MPI für Physik und extraterrestische Physik

The MPI Semiconductor Laboratory

High speed, low noise, low power, radiation hard, high Q.E. .....

# Home made imaging X-ray detectors systems

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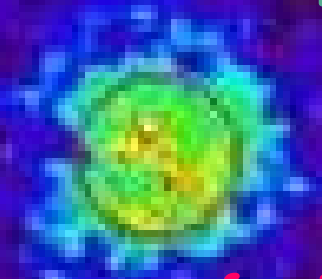
PNSensor GmbH

# OUTLINE

0. Silicon drift detectors for X-ray imaging and spectroscopy
1. The concept of fully depleted back illuminated column-parallel pnCCDs for X-ray spectroscopy and counting
2. Measured properties of pnCCDs as X-ray detector and imager
3. Properties of pnCCDs as detectors for optical and NIR light



4. The concept of active pixel sensors for X-rays
5. Design, layout, and fabrication of DEPFETs
6. Measured properties with DEPFETs
7. Single photon counting with linear DEPFET amplifiers
8. Detectors for future X-ray laser facilities
9. Conlusions

# Scope of the talk

1. X-ray detection from
   - from 50 eV to 30 keV
   - position, energy (or intensity) and time

2. Detection of optical photons (UV to NIR)
   - from 20 nm to 1100 nm
   - position, intensity, and time, single optical photons

3. Detection of particles
   - mips, protons, electrons, alpha particles, neutrons (recoil p), ions, …
   - position for mips, position and energy for alphas, energy and position for electrons, . . .

4. Gamma ray detection (thru coupling to scintillators)
   - energy, position, time, intensity
   - from 3 keV to 3 MeV (and above)

# What will be left out:

- Avalanche amplifying devices
- (Near-) Infrared detectors
- Blocked Impurity Band detectors
- Small-pixel optical detectors
- Tracking detectors
- Materials other than Silicon
- Macropixel detectors

# The Silicon Drift Detector Family

all based on SDD principle - sideward depletion (CHC > $10^6$ electrons)

## SDDs

sensitive area:
from 1 $mm^2$ to 55 $cm^2$

number of read nodes:
from 1 to 512

sensitive thickness:
d = 200 μm - 450 μm
0.1 keV < E < 30 keV

read noise: @ -15° C
@ 5 $mm^2$ from 5 e-
@ 1 $cm^2$ to 10 e-

Count rate per node: $10^6$

Avalanche amplifier: ok

Imaging if timing is available

γ-imaging if coupled to scintillators

## pnCCDs

sensitive area:
from 1 $cm^2$
to 40 $cm^2$

formats: 256x256 up to 512 x 1024
soon: 1024 x 1024
pix.size: 36-150 μm□

№ of read nodes:<1024

sensitive thickness:
d = 50 μm to 450 μm
0.1 keV < E < 30 keV

read noise: from 1.5 e- to 13 e- (@+10°C)

Avalanche amplifier: ok

readout speed: 1200 fps

## CDDs

sensitive area:
up to 3 $cm^2$

№ of read nodes: 200

sensitive thickness:
d = 450 μm
0.1 keV < E<30 keV

read noise: from 15 e- to 25 $e^-$
@ 100 kfps
and @ 25° C

Imaging: no external trigger needed

Avalanche ampl.: ok

readout speed:>100 kfps

## DEPFETs

sensitive area:
from 0.2 $cm^2$
to 1 $cm^2$

formats: from 64 x 64 to 128 x 128
soon: 256x256 or $512^2$
pix. size: from 25μm□ to 1.000 μm□

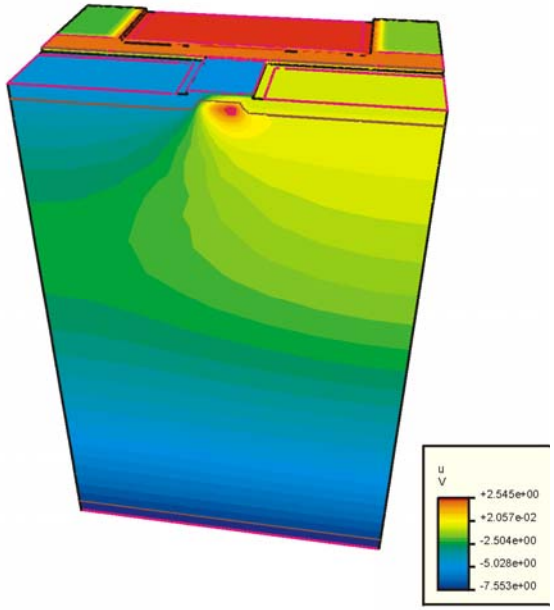
№ of read nodes:
up to 512

sensitive thickness:
d = 450 μm
0.1 keV < E <30keV

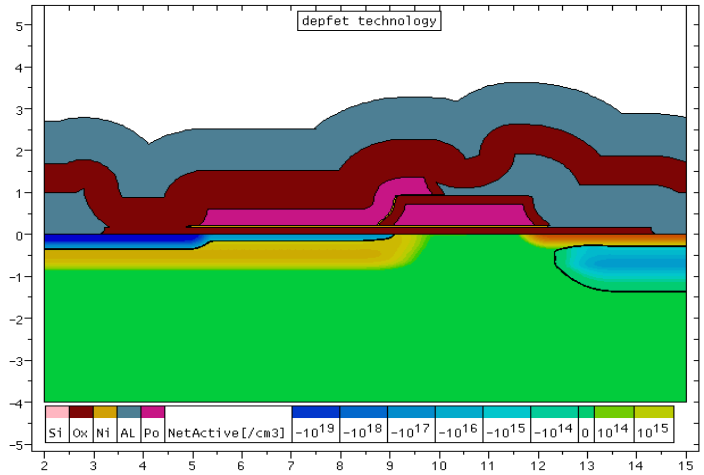
read noise: from 0.2e- to 10 e- (@+10°C)
readout speed: 1500fps

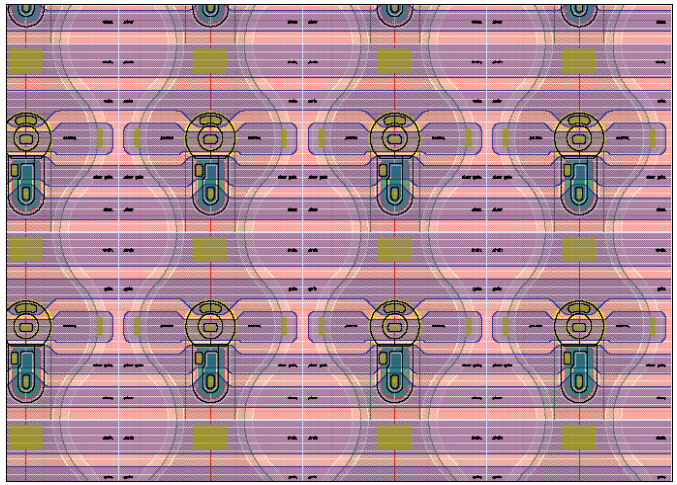
# Detector and electronics simulation and layout

1. The detector idea: simulation of electrical properties



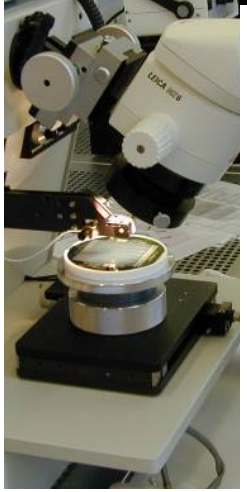

2. Simulation of the production process



3. Design and layout of the entire detetor system, including signal processing and DAQ

# The location



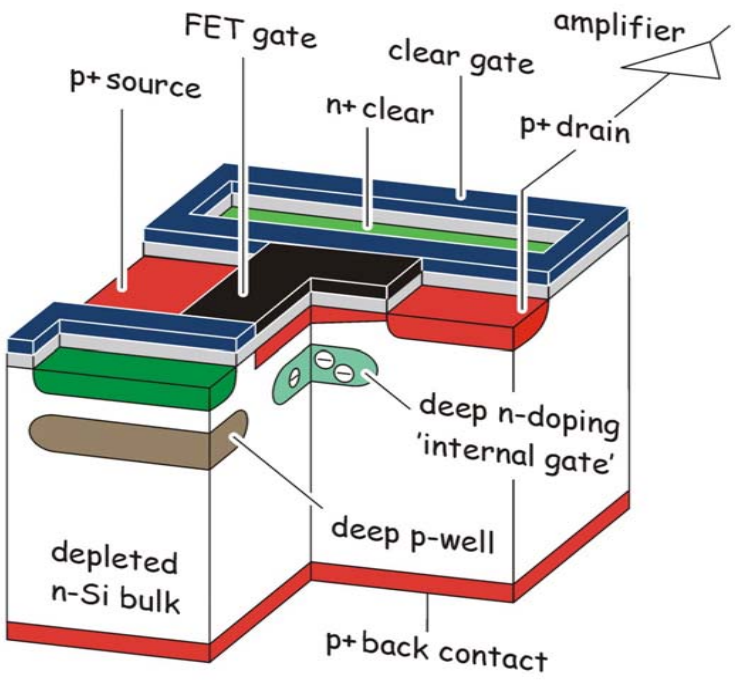
Qu

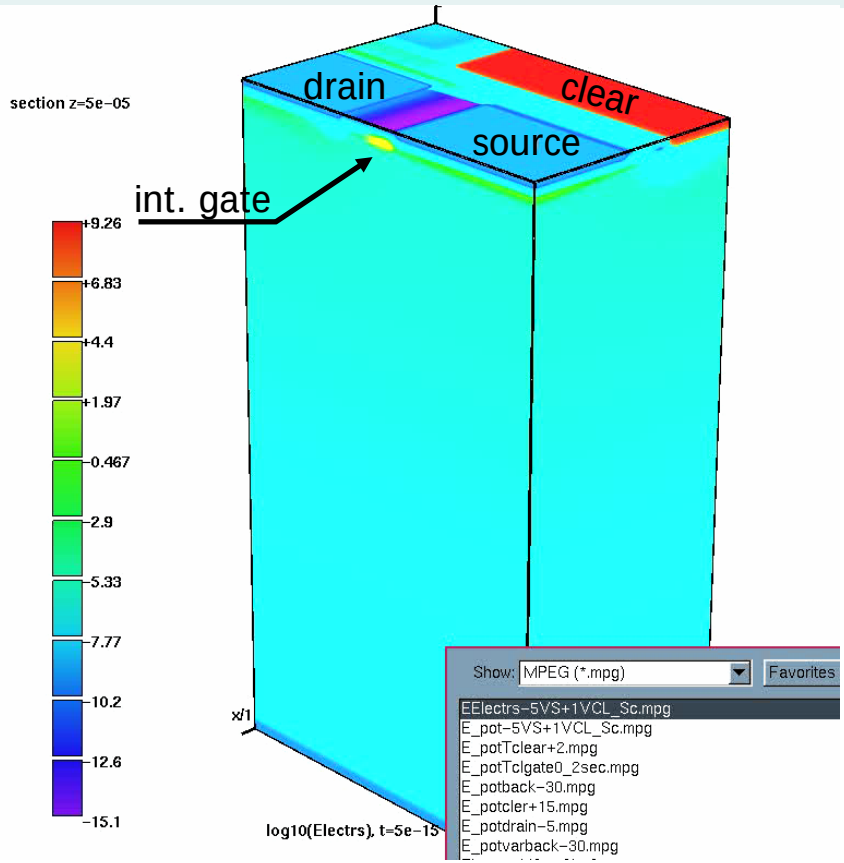
or, Munich, germany

Dicing, r

Device tests and operation

# 3-dim simulation of the DEPFET

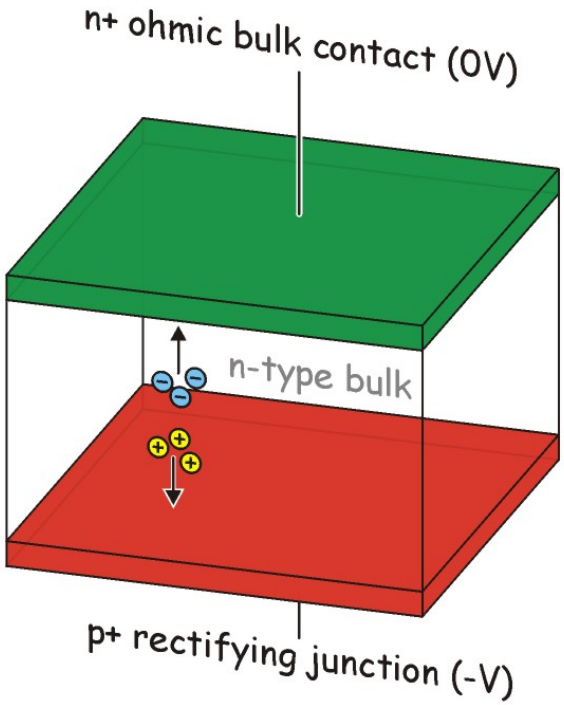



TeSCA 3D Simulation by K.Gärtner, WIAS, Berlin

- fully depleted sensitive volume
- internal amplification
- Charge collection in "off" state, read out on demand

# planar diodes — measururing single and multiple X-rays




electronic noise

$$ENC = \sqrt{\underbrace{a\frac{2kT}{g_m}C_{tot}^2 A_1 \frac{1}{\tau}}_{\text{thermal noise}} + \underbrace{2\pi a_f C_{tot}^2 A_2}_{\text{1/f noise}} + \underbrace{qI_L A_3 \tau}_{\text{leakage}}}$$

optimum shaping time

$$\tau_{opt} = \sqrt{\left[\frac{2A_3}{A_1}\right]\left[\frac{kT}{q}\frac{C_{tot}^2}{I_L}\frac{2}{3g_m}\right]}$$

» For

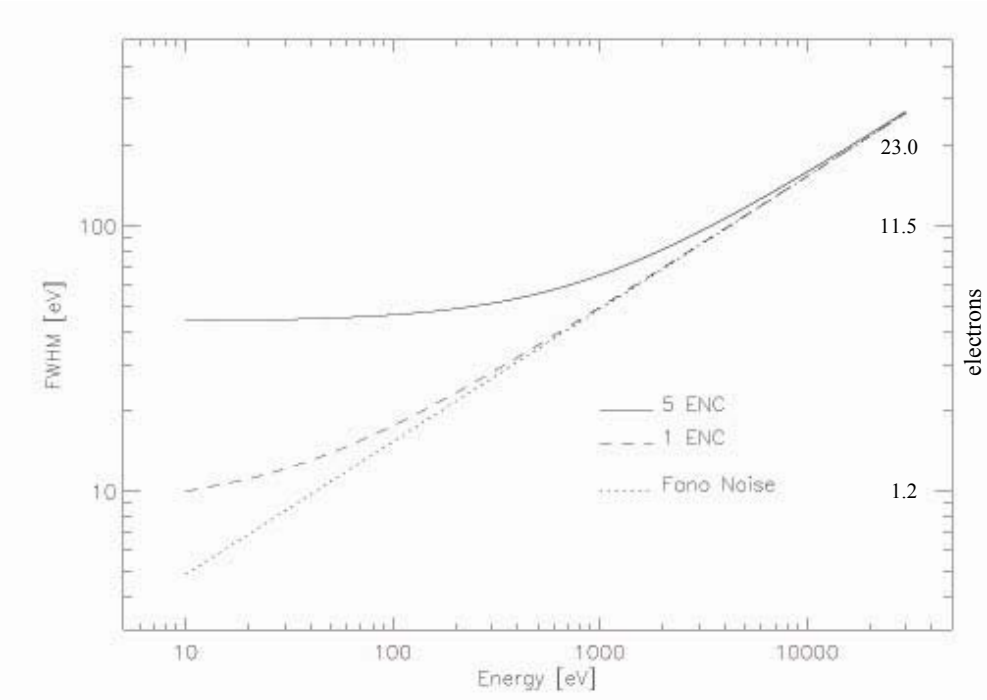
- **good resolution**
- **high count rate capability**

the total capacitance must be minimised!!

