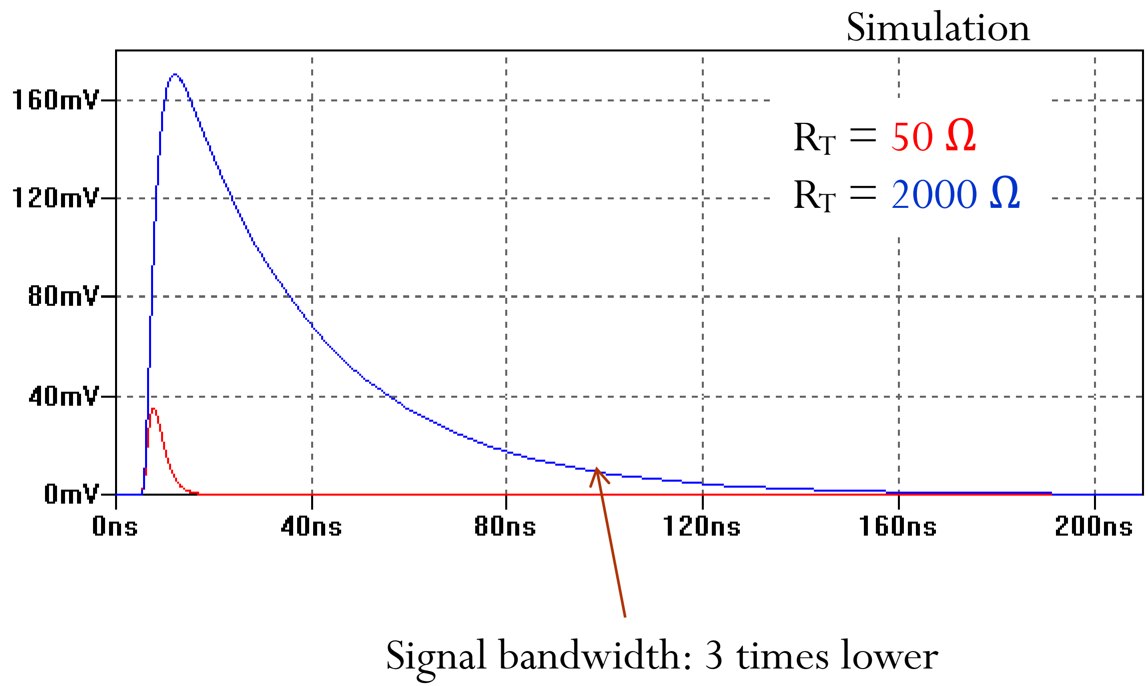
Large dynamic amplitude range can be treated in two ways:

- dual signal path with
  - a high gain covering the low amplitude range (e.g. 0.2 – 200 pe) and
  - a low gain covering the high amplitude range (e.g. 20 – 5000 pe)
- single signal path with **non-linear** signal treatment



Signal shaping





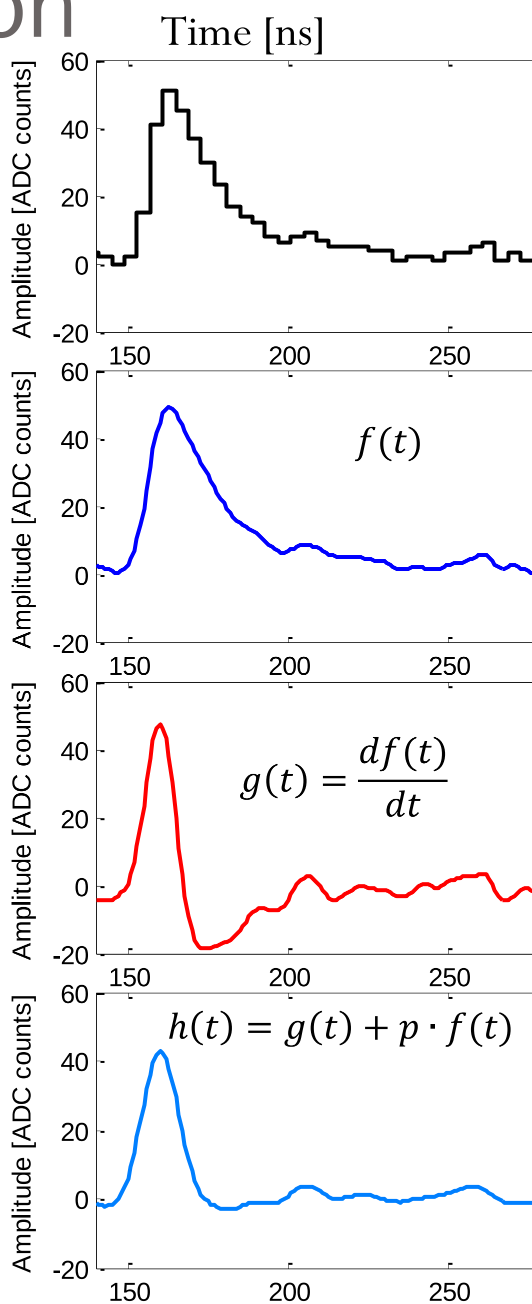
Termination resistor R_T influences signal bandwidth:

50 Ω versus 2000 Ω gives 3 times lower bandwidth

⇒ Larger termination resistor allows to digitize signals with a lower sampling rate (~ 3 times)

⇒ Use of reconstruction algorithm on digitized data still produces good timing and amplitude resolution

