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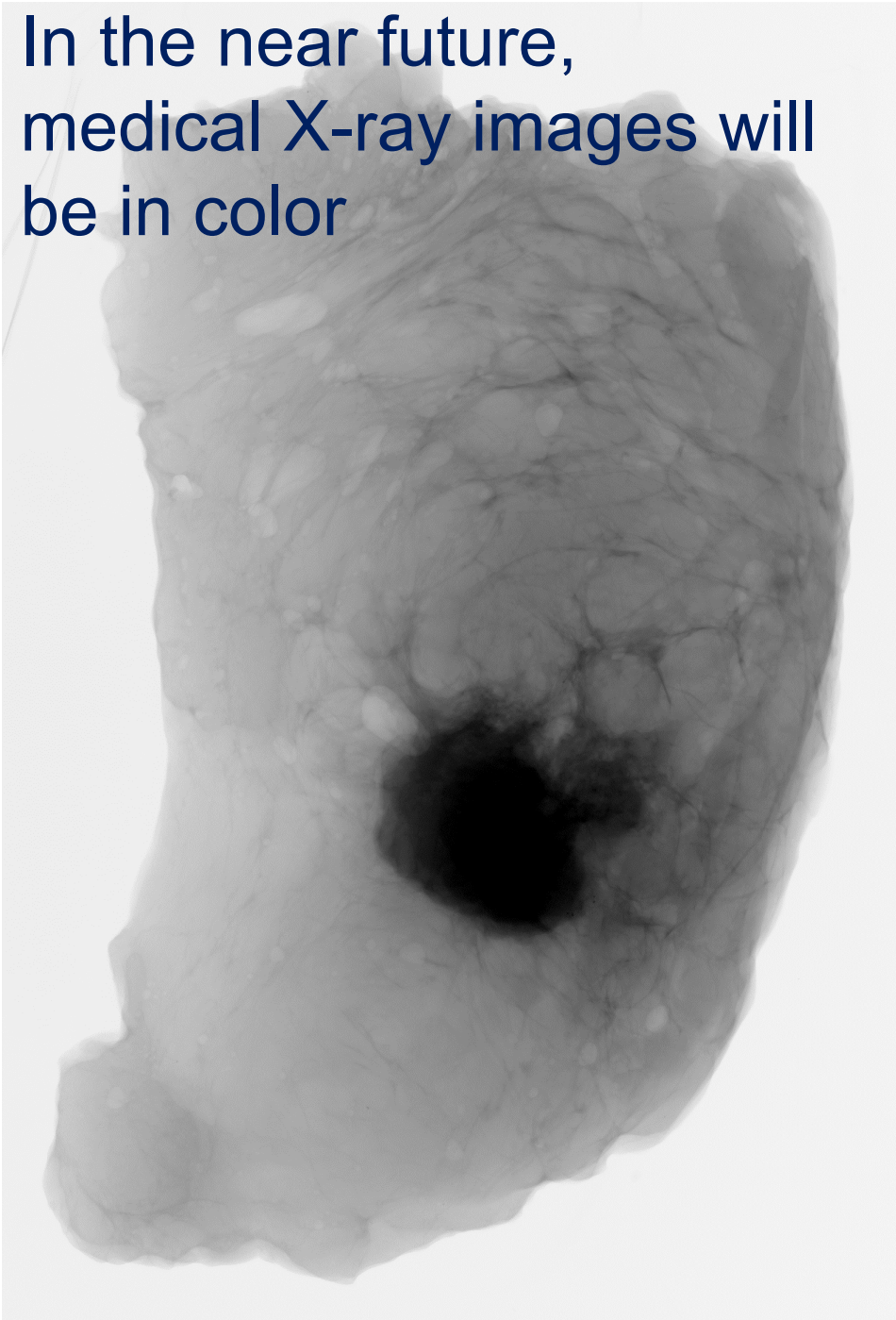
also with

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Towards photon counting X-ray image sensors

In the near future,
medical X-ray images will
be in color



Challenge addressed in this paper

X-ray Photon Counting has multiple advantages over classic charge integration

- ⇒ Quantum limited noise and sensitivity
- ⇒ Color X-ray
- ⇒ Maximum image sharpness

Realization of large XPC detectors is hindered by

- ⇒ Technical factors: pixel complexity, noise performance
- ⇒ Economical factors: yield, price

⇒ Can we manufacture large 2D photon counting X-ray detectors?