» Energy to create 1 e – h pair: 3.65 eV (in Si)

- **@ 10 keV: 2740 $e^-$ ± 18 e-**
- **@ 277 eV: 76 $e^-$ ± 3 e-**

# Limits of energy and counting resolution of X-rays



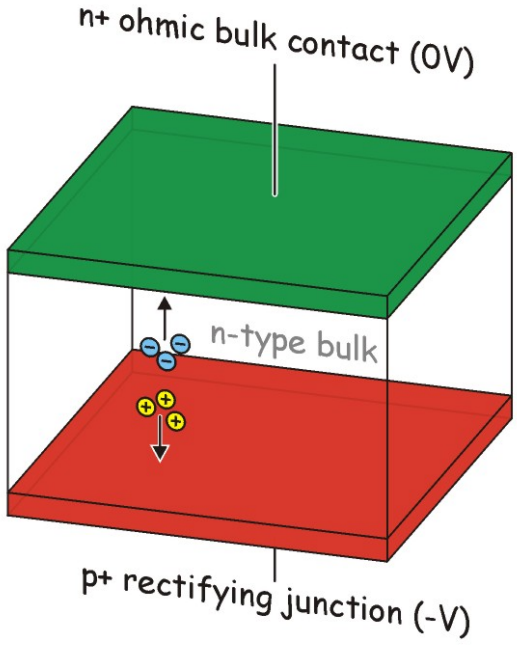

$$\mathrm{ENC}^2_{\mathrm{fano}} = \frac{F \cdot E}{w}$$

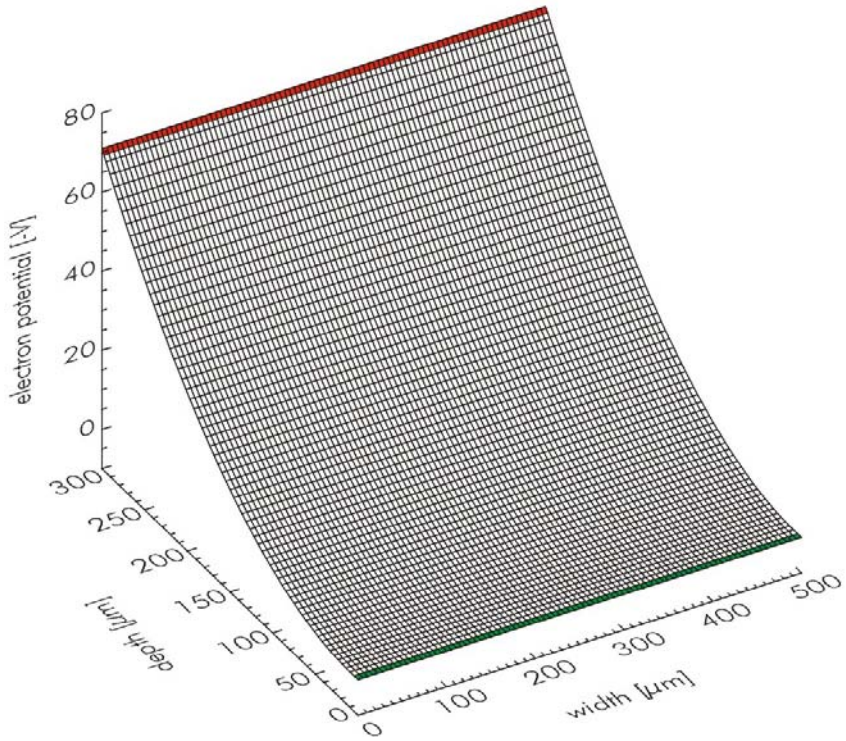
$$\mathrm{ENC}^2_{\mathrm{trans}} \approx (1 - \mathrm{CTE})\, \mathrm{N}_{\mathrm{trans}}$$

$$\mathrm{ENC}^2 = \left(\alpha \frac{2kT}{g_m} C^2_{tot} A_1\right)\frac{1}{\tau} + \left[\left(2\pi a_f C^2_{tot} + \frac{b_f}{2\pi}\right)A_2\right] + A_3\left(qI_l + \frac{2kT}{R_f}\right)\tau$$

$$ENC^2_{tot} = ENC^2_{el} + ENC^2_{fano} + ENC^2_{trans} + \ldots = (0.1\ e^- - 5\ e^-)^2$$

# Diode type detectors

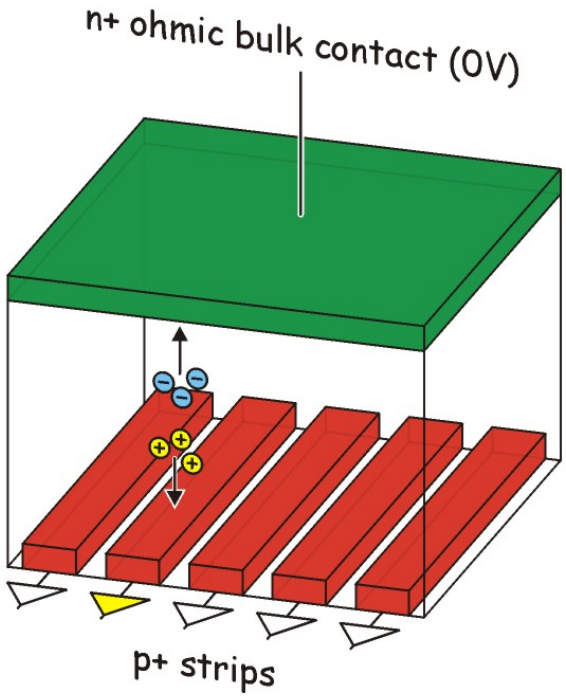


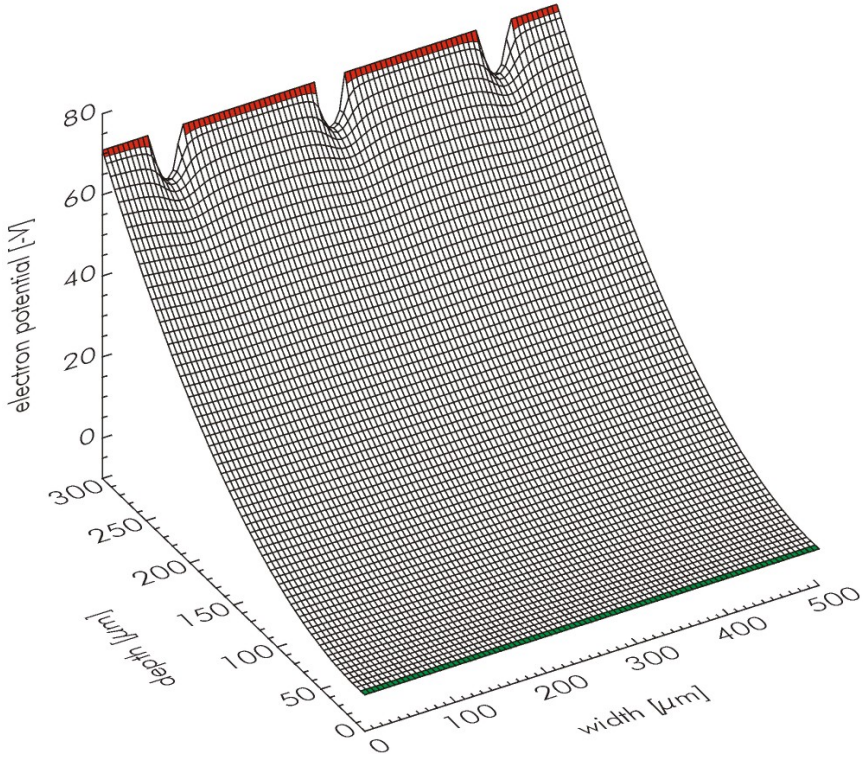




$$C = \frac{A\varepsilon_r\varepsilon_0}{d}$$

$$d = \sqrt{\frac{2\epsilon\epsilon_0(N_\mathrm{A}+N_\mathrm{D})}{qN_\mathrm{A}N_\mathrm{D}}(V_\mathrm{bi}-V)}$$