Signal reconstruction



1. Measured and digitized PMT signal (4 ns sample interval)

2. Up-sampling: linear interpolation (1 ns sample interval) and smoothing (moving average filter)

3. Differentiation and smoothing
   ⇒ Center of gravity above zero = photon arrival time

4. Base line restoration: pole-zero cancellation ($0 < p < 1$) and smoothing
   ⇒ Peak maximum = pulse amplitude
   ⇒ Peak area proportional to pulse amplitude

Signal reconstruction

1. Measured and digitized PMT signal (4 ns sample interval)

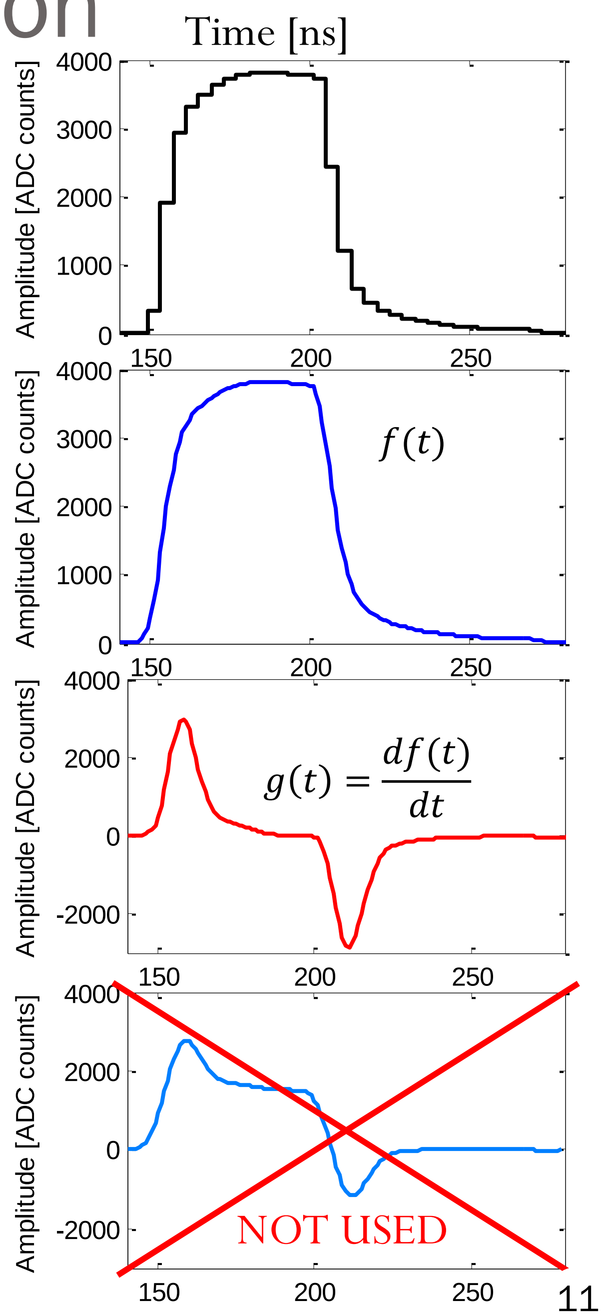
2. Up-sampling: linear interpolation (1 ns sample interval) and smoothing (moving average filter)