Outline

X-ray detection concepts

- ⇒ Direct and indirect X-ray detection
- ⇒ Photon counting X-ray imaging
- ⇒ “Color “ X-ray imaging

Design of a photon counting demonstrator

- ⇒ Specifications of the demonstrator array
- ⇒ Pixel designs
- ⇒ First measurement results

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→ X-ray detection concepts

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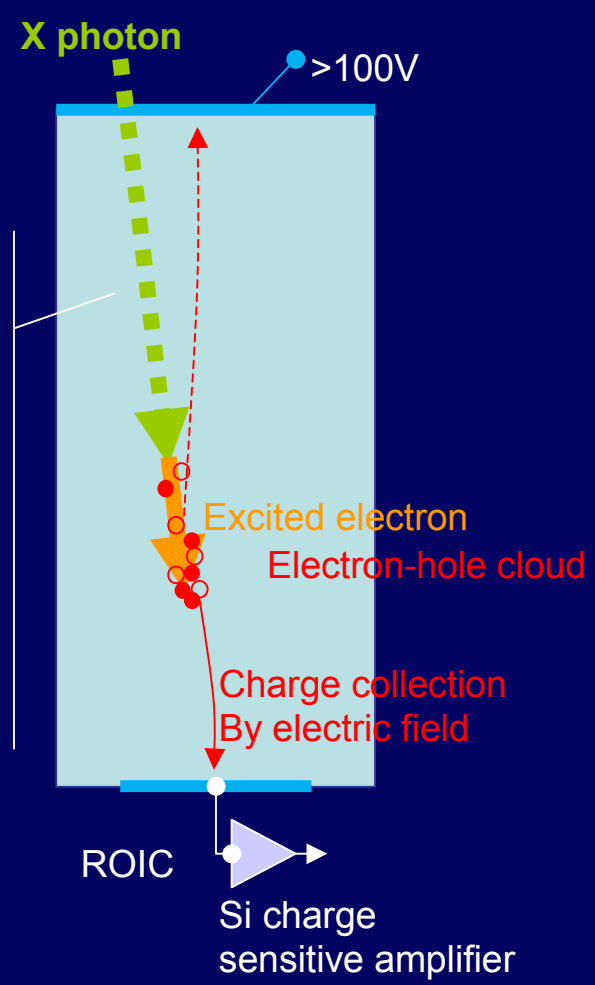
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Direct and indirect X-ray detection pixel

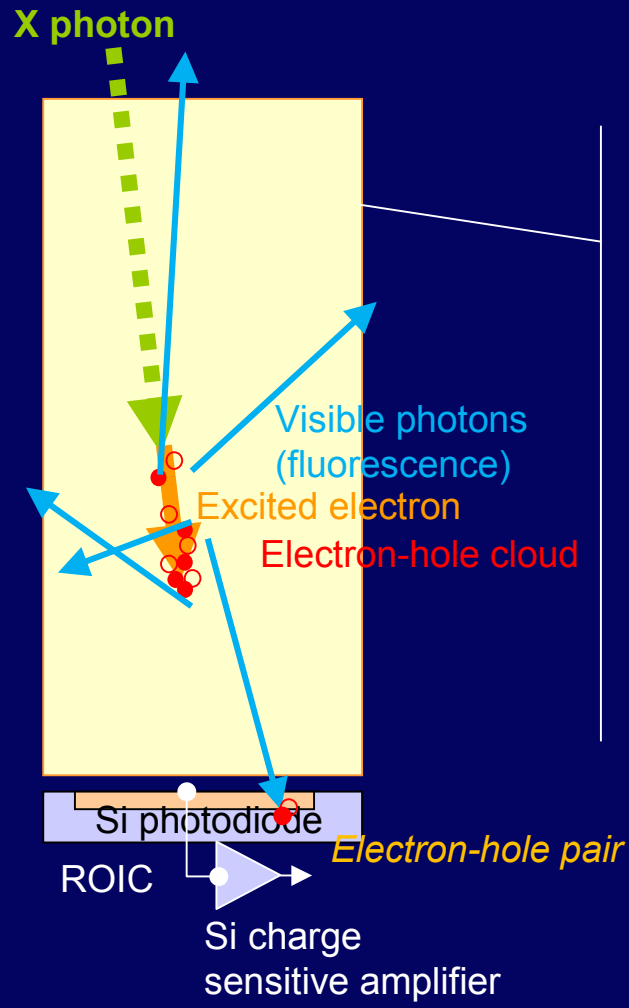
Direct detector
=semiconductor

- Si
- α Se
- InP
- CdTe
- CdZnTe
- ...