# Structured Diode – Strip Detector

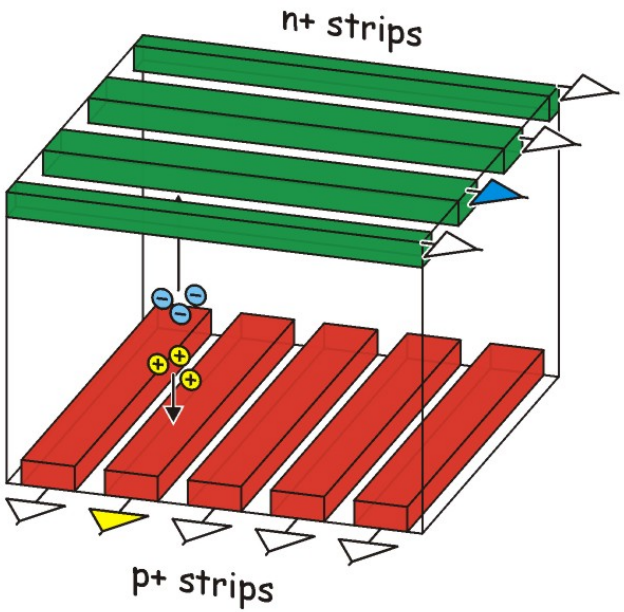


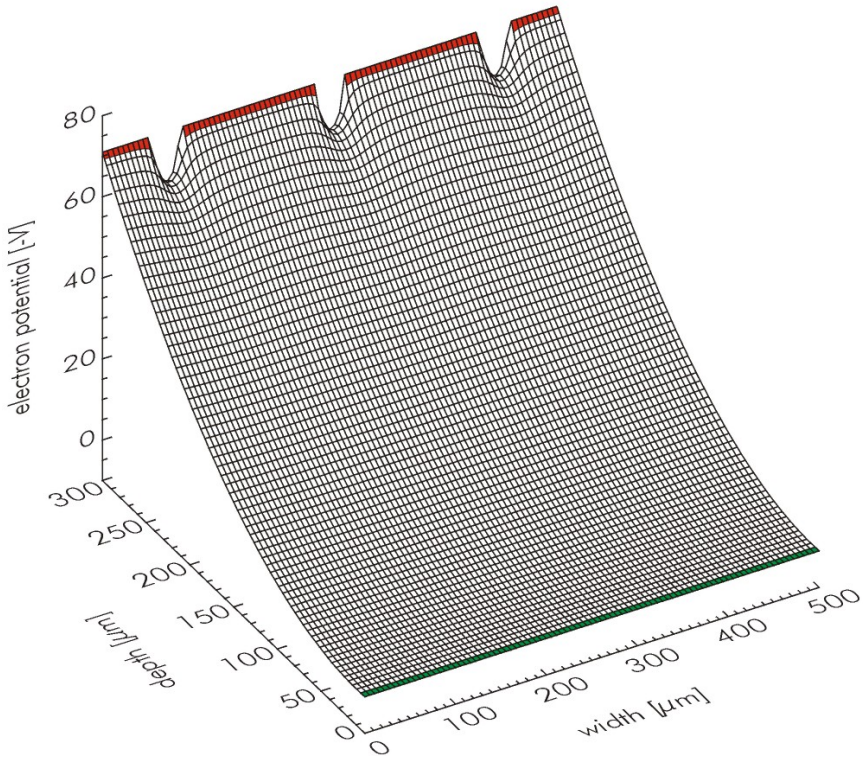




particle tracking = detection of individual charged particles

1D resolution

# Structured Diode – Strip Detector

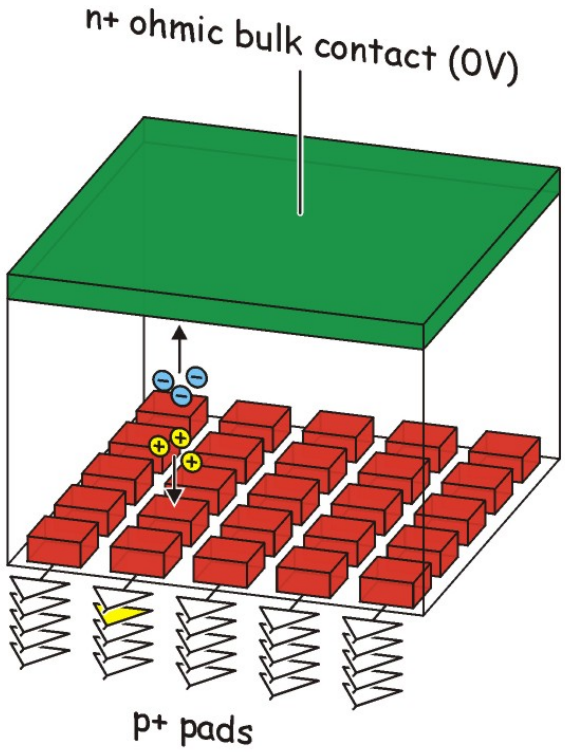


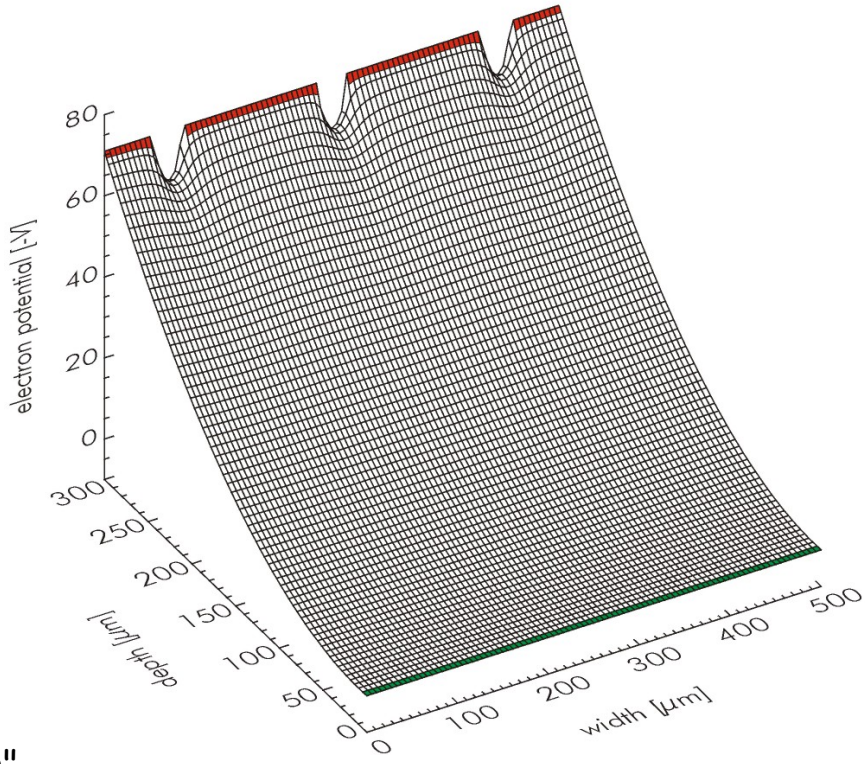

particle tracking

2D resolution

# Structured Diode
# Pad Detector / Pixel Sensor



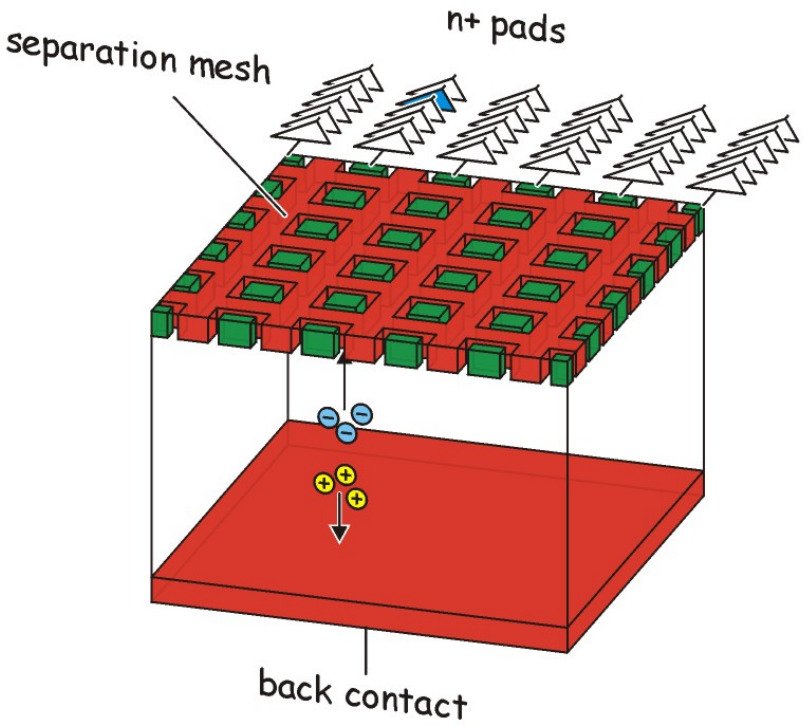

"p on n"

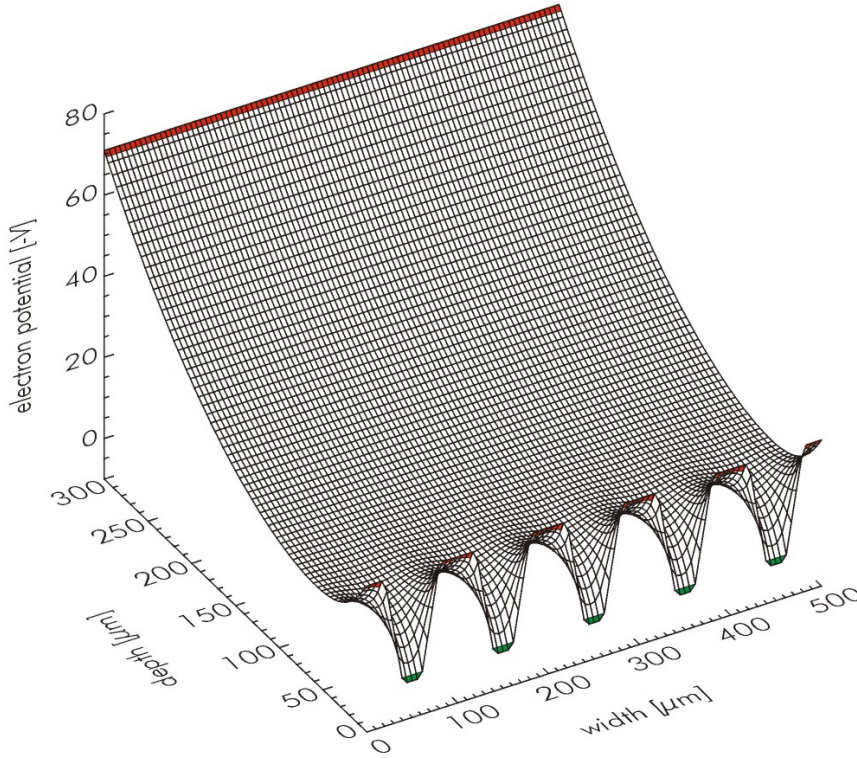



2D resolution

- particle tracking = detection of individual charged particles
- imaging = count / integrate particles or photons

# Structured Diode
# – Pad Detector / Pixel Sensor



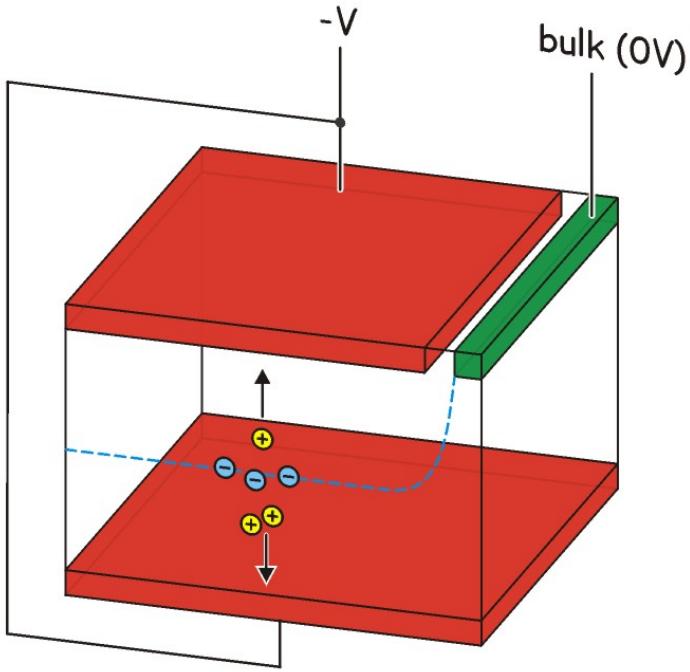




"n on n"

2D resolution

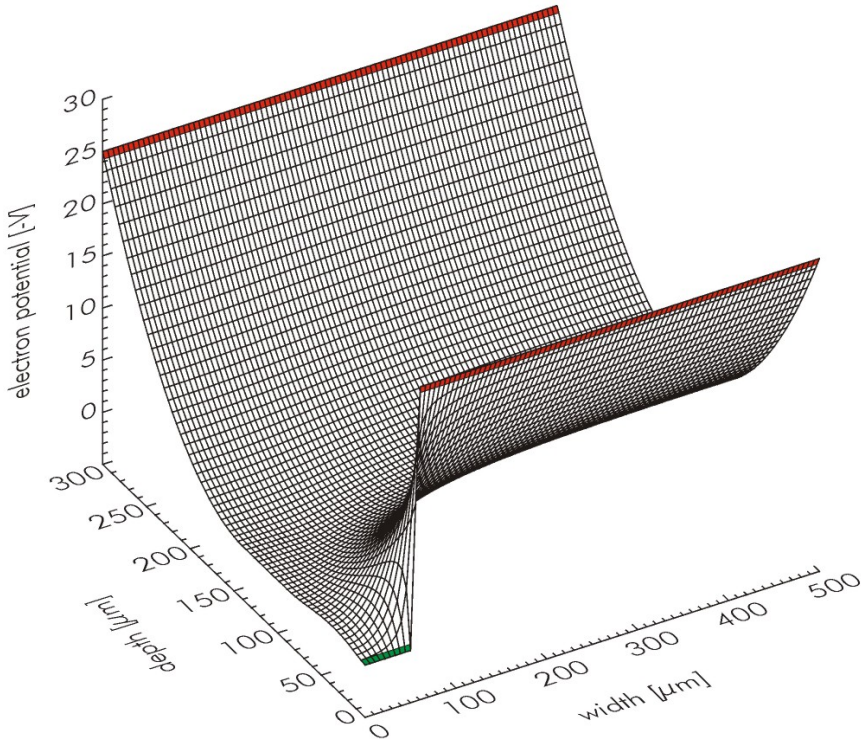
- particle tracking = detection of individual charged particles
- imaging = count / integrate particles or photons

# Sideward Depletion Structure



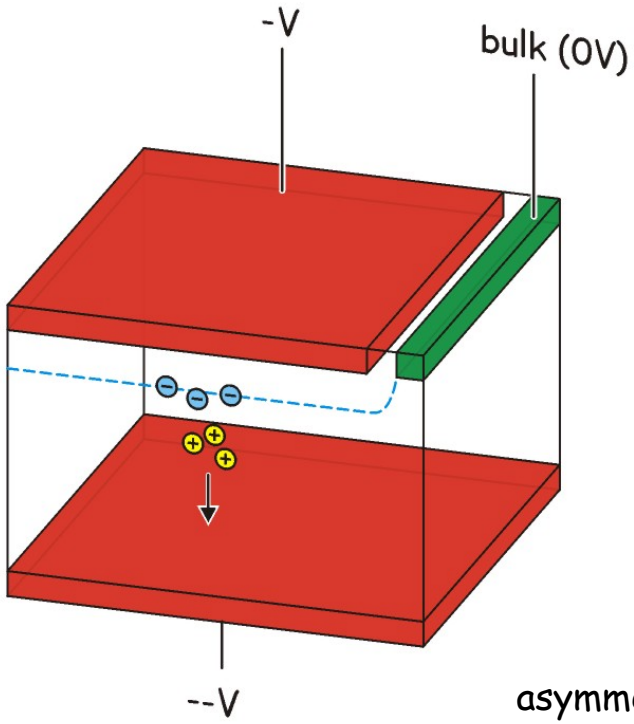

symmetric bias

Emilio Gatti & Pavel Rehak, 1983



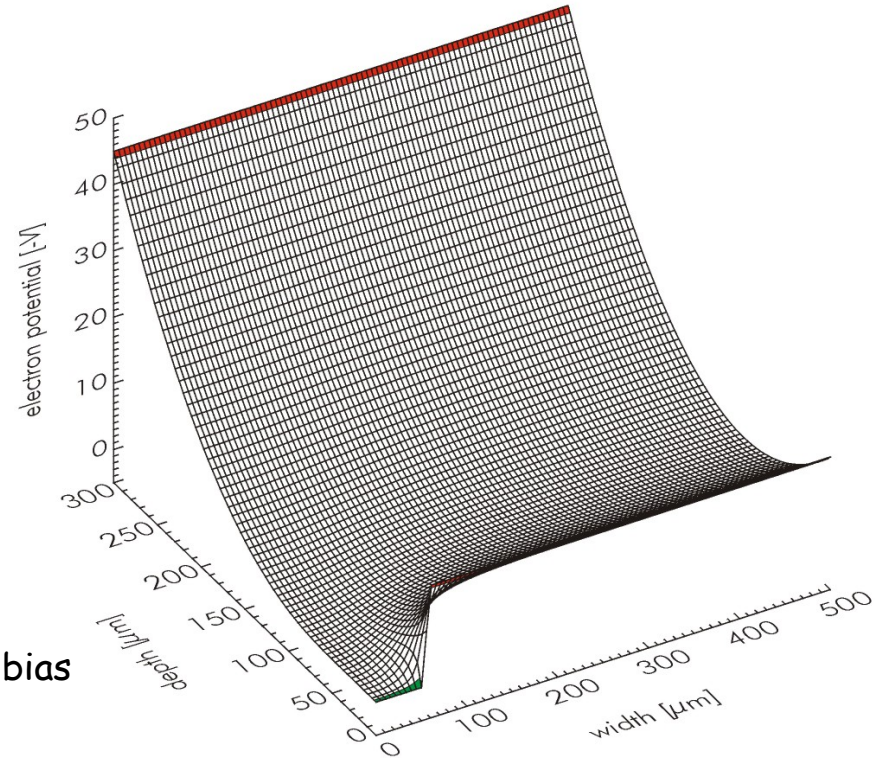

- fully depleted volume
- minimum capacitance of bulk contact (independent of sensitive area)

# Sideward Depletion Structure




asymmetric bias

Emilio Gatti & Pavel Rehak, 1983

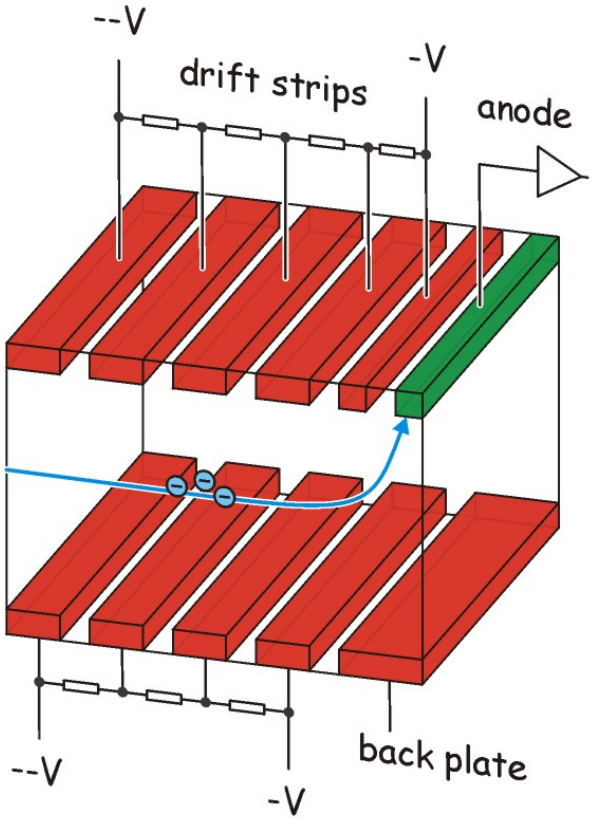



- fully depleted volume
- minimum capacitance of bulk contact (independent of sensitive area)

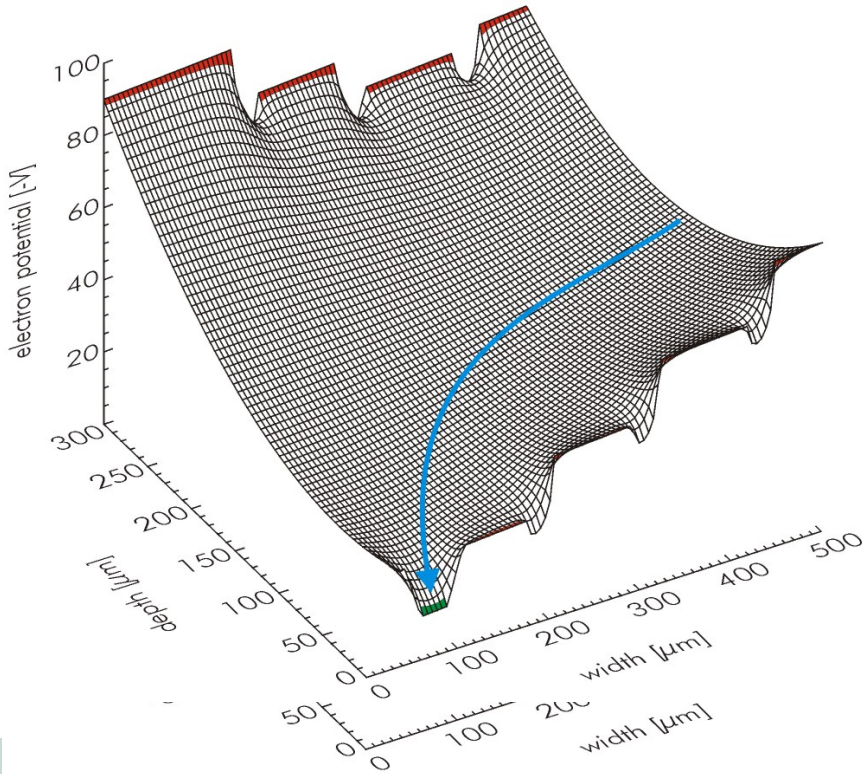
?? signal extraction ??