3. Differentiation and smoothing

   ⇒ Center of gravity above zero = photon arrival time

4. Amplitude determined by integration of up-sampled signal over fixed window size (typically 200 ns)

   ⇒ Peak area proportional to pulse amplitude: $A = \int_{k=i}^{i+200} f(t)\,dt$

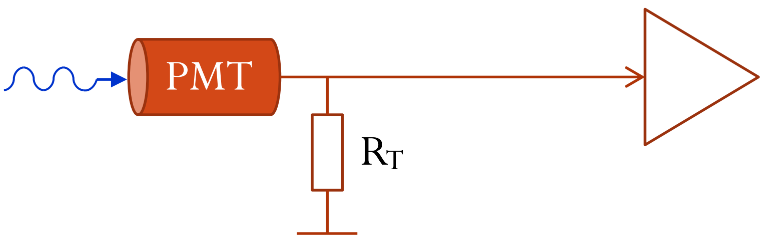


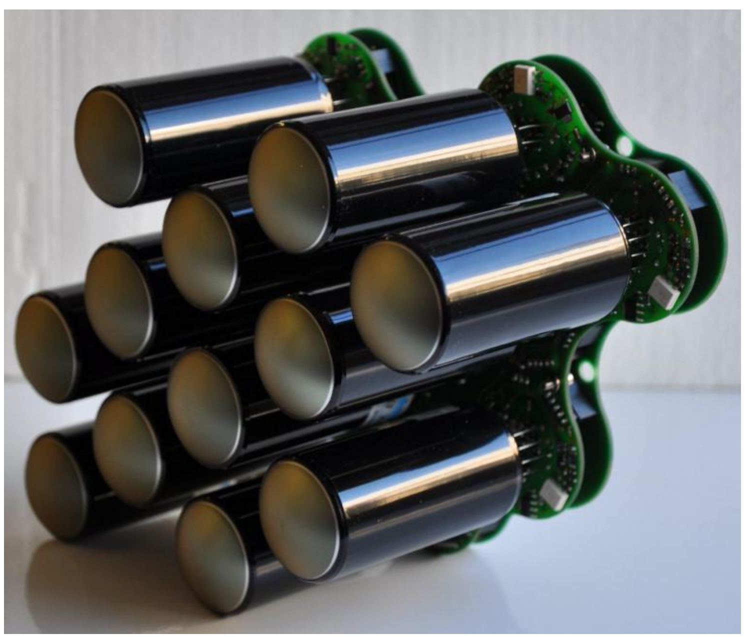
Towards a real camera…

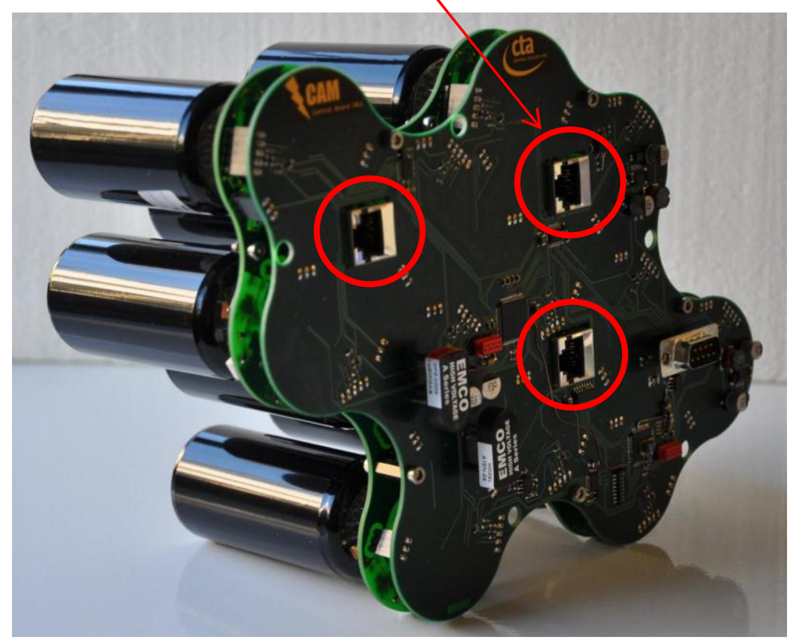
The Photo-Detector-Plane

Photo-Detector-Plane (PDP) consisting of:

- Photomultiplier
- Signal amplifier: analogue signal transmission over CAT5/6 cables
- HV generators: 500 and 1500 kV
- CAN bus for slow control



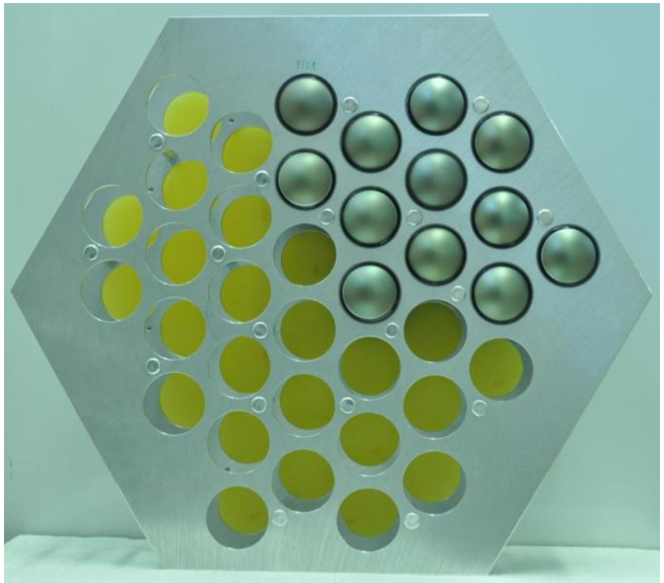




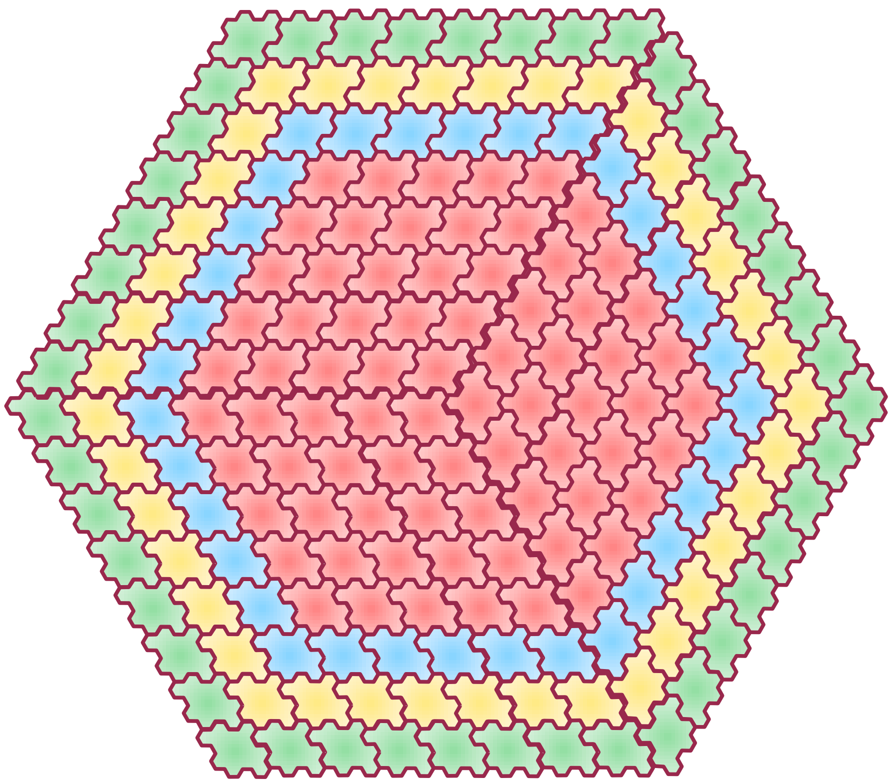
Developed and built at University of Zurich