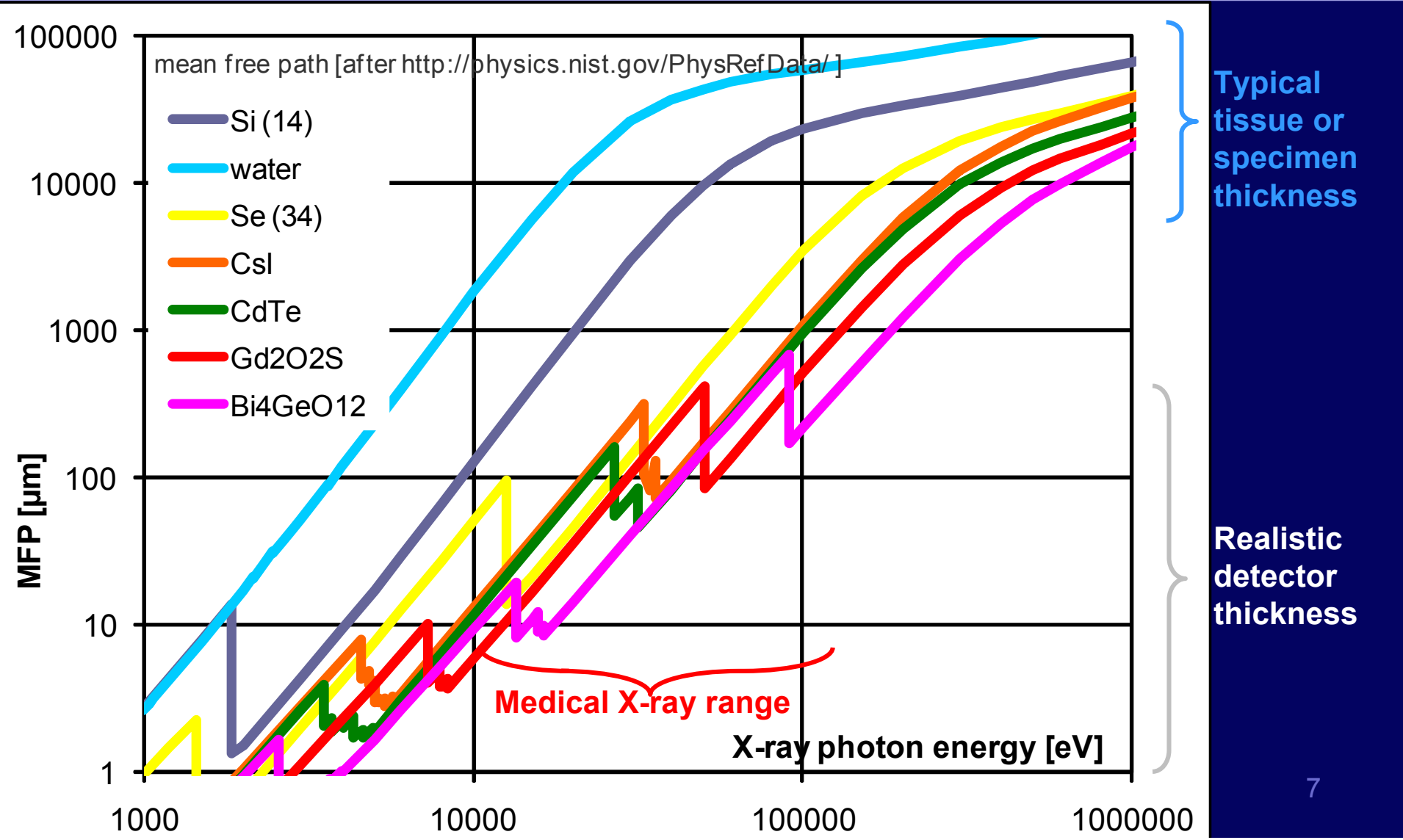


“indirect”=
Scintillator

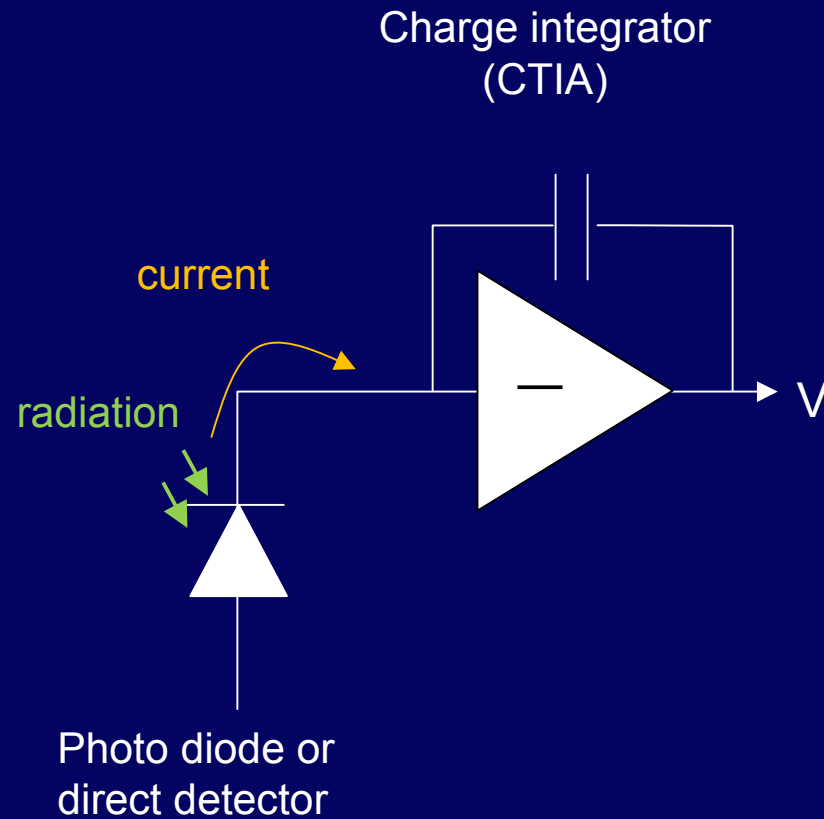
- CsI
- Bi₄Ge₃O₁₂
- ZnSe
- Gd₂O₂S
- NaBiW₂O₈
- CdWO₄
- ...
- ...
- ...