» advanced detector concepts

# Silicon Drift Detector (SDD)

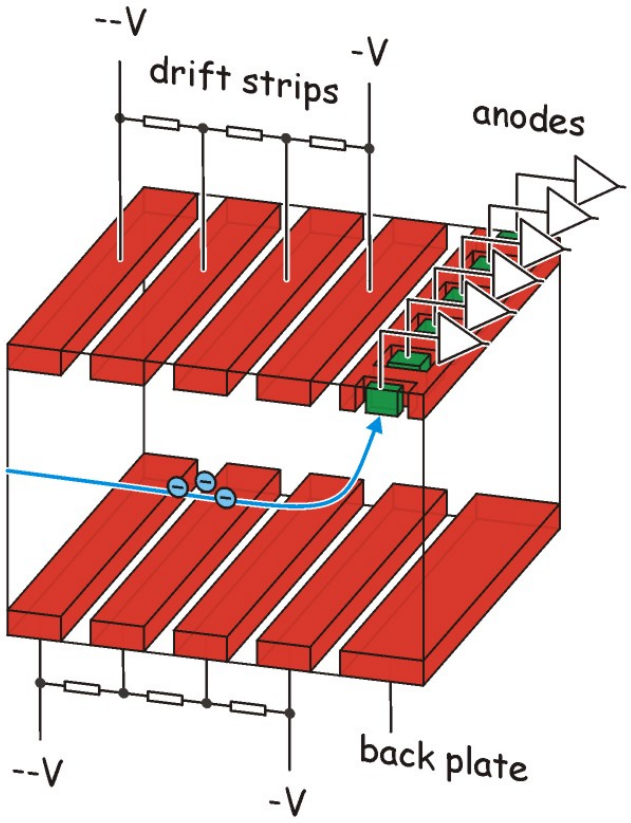



Emilio Gatti & Pavel Rehak, 1984

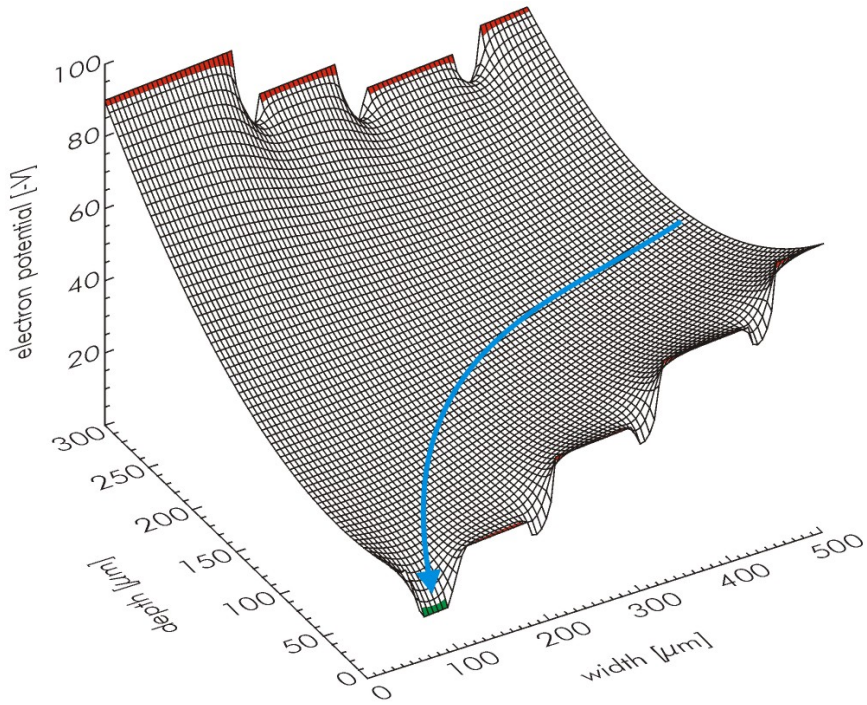



- drift field || surface
- 1D position resolution by drift time measurement start trigger!!