The Photo-Detector-Plane

Lab test setup: PDP with 12 PMTs

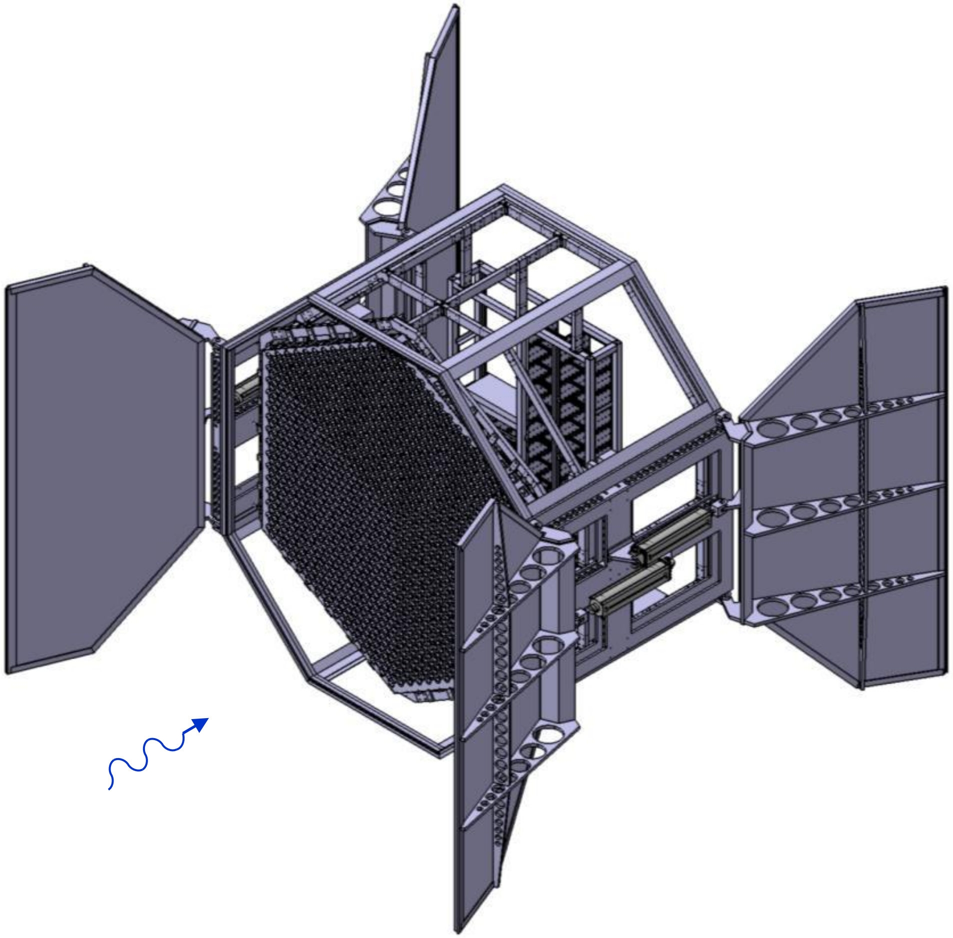


Possible PDP assemblies for different telescope sizes



- 900 pixel, 1550 mm flat to flat
- 1296 pixel, 1860 mm flat to flat
- 1764 pixel, 2170 mm flat to flat
- 2304 pixel, 2480 mm flat to flat