X-ray absorption = $f(x, Z, hv)$



Charge integration general concept



Voltage readout
~
Integrated current
~
Radiation energy

X-ray photon counting

Counting photons is noise free. One can improve the image quality for the same dose, or reduce the dose for the same image quality.

Measuring the energy per individual photon, “color X-ray”, improves diagnosis by information on the chemical composition of the tissue.

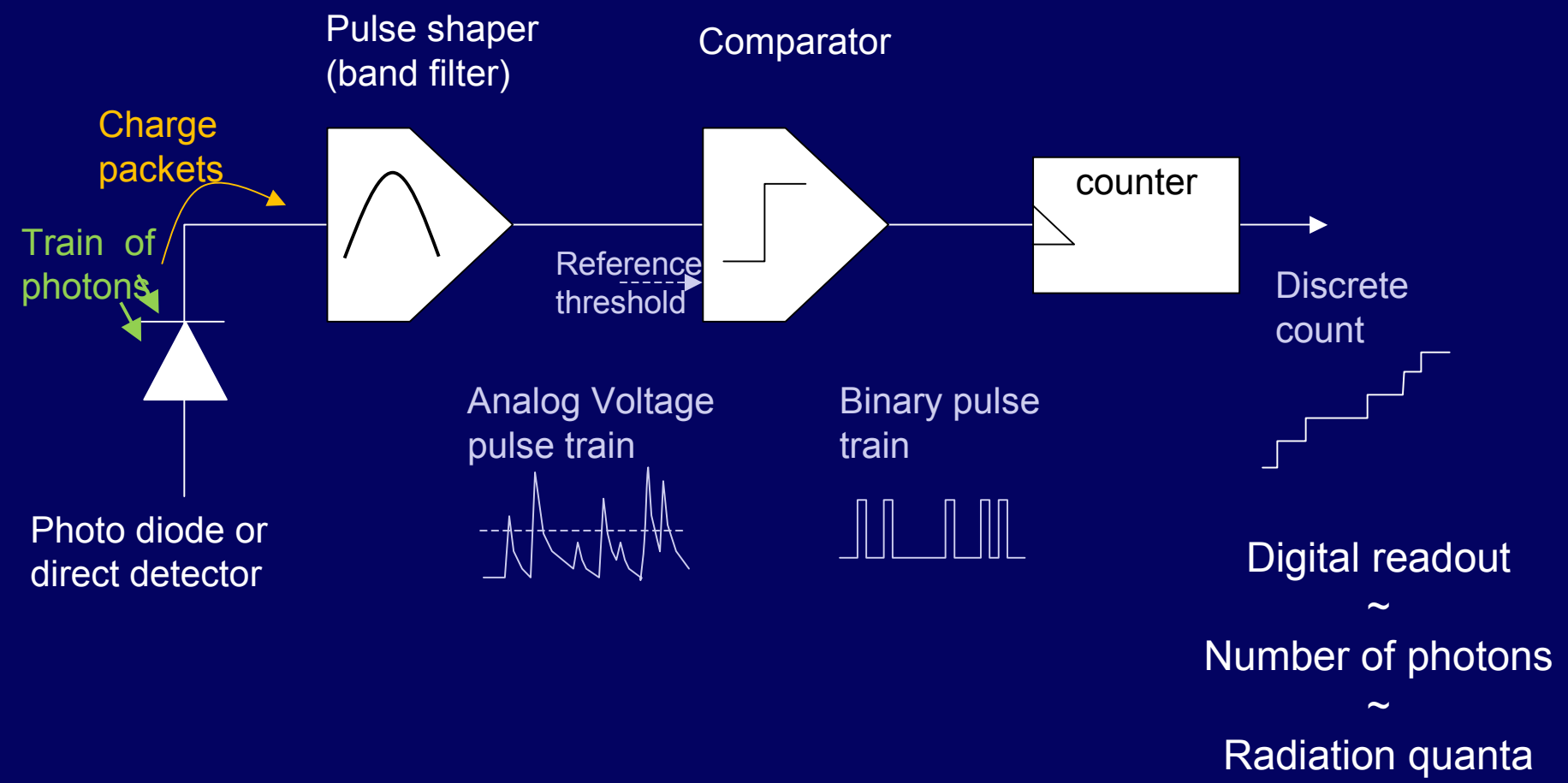
One can recover photon per photon the center of impact, and as such improve the image sharpness