# Silicon Drift Detector (SDD)




Emilio Gatti & Pavel Rehak, 1983

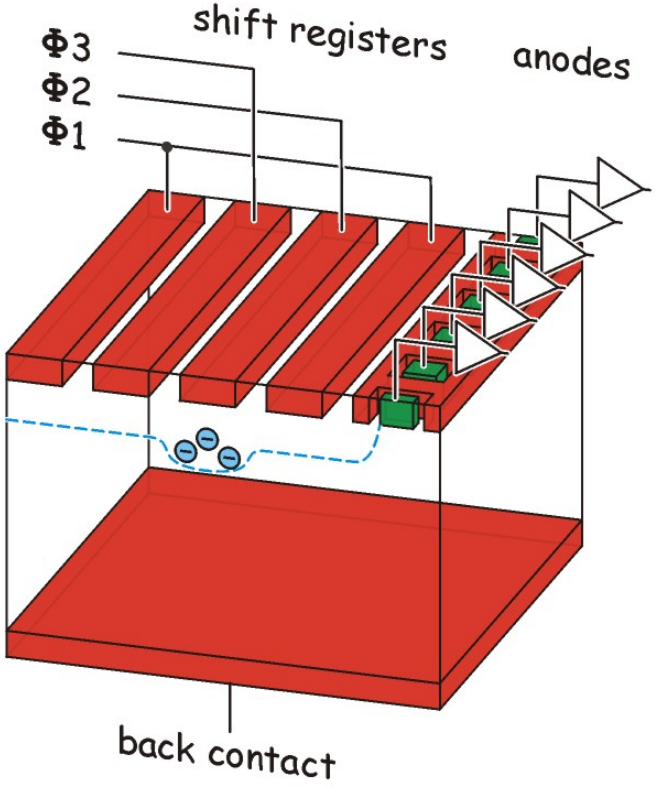


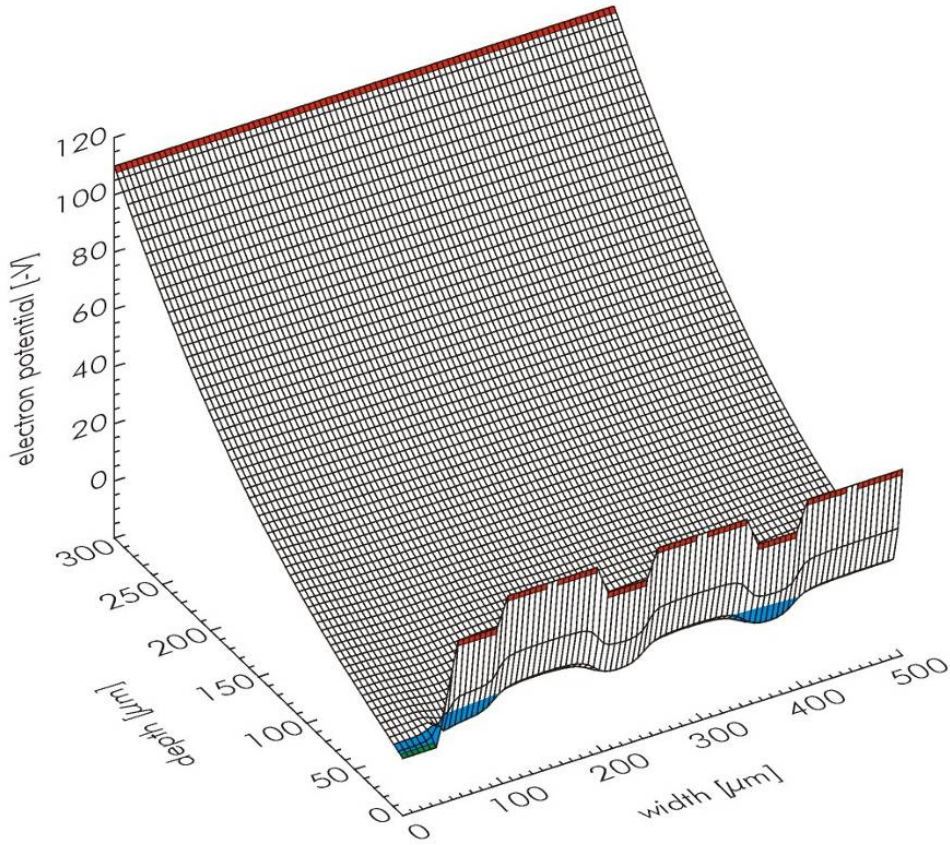

2D position resolution by

- drift time measurement
- segmentation of the anode

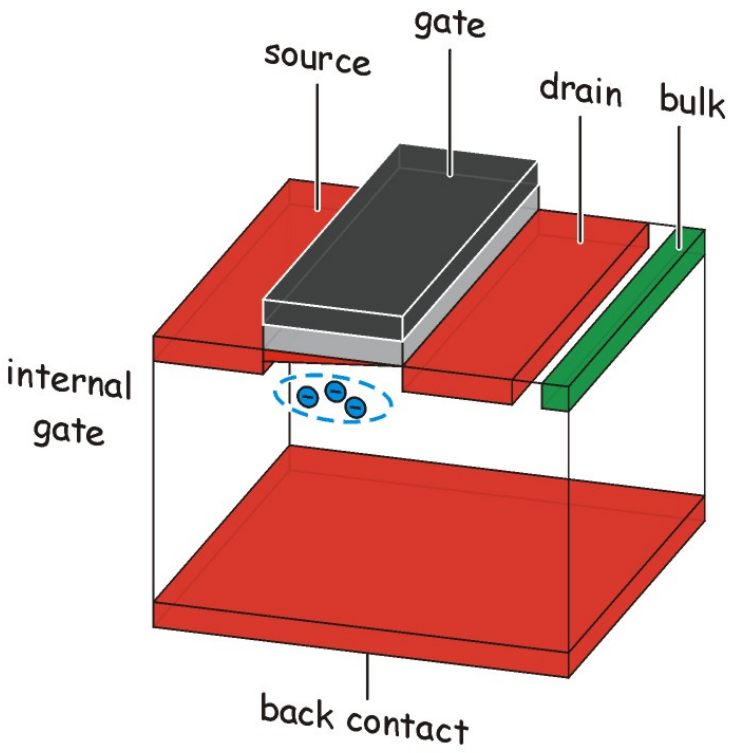
# From SDDs to pnCCDs

L. Strüder et al., 1984



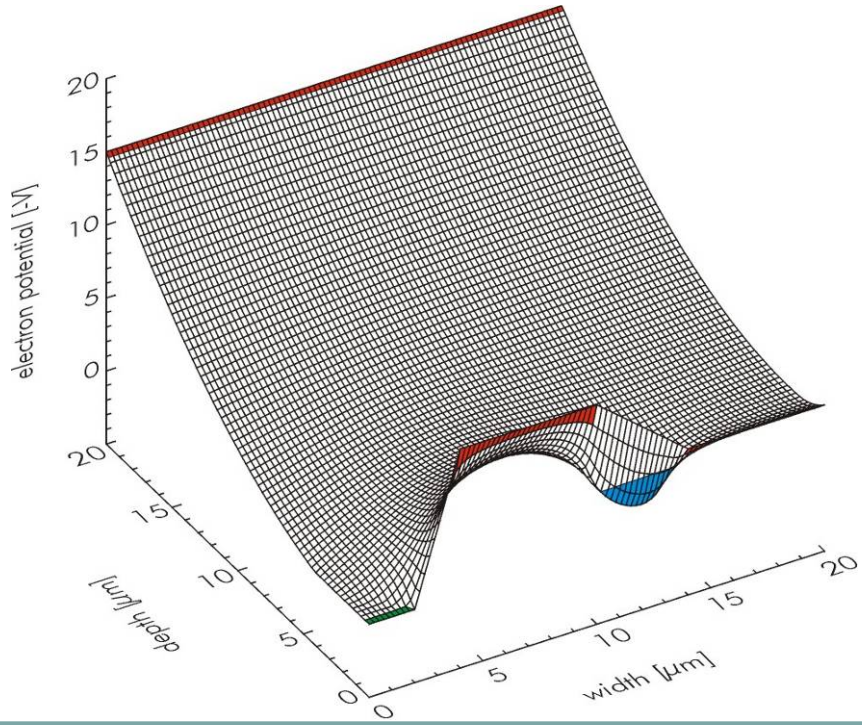
# The DEPMOSFET active pixel sensor



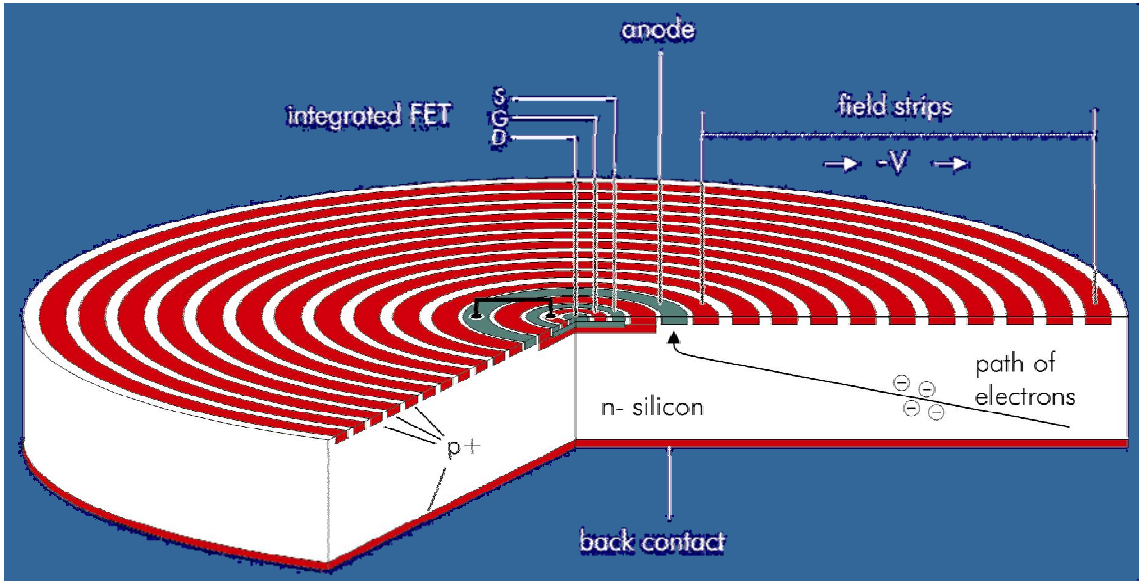

**1 electron increase current by 0.3 nA to 1 nA**

**electrons stored in the internal gate increase source-drain current**

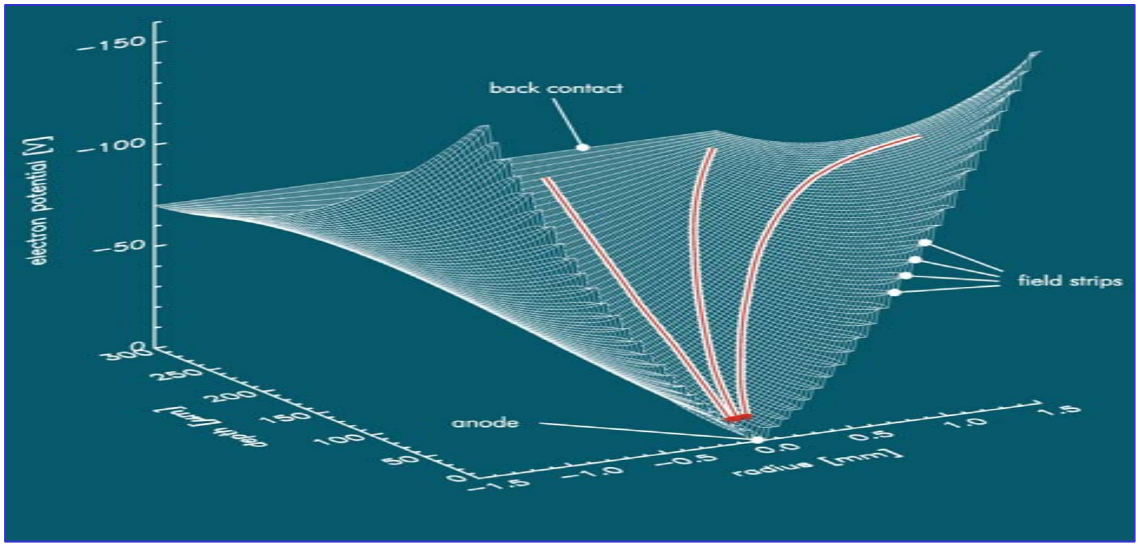
*G. Lutz and J. Kemmer, 1984*



# SDDs for astrophysics and industrial applications



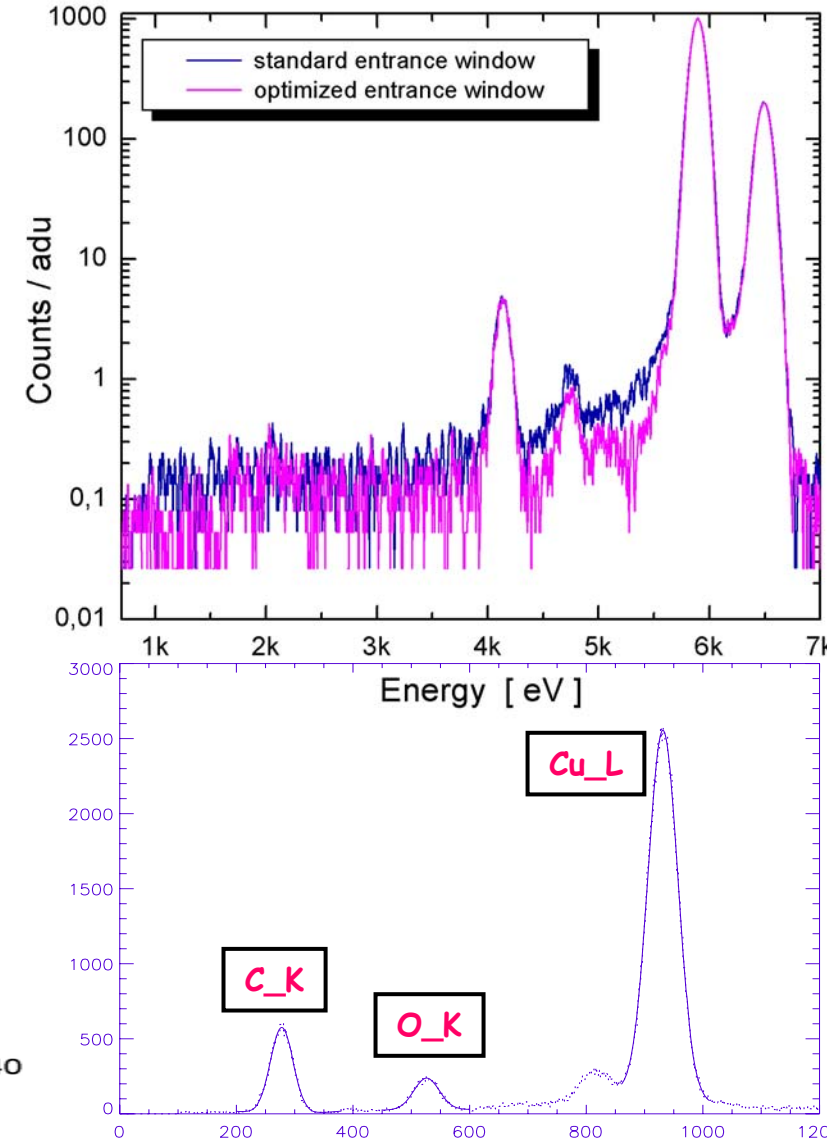

**SDD with integrated SSJFET**

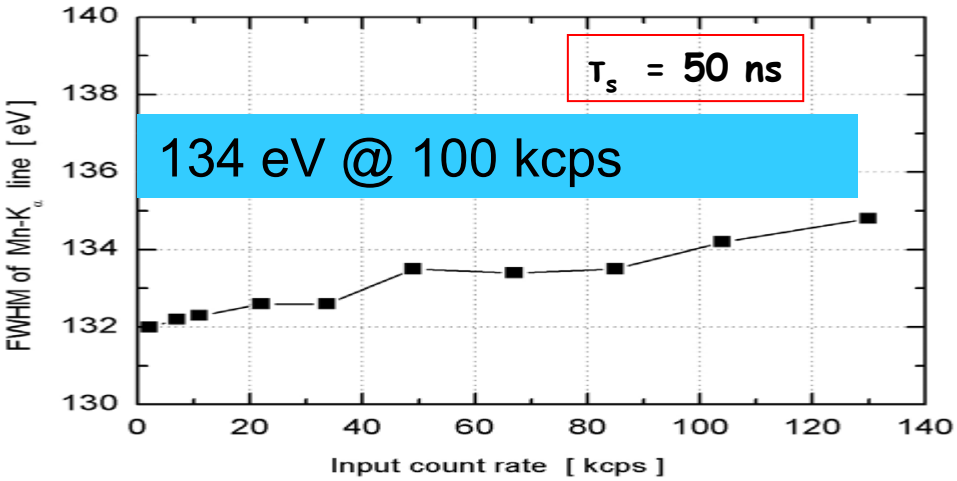



**Electrical Potential in a circular SDD**

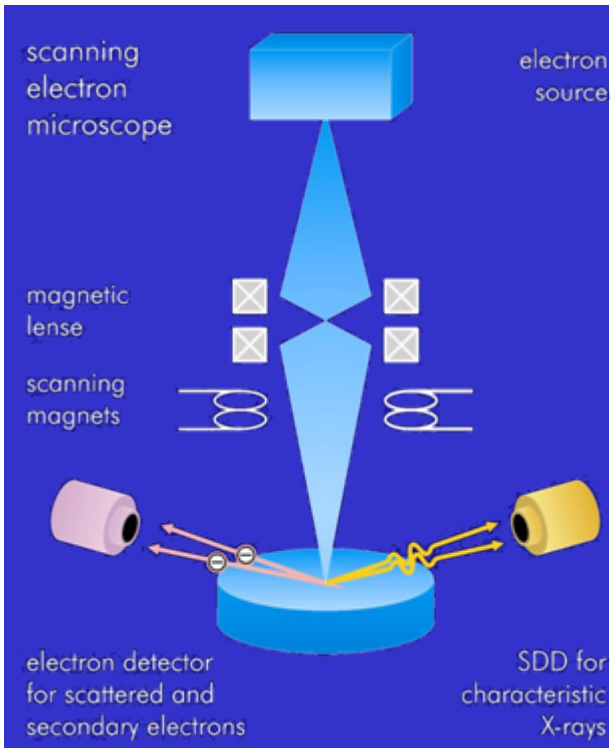
# SDD properties

- Energy resolution: $\Delta E_{FWHM}$ = 122 eV
- Count rate capability: up to $10^6$ cps
- Peak/Background ≈ 10.000 : 1
- Quantum efficiency: > 90% @ 0.3-10 keV
- Rad. hardness: > $10^{14}$ $Mo_K$ Photonen
- Operating temperature: T ≈ - 10° C
- Random shape and size
- Triggersignal: Δt ≈ 3 – 5 ns
- Antireflective coating

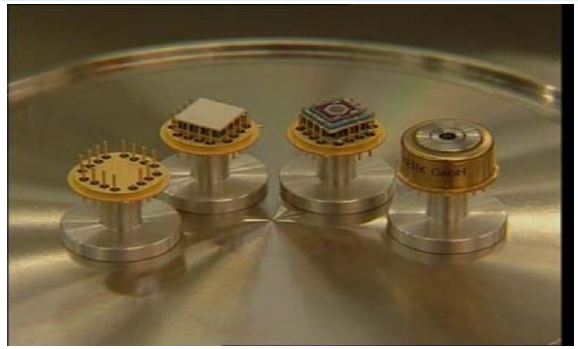


# Applications of SDDs



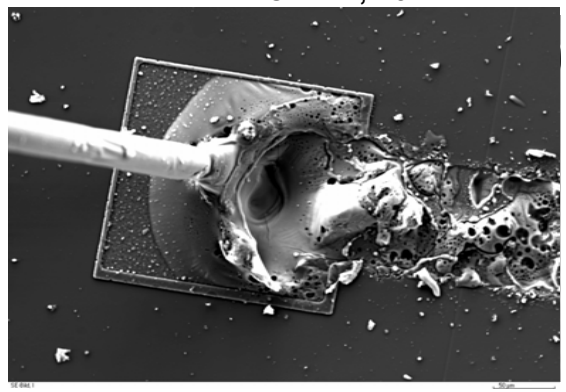

Scanning electron microscope with separated electron and X-ray detector



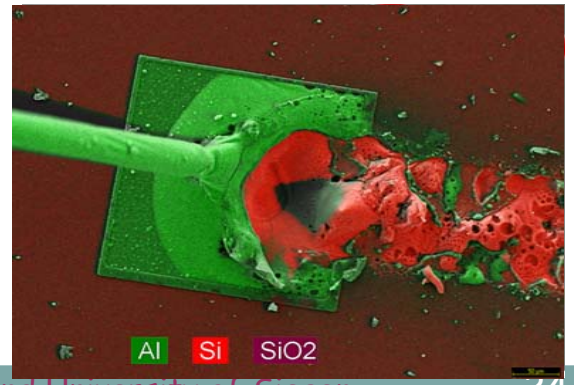
**SDD – Modules from 5 mm² bis 100 mm², 1 – 61 Module/Chip**

**Measurements made by RÖNTEC, Berlin**

**SEM – image**



**``colour – image´´**



# Mars Exploration Rover (MER)

**mission profile**

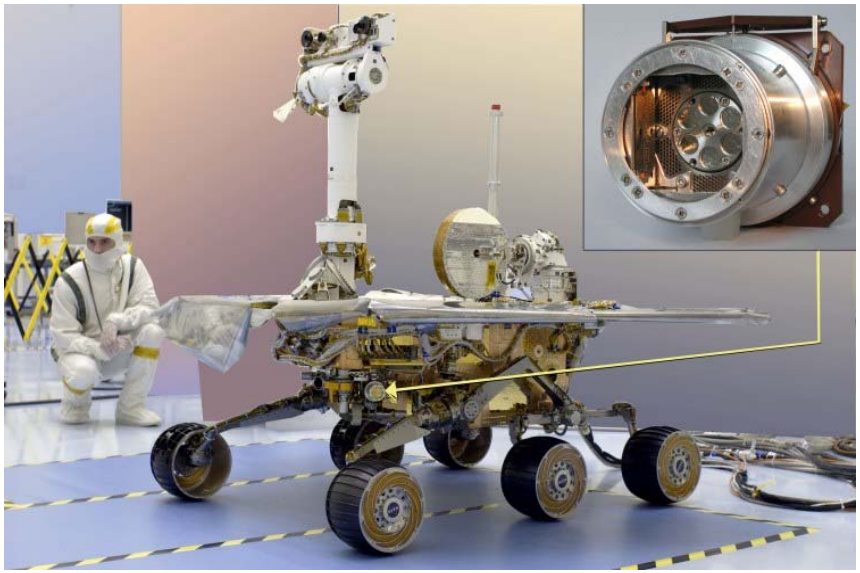
- 2 independent mobile landers "Spirit" & "Opportunity"
- arrived 04./25.01.04
- scheduled for 3 months / 600 m but still active

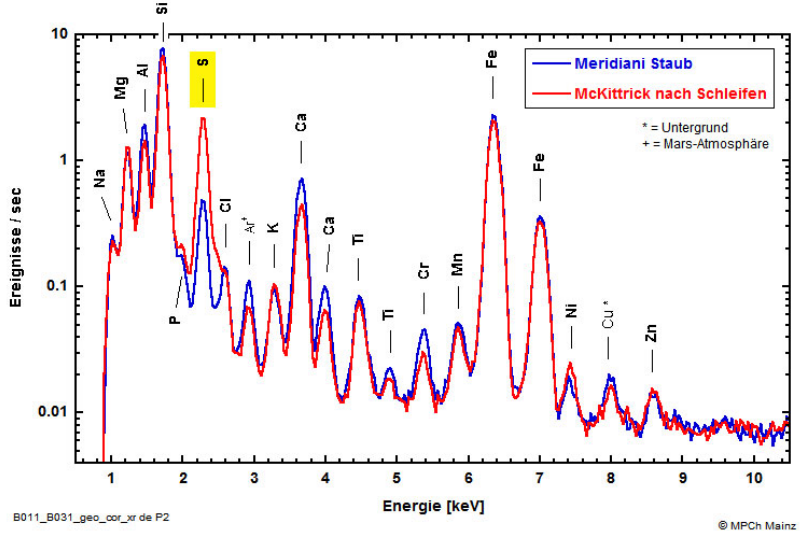
**mission goals**

- find traces of water
- investigate the geology of Mars
- prepare manned mission