Mechanical structure

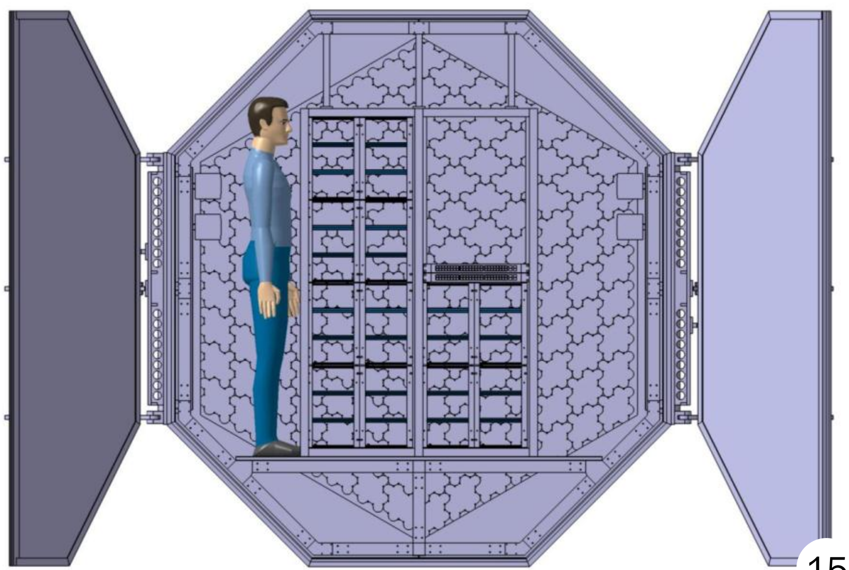


Design study by S. Steiner, UZH

A possible design of the mechanical structure

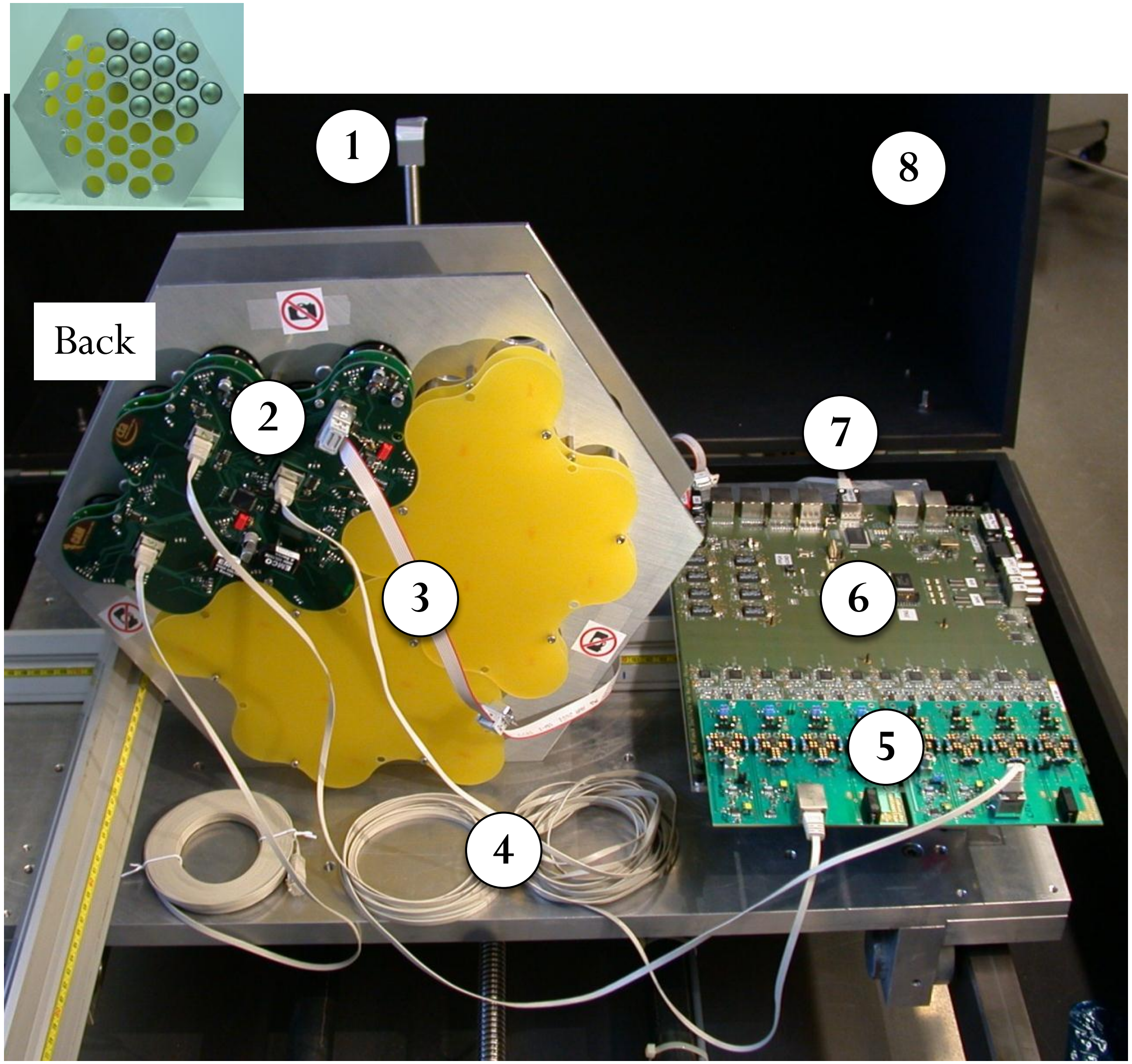
- ~2.7 m flat to flat
- ~2 m depth
- 1.7 t weight

Back view



Test camera setup

Front



1 Laser pulses fed in with optical fiber

2 Board with 12 PMTs

3 CAN bus (slow control + 24V)

4 Analogue pixel signal transmission via CAT 5 cables (1 cable per 4 pixels)

5 FADC drivers for 8 FADC

6 FPGA board

7 Event transmission via LAN to computer disk

8 Dark box

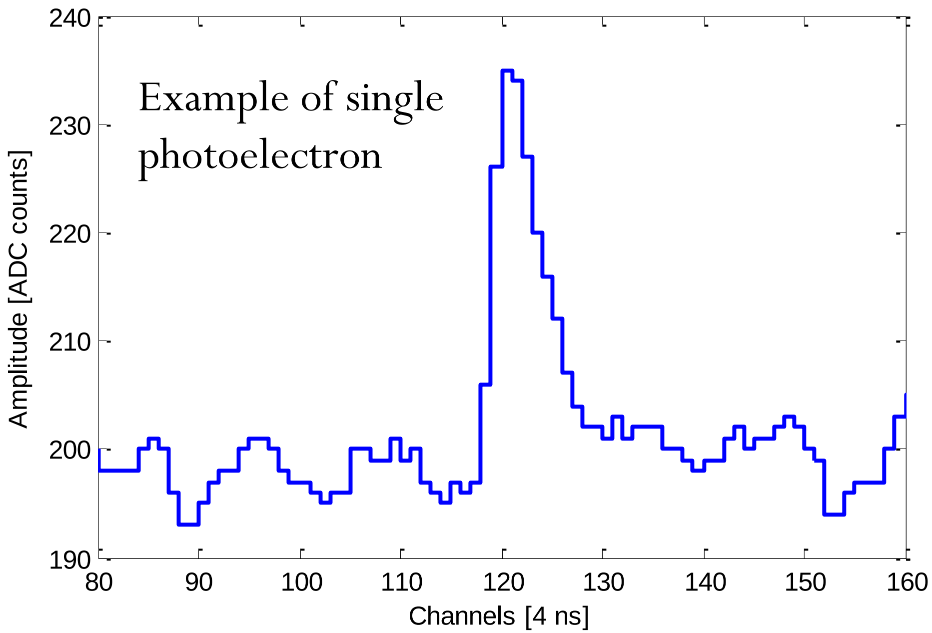
Not shown:

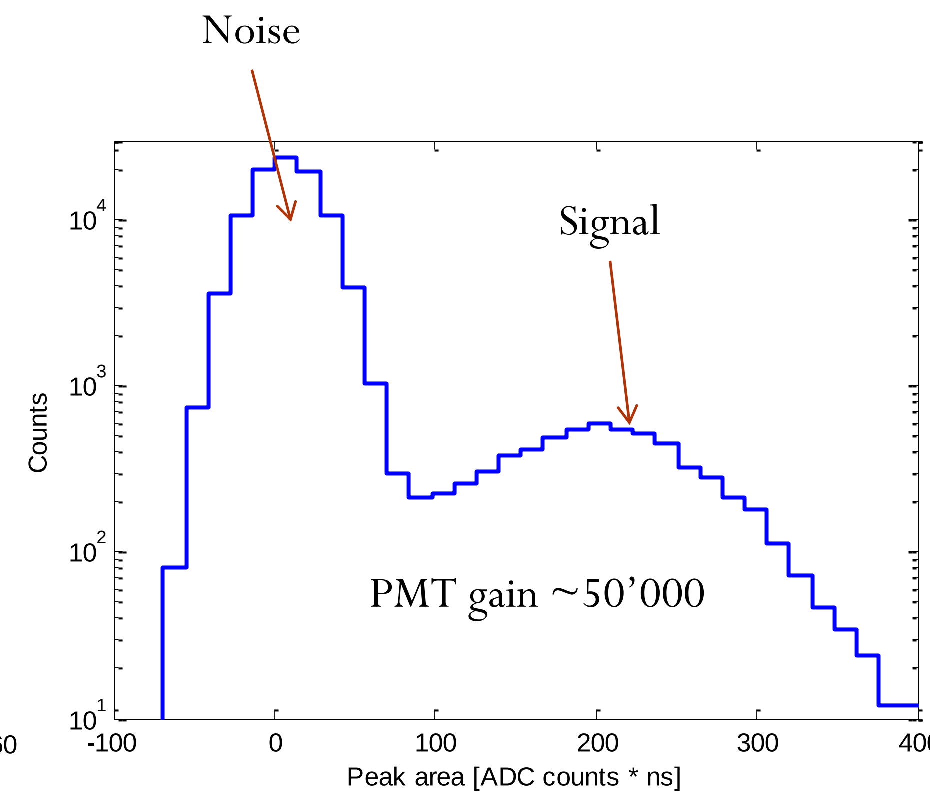
- PC with offline analysis software
- Slow control PC
- 24 V power supply

Single photoelectron response

Measured with:

- High voltage of (1000 ± 20) V
- Amplifier gain of 12

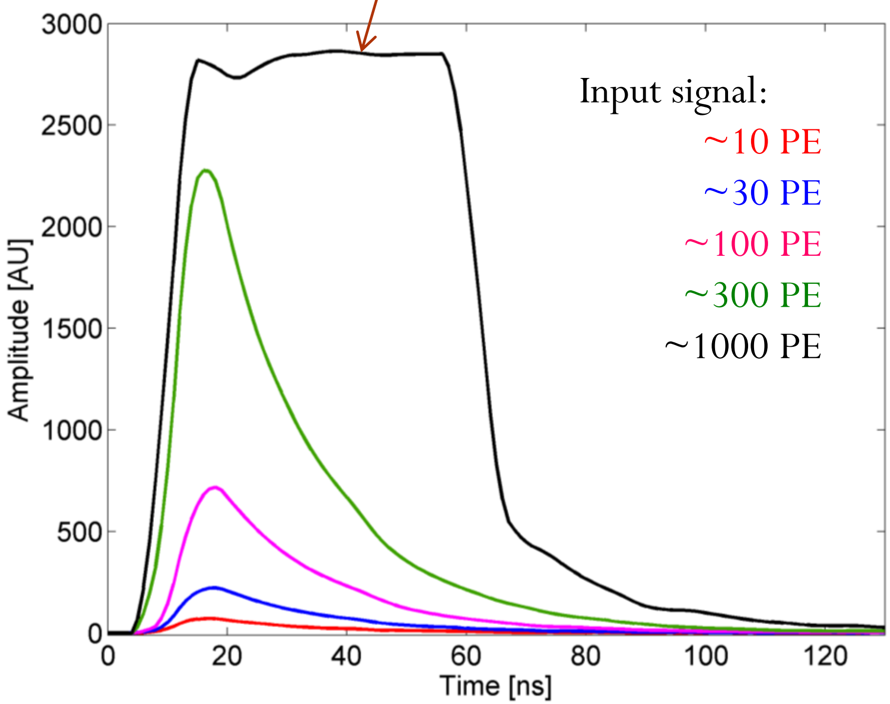




Full range resolution

Measurement of linearity with **electric pulser**

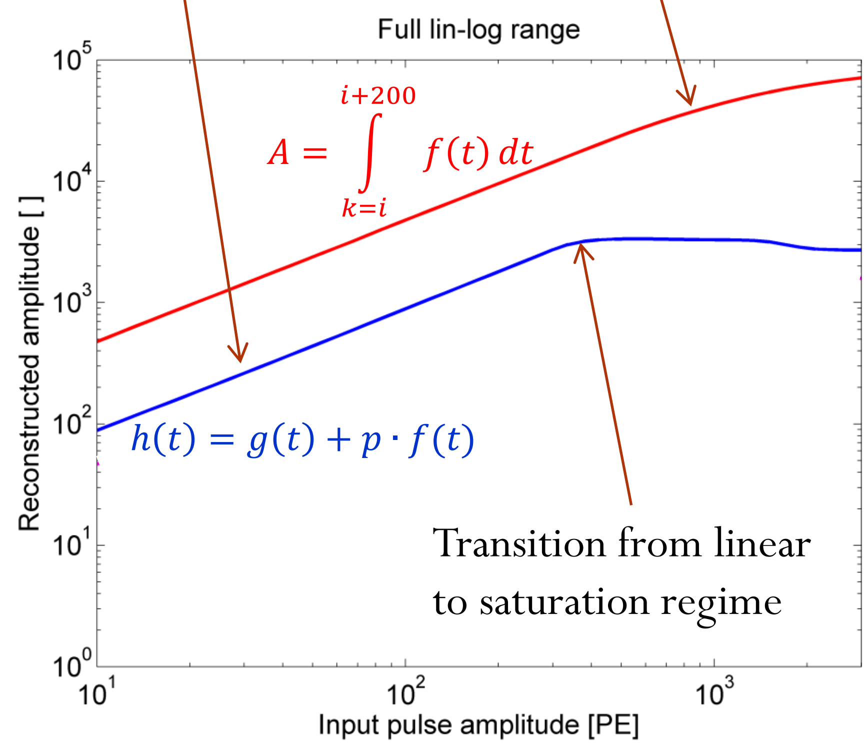
Output of preamplifier saturatates while input · gain is larger than output swing. Eventually, the output recovers as saturation conditions fail.



Measured signals, resolution 1 ns / sample

Pulse amplitude reconstructed by pulse area

Pulse amplitude reconstructed by pulse maximum



Transition from linear to saturation regime

Summary

- Investigation of a single signal path concept for signals with large dynamic range
- Development of signal reconstruction algorithms

- Advantages
  - Lower power consumption
  - Lower costs (everything is needed only once)
  - Digitized signals don't produce huge data streams

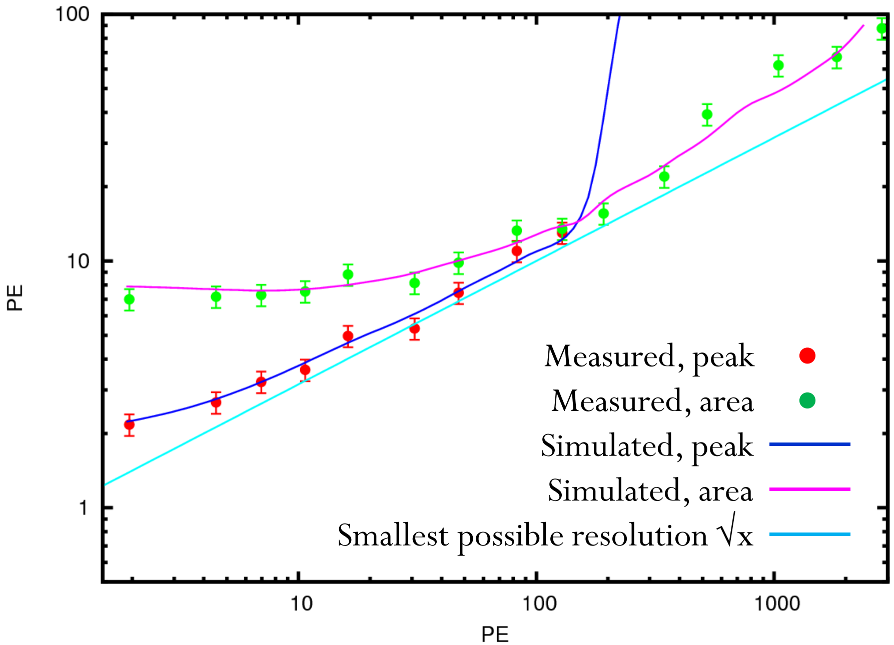
- Disadvantages
  - Amplitude and time resolution slightly worse than dual signal path concept

- Concept may be installed in first Cherenkov camera for the Cherenkov Telescope Array