X-ray (Röntgen) radiation, as all EM radiation, interacts as particles called “photons”

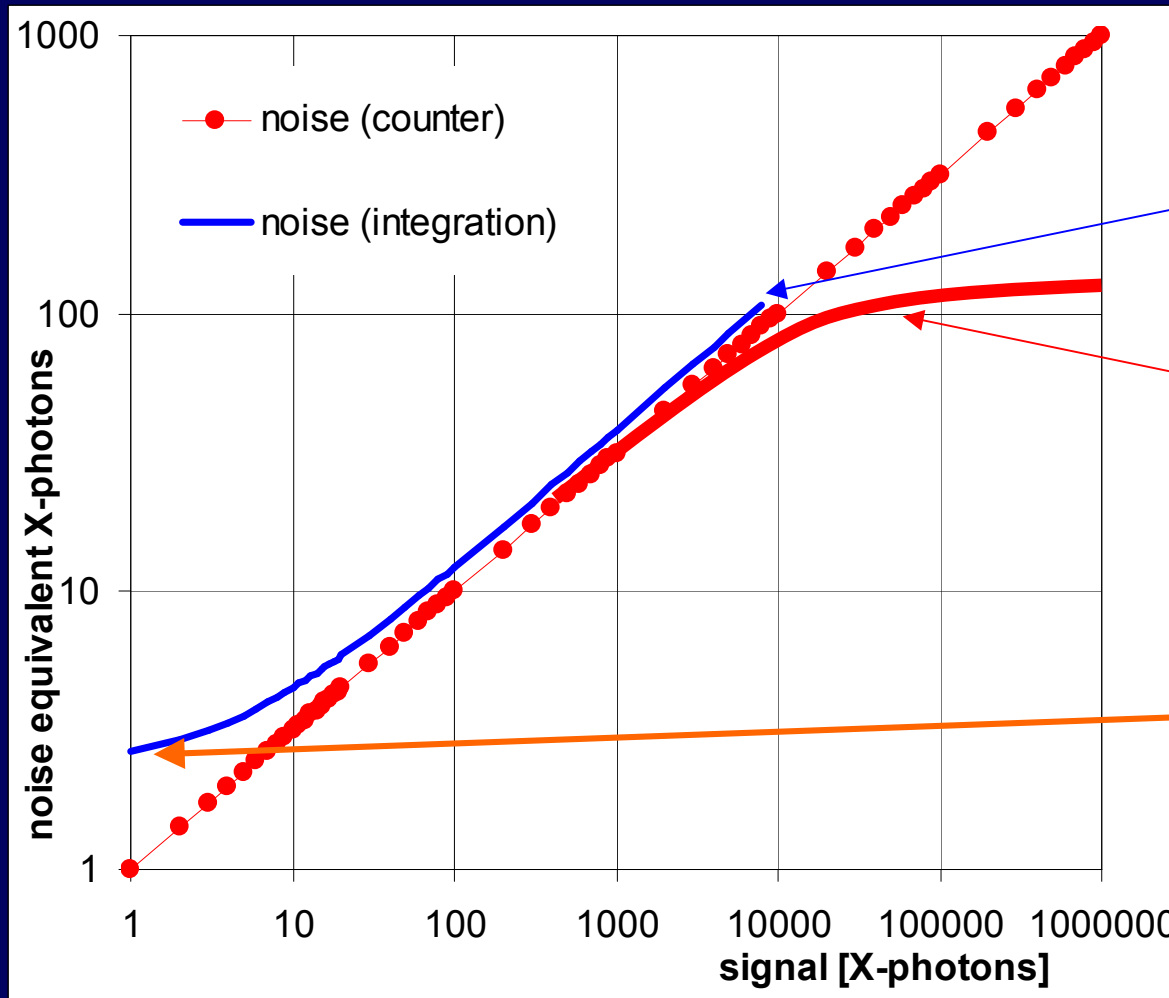
Classic X-imaging: measure total converted energy, from integrated charge, per pixel per frame