PI of APXS system: R. Rieder
MPI für Chemie, Mainz

# SDDs on Mars Explorers Spirit and Opportunity






**The APXS system of the MPICH in Mainz:**

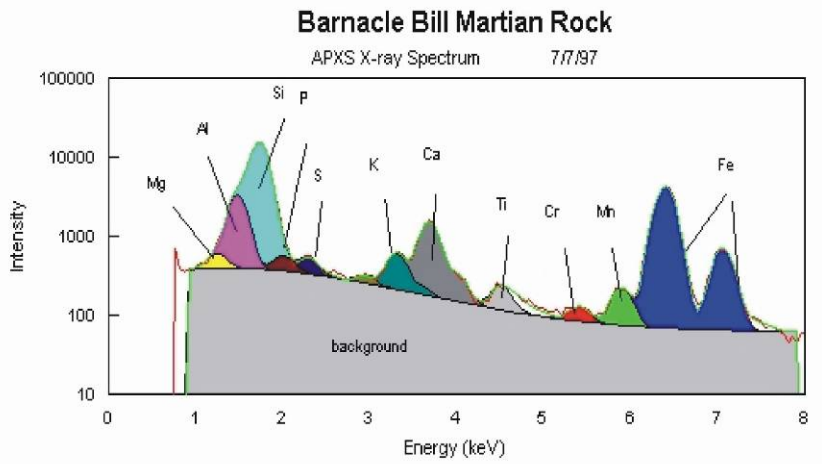
**Excitation with Curium-244:**

**α – particles**

**X – rays**

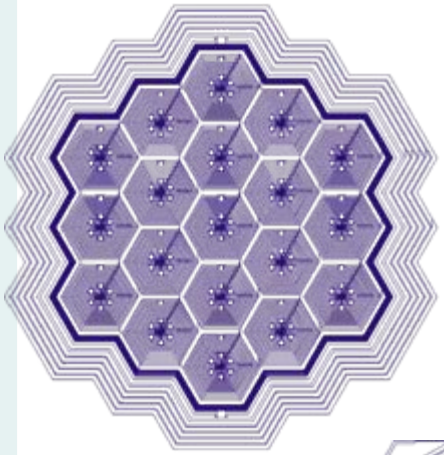
**ΔE @ Spirit&Opportunity @ 1.5 keV: 80 eV**

**ΔE @ Pathfinder @ 1.5 keV: 280 eV**

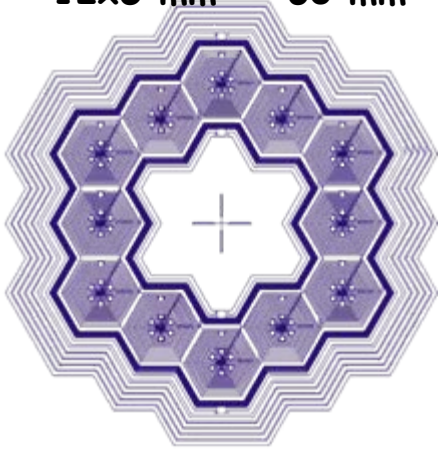


# Multichannel SDDs

19x5 mm² = 95 mm²

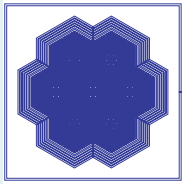


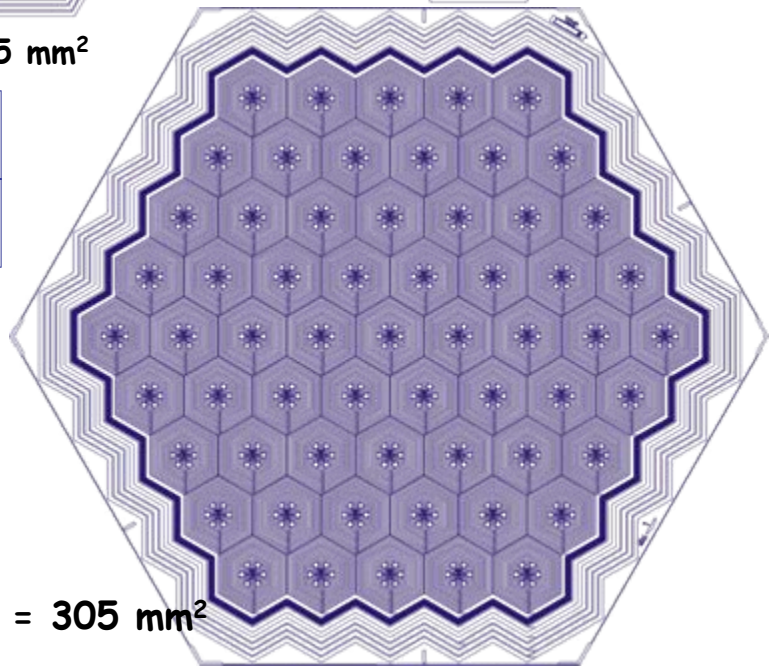
12x5 mm² = 60 mm²



6x5 mm² = 30 mm²

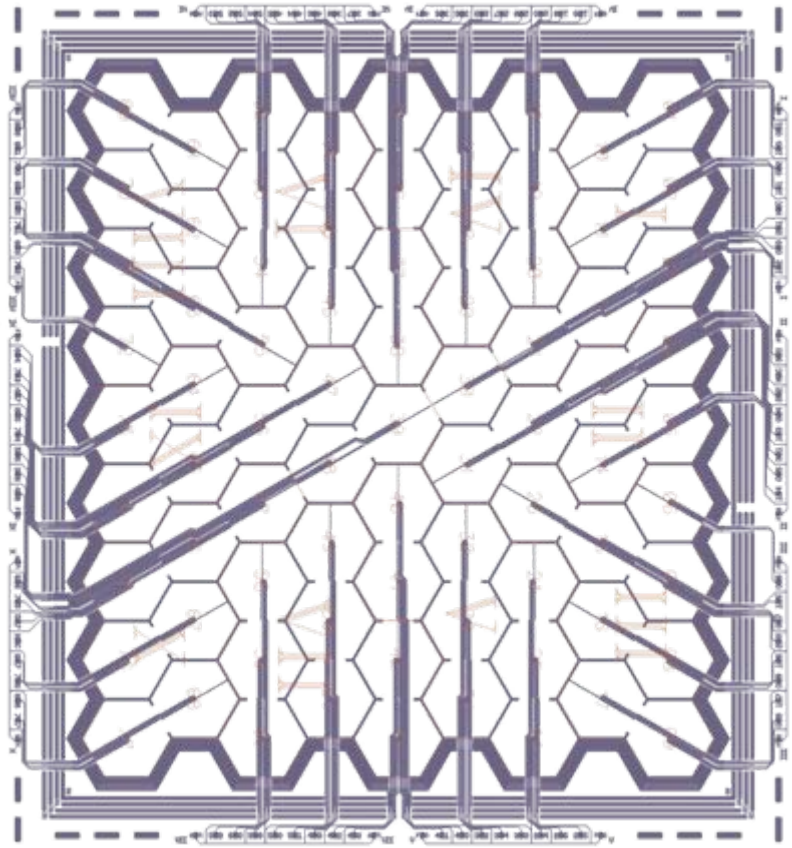
7x5 mm² = 35 mm²





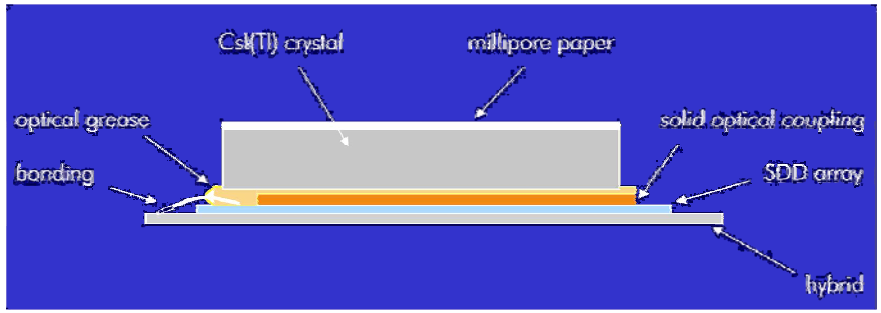
61x5 mm² = 305 mm²

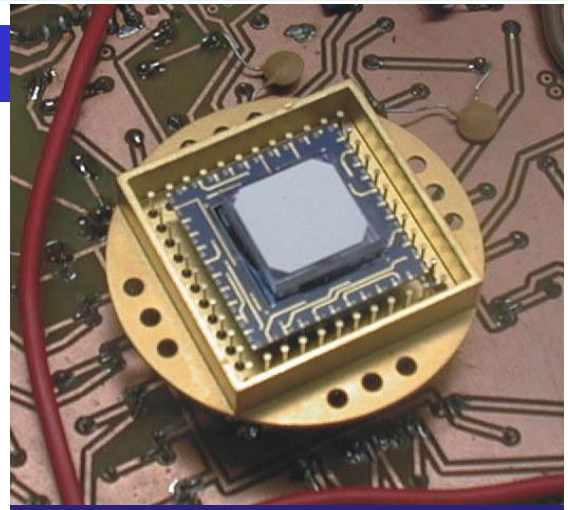
77x7 mm² = 539 mm²



# Multichannel SDD applications

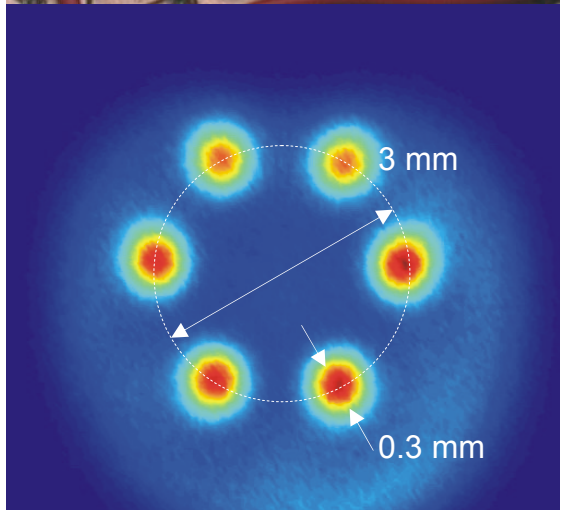
## scintillator readout, medical γ-ray imaging



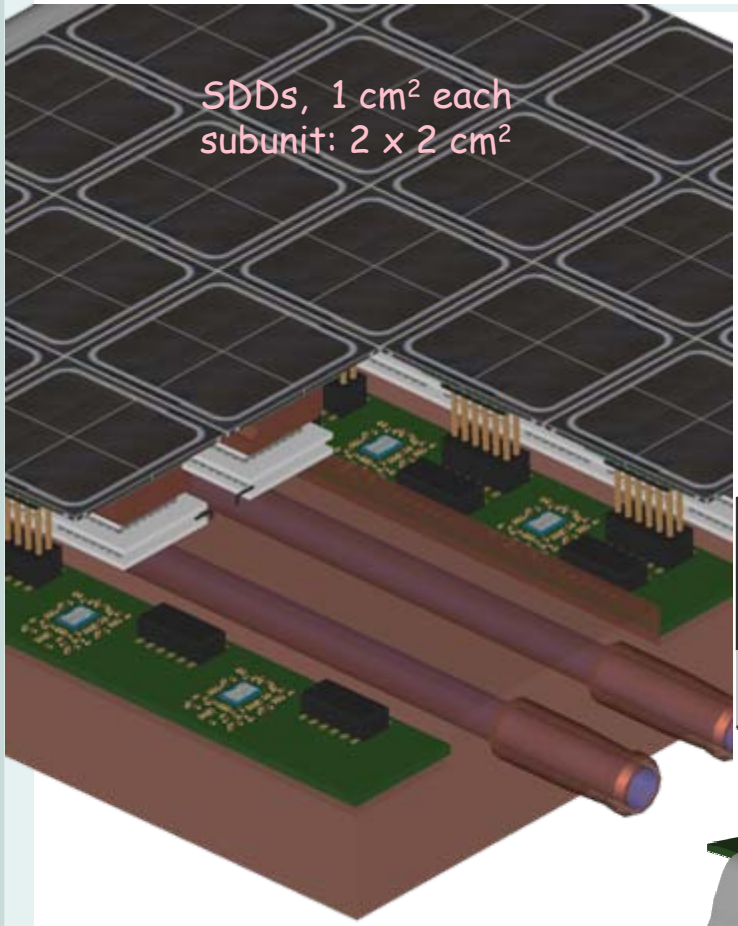
- CsI(Tl), 3mm
  η = 80 % (122 keV)
- gain
  15.4 el./keV
- position resolution
  0.35 mm FWHM
  (incl. hole diameter)
- energy resolution
  17 % FWHM
  E(min) = 2 keV

**The deconvoluted position resolution is 170µm (FWHM) achieved with 19 readout channels per cm² ! ! !**
**This corresponds to 3500 pixel per cm²**