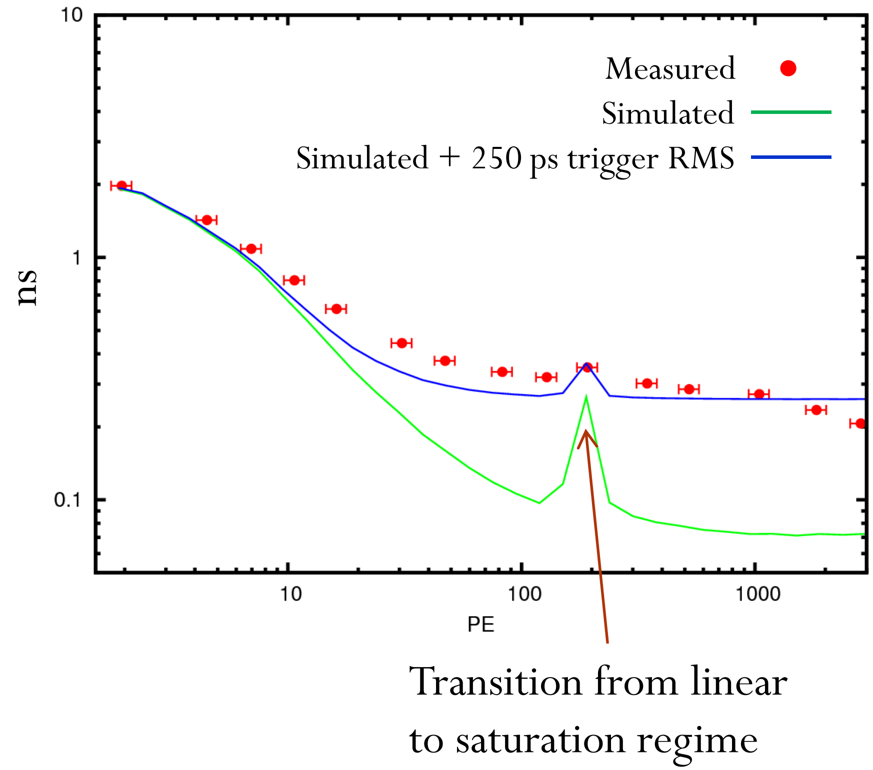
Full range resolution

Measurement of linearity with **pulsed laser**, light bulb as noise source (0.24 events / ns) and **PMT**

Amplitude resolution



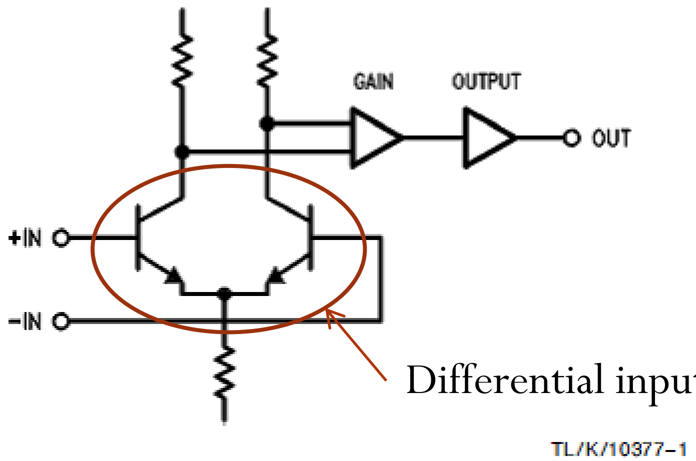
Time resolution



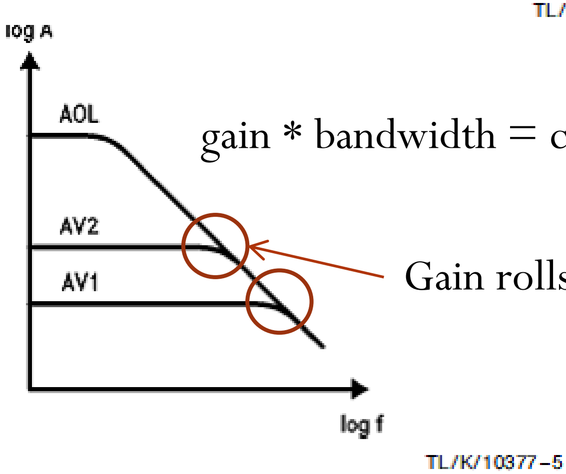
Simulation results kindly provided by T. Kihm

'*Non-linear*' amplifier

Voltage-feedback-operational-amplifier



Differential input stage

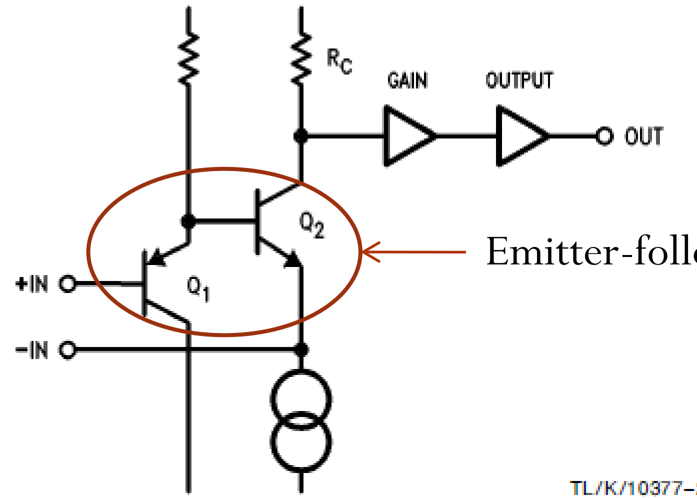


gain * bandwidth = const.

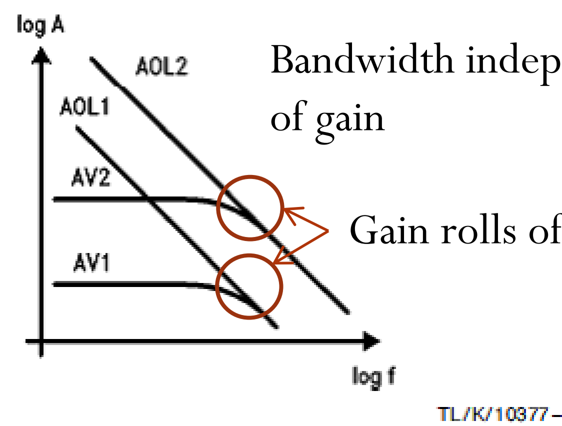
Gain rolls off earlier

$$\frac{U_{out}}{U_{in}} \sim \frac{1}{1 + \frac{1}{A_{OL}(j\omega)} \cdot \frac{R_F + R_G}{R_G}}$$

Current-feedback-operational-amplifier



Emitter-follower



Bandwidth independent of gain

Gain rolls off same

$$\frac{U_{out}}{U_{in}} \sim \frac{1}{1 + \frac{1}{Z_{TR}(j\omega)} \cdot R_F}$$