By counting photons, and classifying them on-the-fly, one can drastically enhance the accuracy

photon counting pixel concept



Counting has a perfect S/N ratio

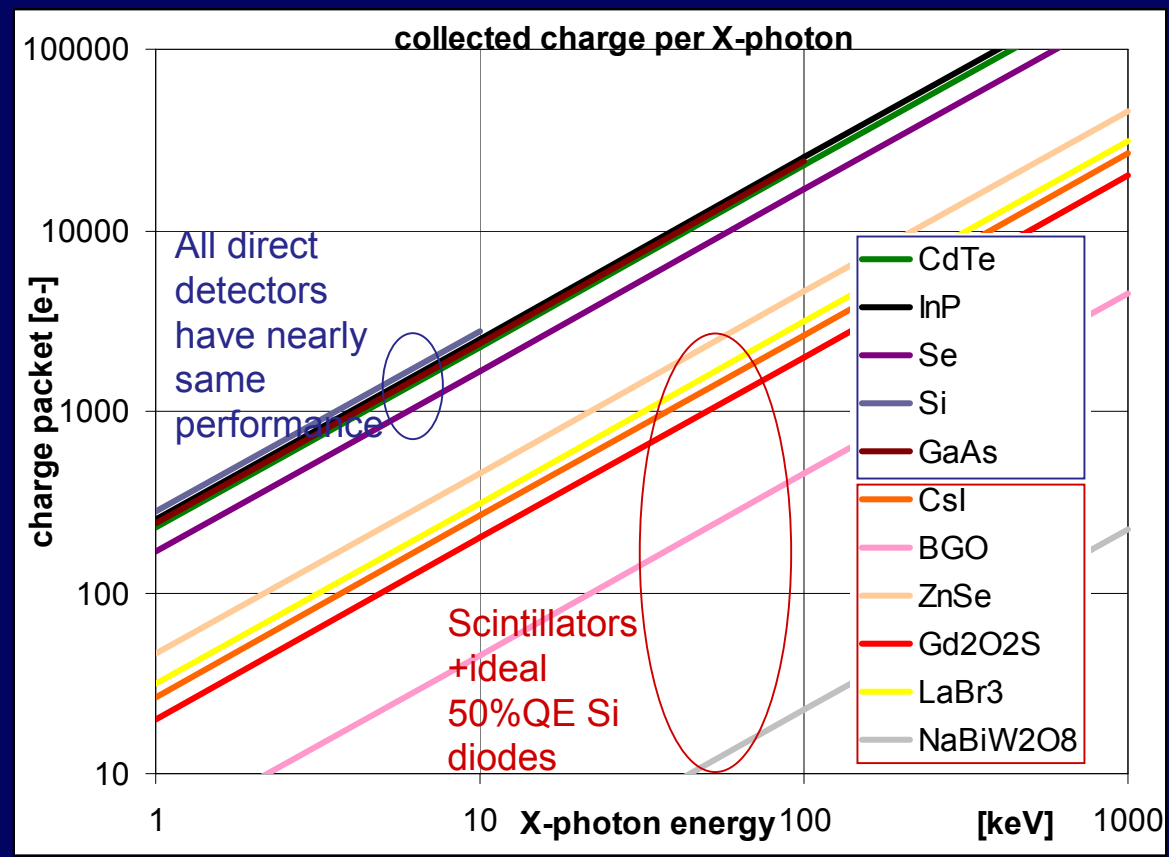


Charge integration:
hard stop where the
capacitor is filled

Counting: soft stop at
max count frequency

Integrator read noise
(=N) spoils the S/N at
low intensities

Direct detectors: more electrons per X-photon



Typical pulse shaper noise floor

Typical range Medical X-ray