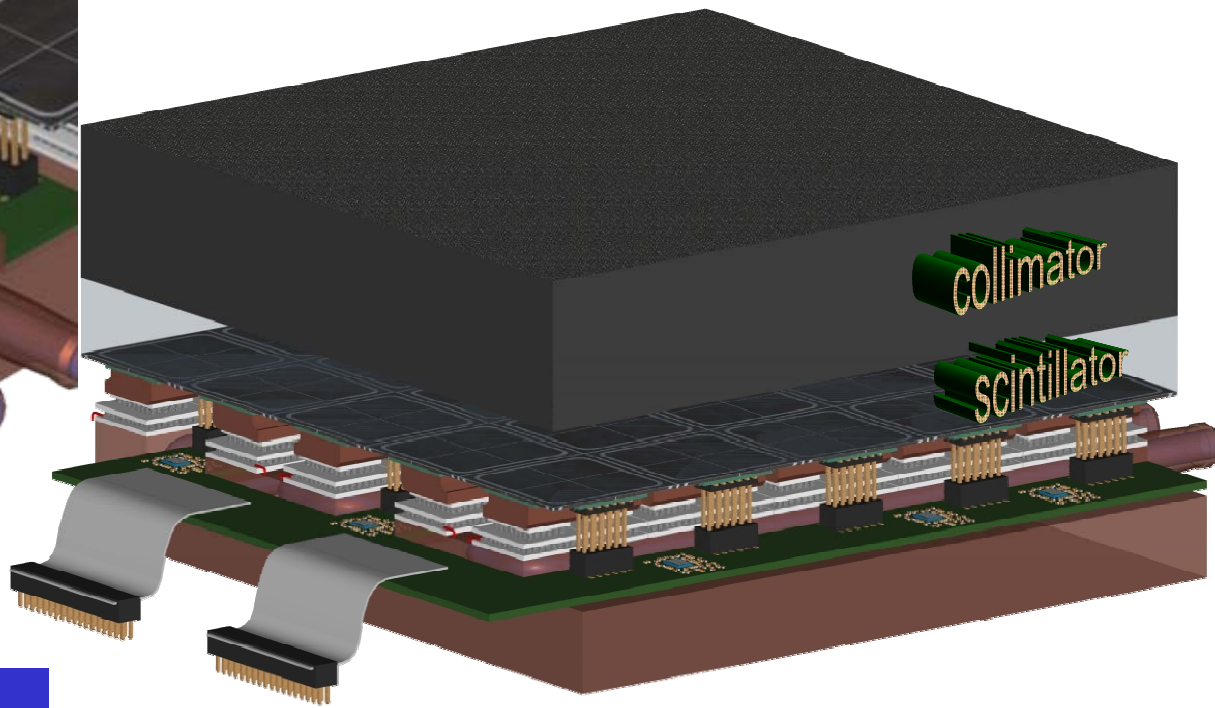



experiment & figures by C. Fiorini, Politecnico di Milano

# Complete Anger Camera: HICAM



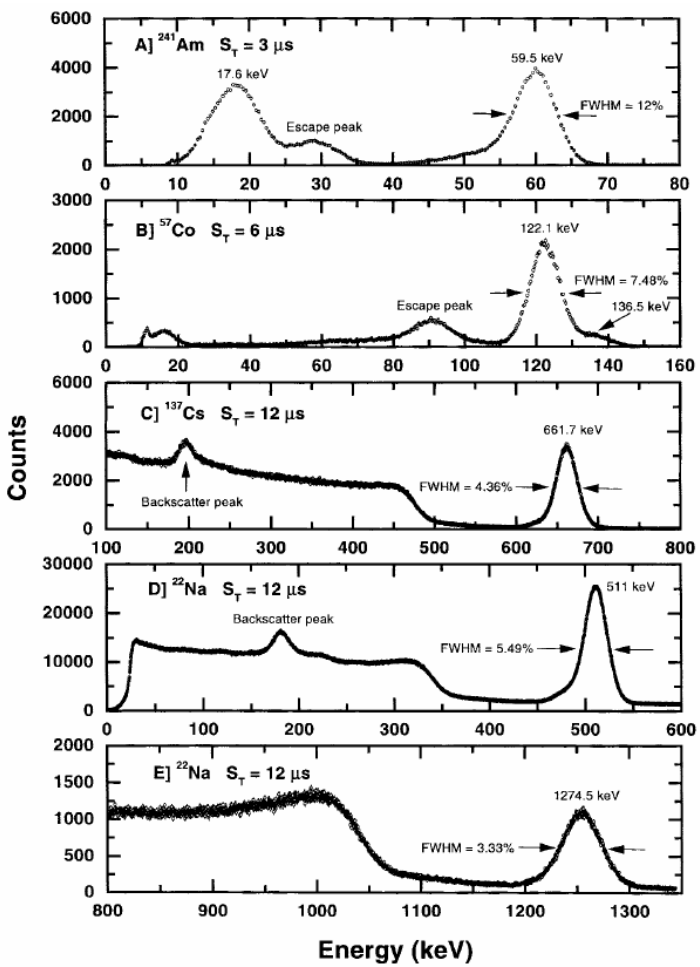

SDDs, 1 cm² each
subunit: 2 x 2 cm²
**full system 10 x 10 cm²**

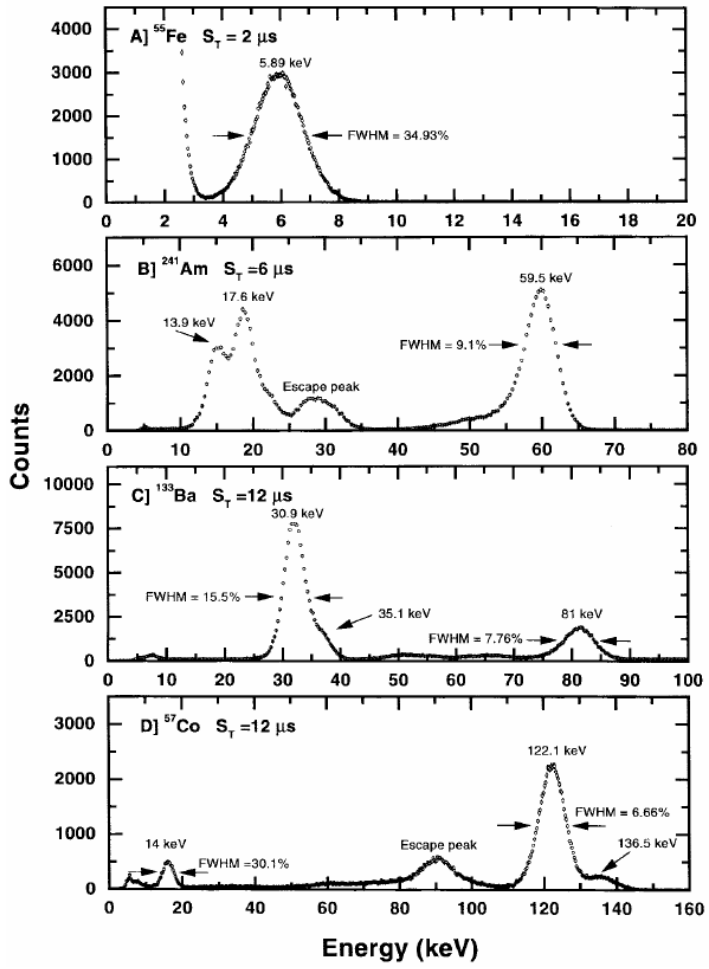



design by C. Fiorini,
Politecnico di Milano

# Spectroscopic response of SDDs coupled to scintillators

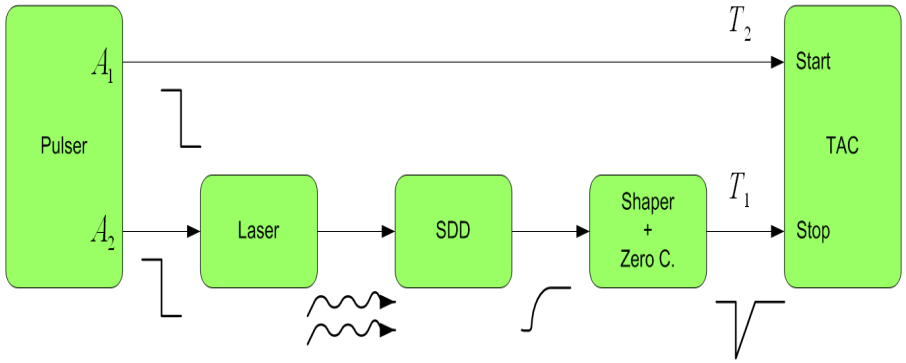
**Measurements by C. Fiorini, A. Longoni, Politecnico di Milano**



# Timing performances with laser pulses

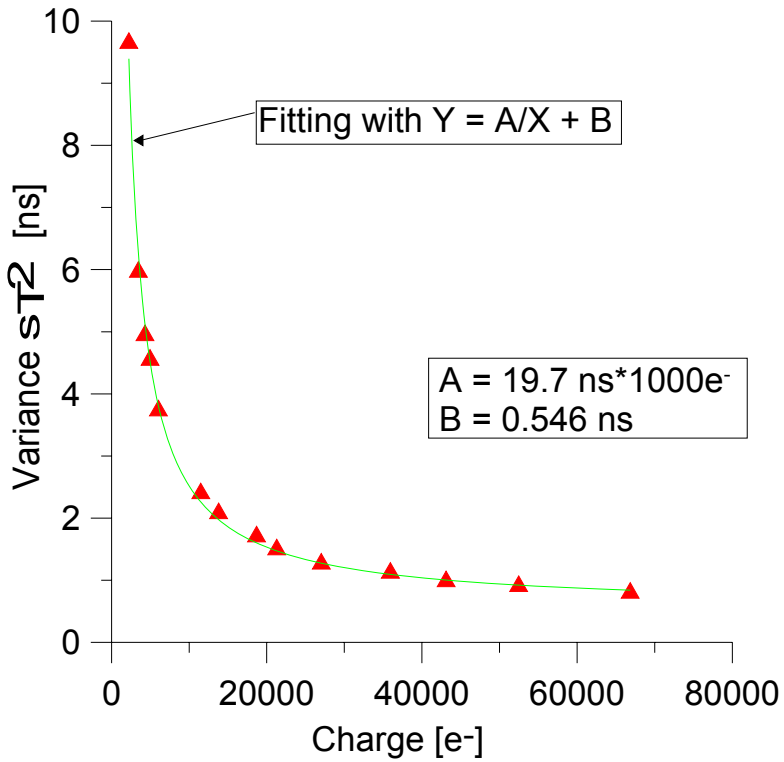
(measurements by C. Fiorini)

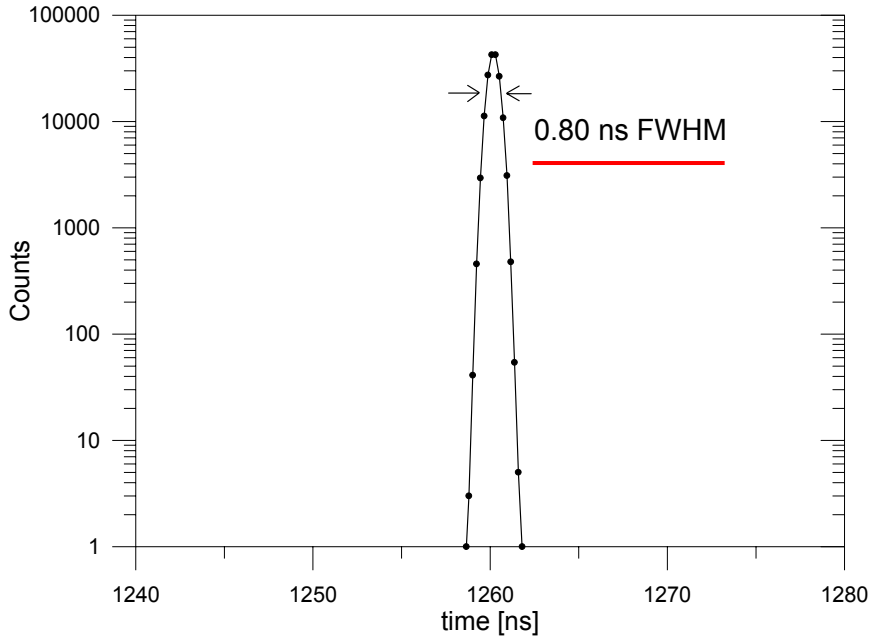



- Good agreement with the 1/X fit
- Measured resolution of 19.7ns for 1000 e- signal (room T)

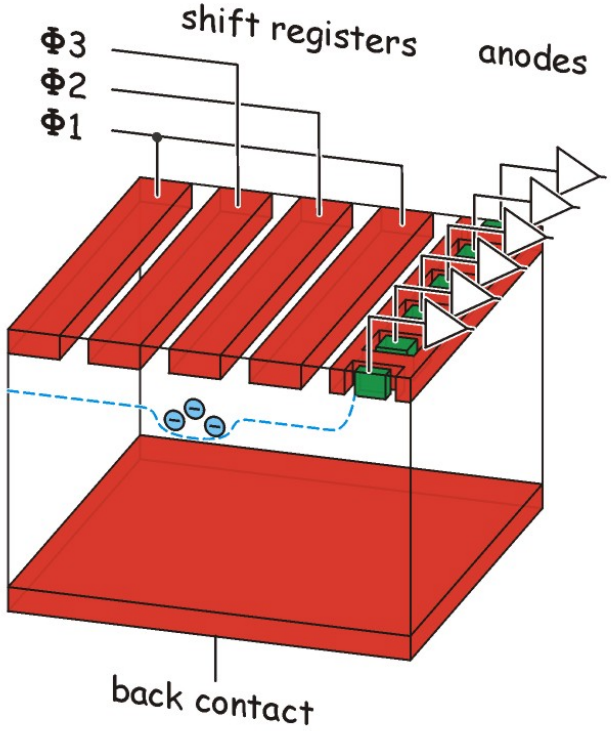
  theoreticaly expected: 18.6ns x 1000e-
- Best resolution of 0.8ns with 67.000 e-

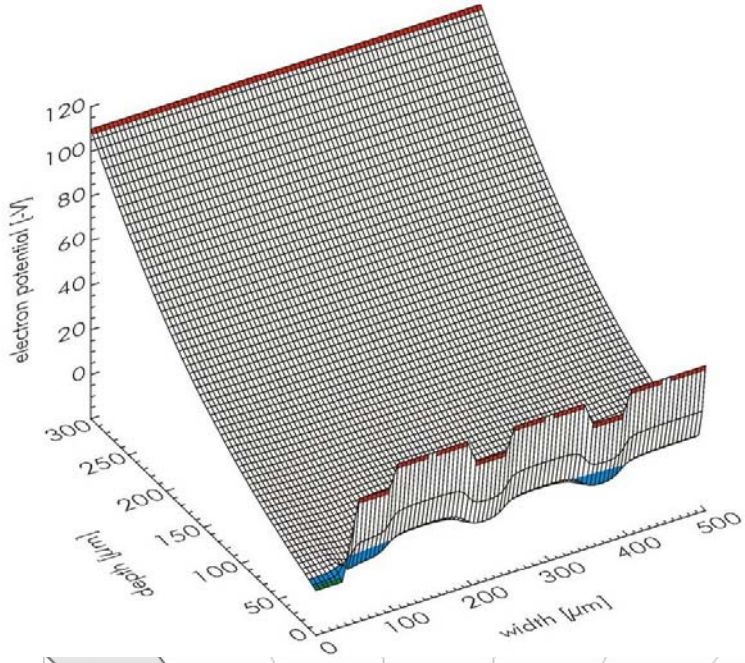
  $\Rightarrow$ no noticeable limitations due to jitter effects of the drift mechanism

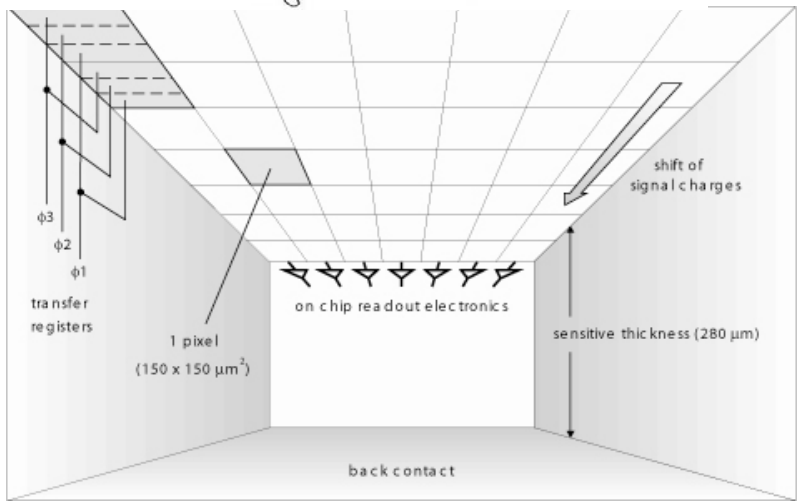


# CCD basics




- **full depletion (50 µm to 500 µm)**
- **back illumination**
- **radiation hardness**
- **column parallel readout**
- **high readout speed (up to 1.200 fps)**
- **pixel sizes from 30 µm to 1 mm**
- **charge handling: more than $10^6$ $e^-$/pixel**
- **high quantum efficiency**

# What determines the charge handling capacity in a pixel ?
# What limits power dissipation ?
# What limits operation temperature ?

**pixel volume**:
$20 \times 40 \times 12\ \mu m^3 \approx 1 \times 10^4 \mu m^3$

**Doping**: $10^2$ per $\mu m^3$
**CHC** = $1 \times 10^6$ per pixel

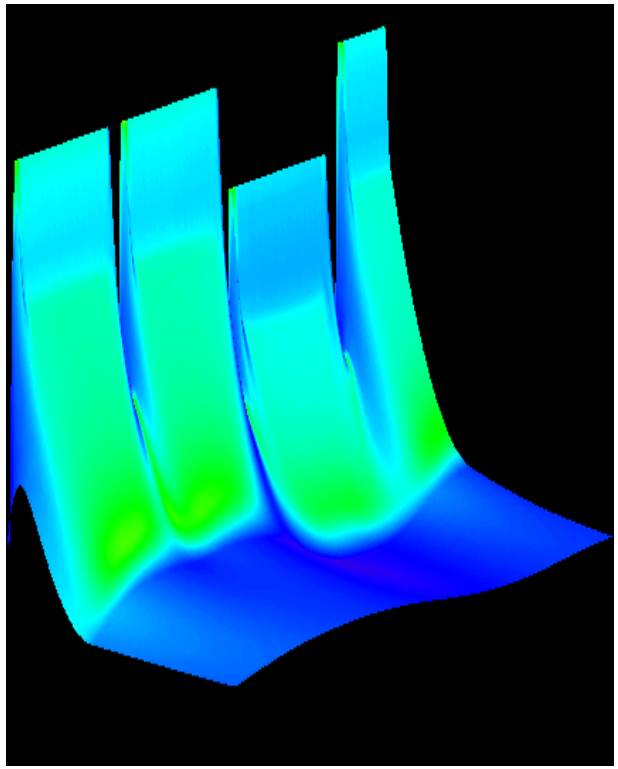
can be **increased** by **external voltages and by doping**

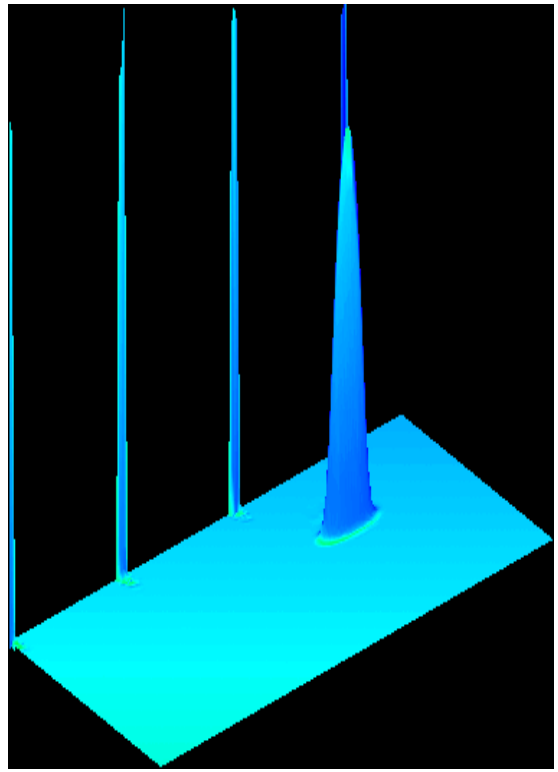
$T_{op}$ = - 60°C (face $10^9$ 10 MeV p in 5 y)

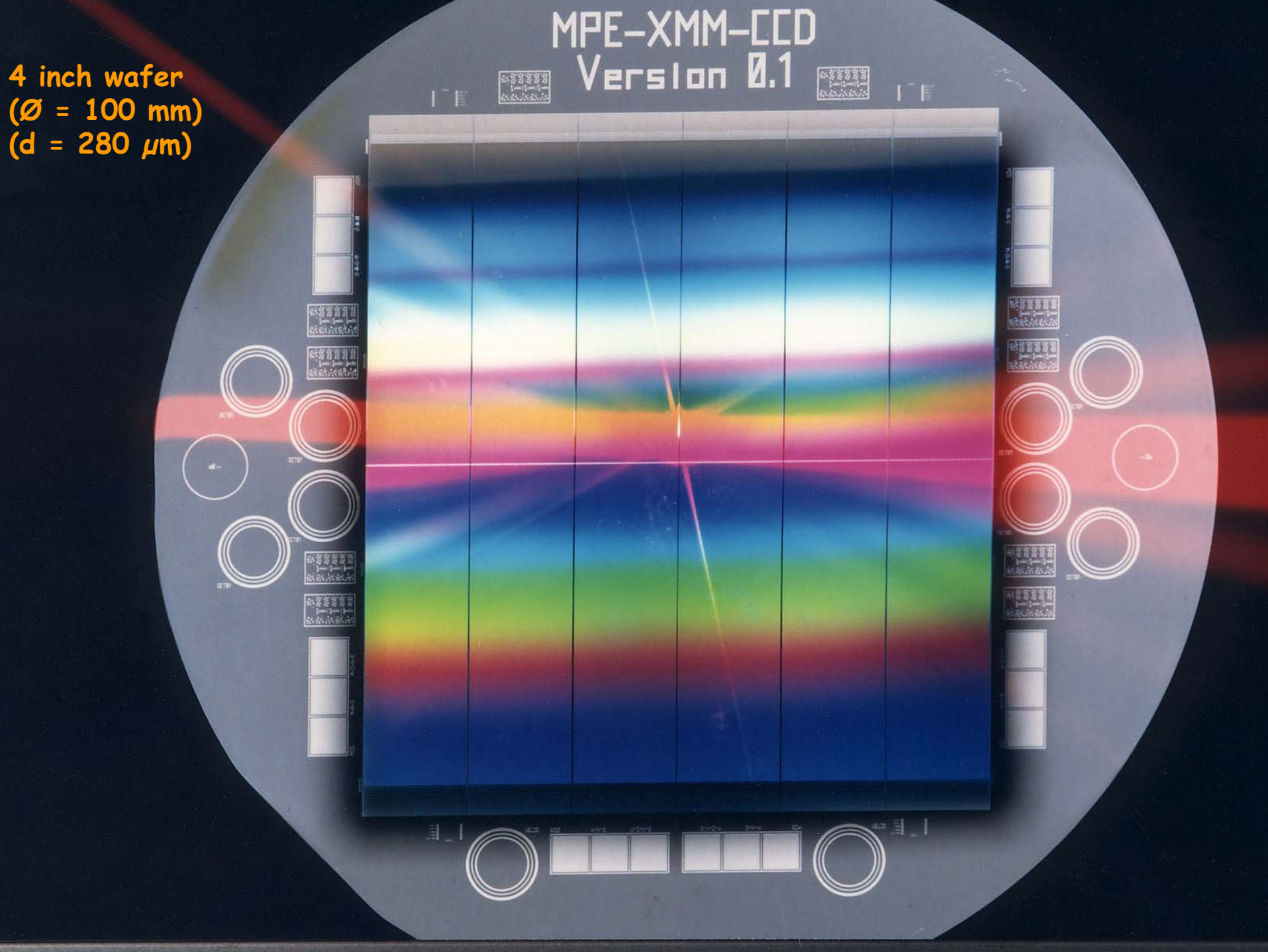
$\Delta V_{reg}$ = 1.2V ... 5V

all shift registers aluminized

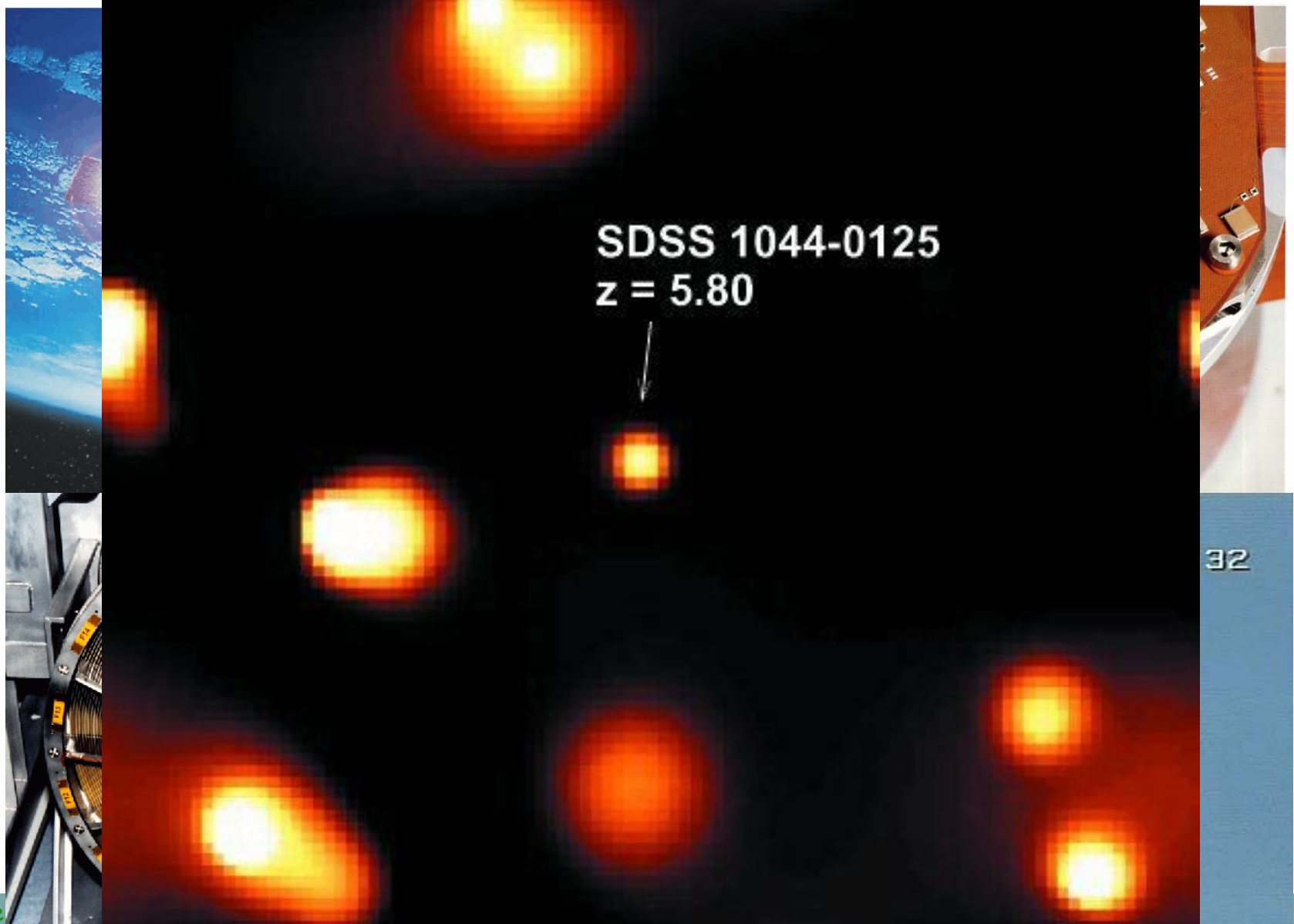
$P_{tot}$ = 0.06 W per $cm^2$ @ 20 fps including pre-amps, shaper, S&H, multiplexer, line driver





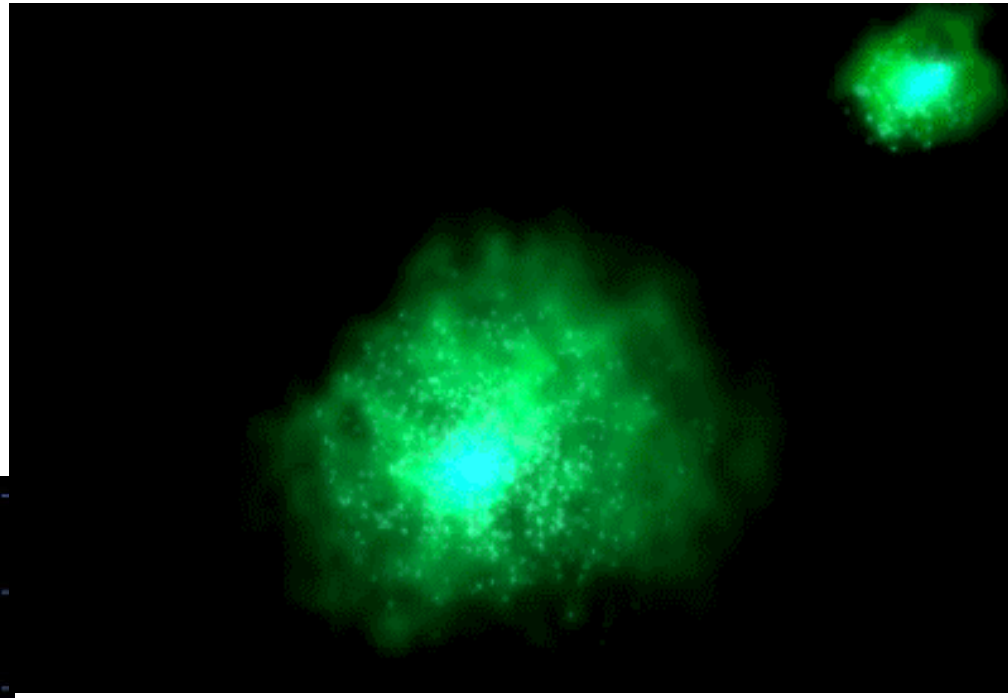

4 inch wafer
(Ø = 100 mm)
(d = 280 µm)
MPE-XMM-CCD
Version 0.1

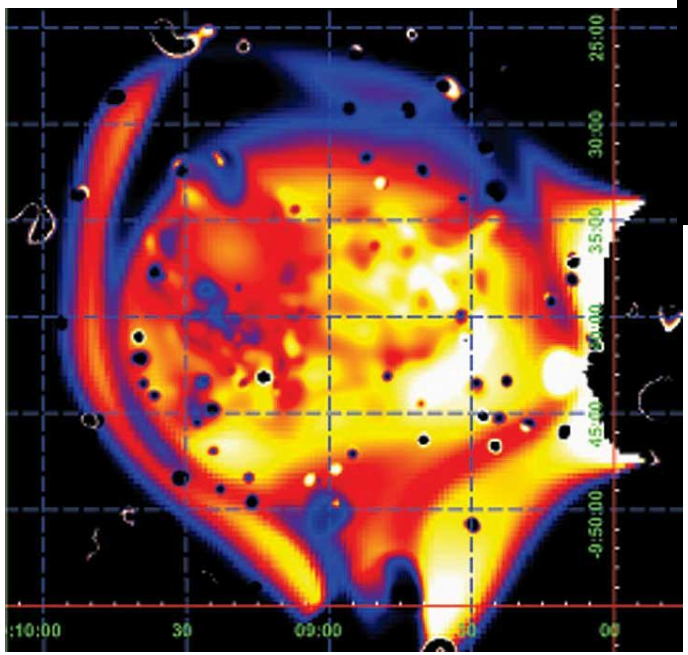
# XMM – Newton launched on 10.12.1999



# Head-on collision of clusters of galaxis observed with XMM

model of the ``cosmic thunderstorm´´






measured temperature and density maps from XMM – Newton of Abell 754 (Sternbild Hydra), d = 800 M LJ