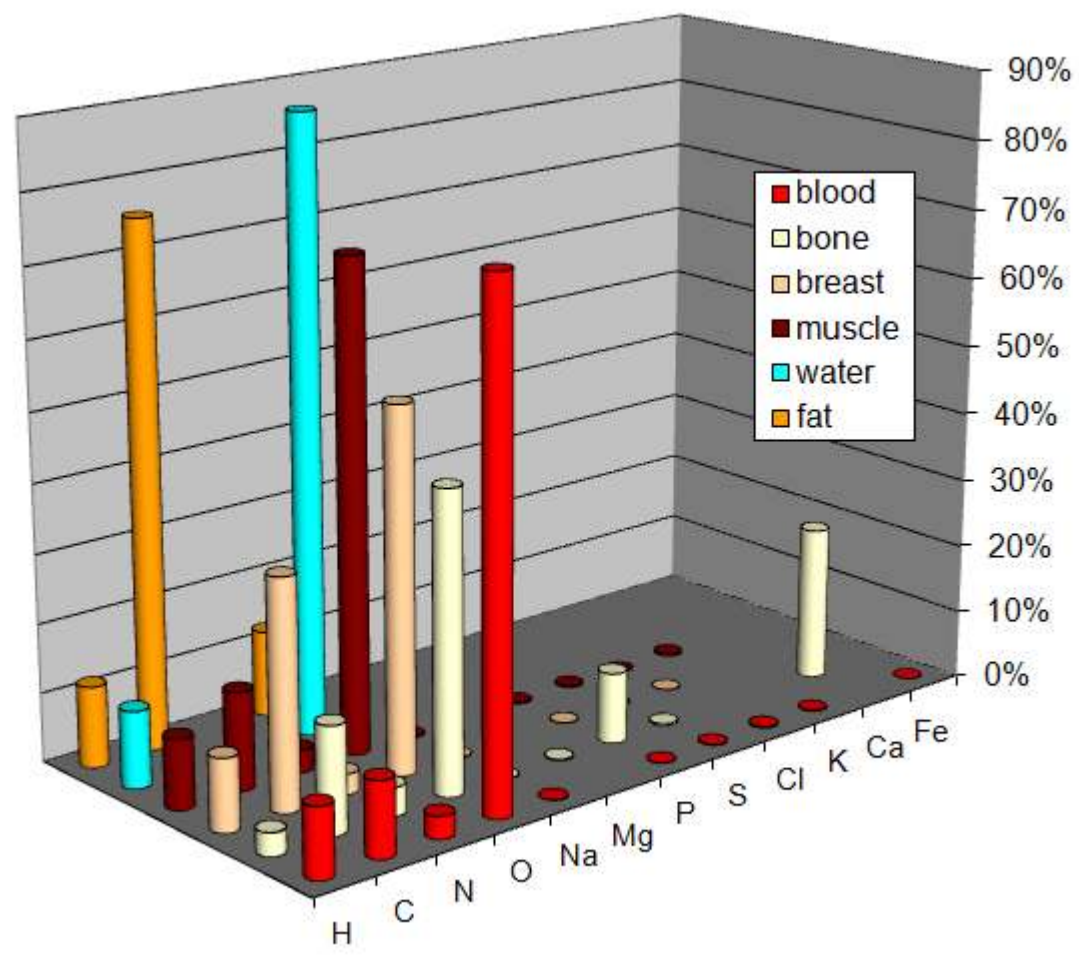
Color X-ray

X-ray absorption in matter has a strong spectral dependence.

X-ray absorption essentially depends on the element's (atom's) Z-number

By examination of the absorbed or transmitted spectrum, one deduces information on the relative concentration of the elements.

Tissue discrimination = element relative concentration



C:

- fat

C+O:

- Collagen
- Proteins
- DNA

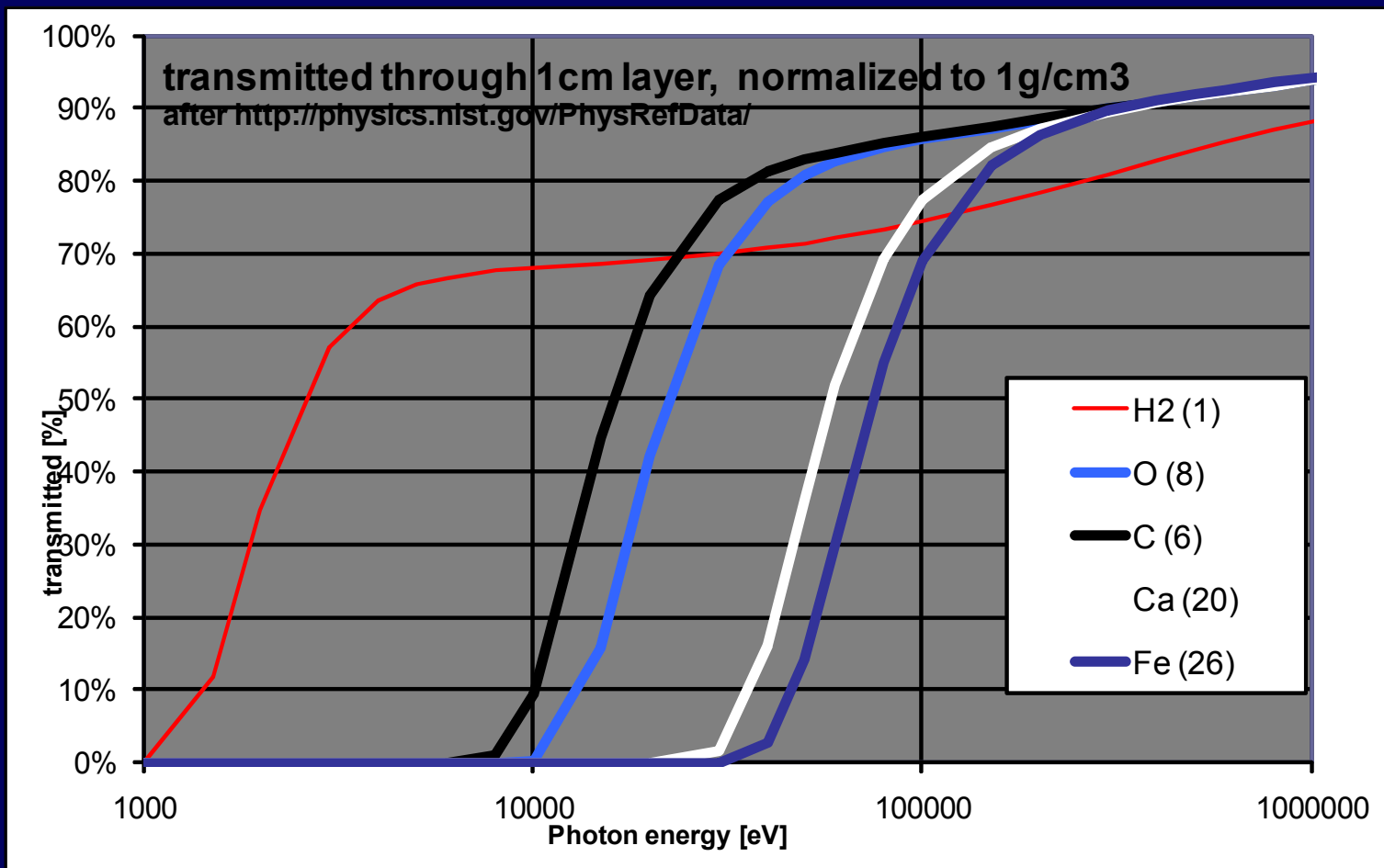
O:

- Water
- blood

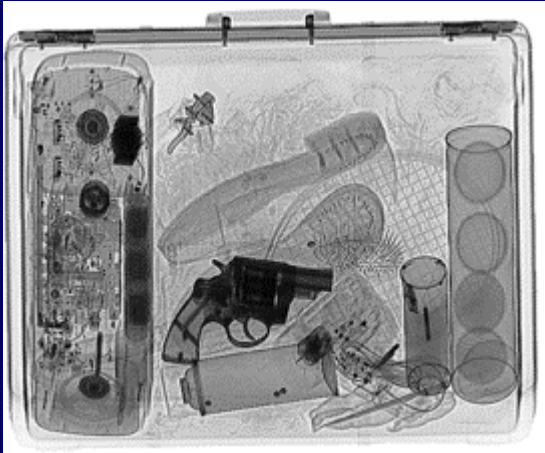
Ca:

- Bone
- Calcifications
- Degenerate tumors

The absorption of X-rays tells the atomic composition



Color X-ray exists. E.g. border control X-ray



(cited from Smith-Heimann website)

In the multi-energy method for evaluation of material information of the X-ray signal, the high and low energy radiation fractions obtained after penetration of the object, are compared. By means of this method conclusions concerning material origins can be made.

The classification of materials is carried out according to the atomic numbers Z . Three main groups of elements are distinguished by colors of a continuous color scale:

- $0 < Z < 10$ orange (low)
- $10 < Z < 18$ green (medium)
- $18 < Z < 40$ blue (high)

Color assignment

The scale comprises colors of orange for elements of low atomic number, i.e. elements which can be found in organic material, green for elements of medium atomic number and blue for elements of higher atomic number. The information concerning material thickness respectively absorption factor is furnished by means of the degree of brightness for the color signal. Therefore, items composed of the same material but which are different in thickness, show the same color while differing in brightness.

Do not do this on people!
2-3x radiation dose



Medical use of photon counting X-ray

Better diagnostics with the same (or lower) radiation dose

- ⇒ Sharper images: better insight in shape and size of lesions
- ⇒ Lower noise, better noise-equivalent contrast
- ⇒ Differentiation to atomic weight of the tissue: color X-ray

Application domain: Medical X-ray

Mammography

- ⇒ X-ray is first line breast cancer screening
- ⇒ purpose: optimize the diagnostic quality without additional radiation
- ⇒ Tissue-specific segmentation and sharper images aid early detection
 - Better visualization of cancerous tissue amid normal tissue
 - Accurate flagging of fine Calcium particles that are seen in early cancerous tissue
- ⇒ Benchmark vs. other technologies
 - Lower cost, higher contrast, less false positives than magnetic resonance imaging

Color X-ray experiment

Purpose

- ⇒ In screening mammography: Has color X-ray diagnostic relevance?
- ⇒ Let's check color X-ray first on surgical specimens
- ⇒ Or: does it makes sense to develop photon counting with color X-ray?

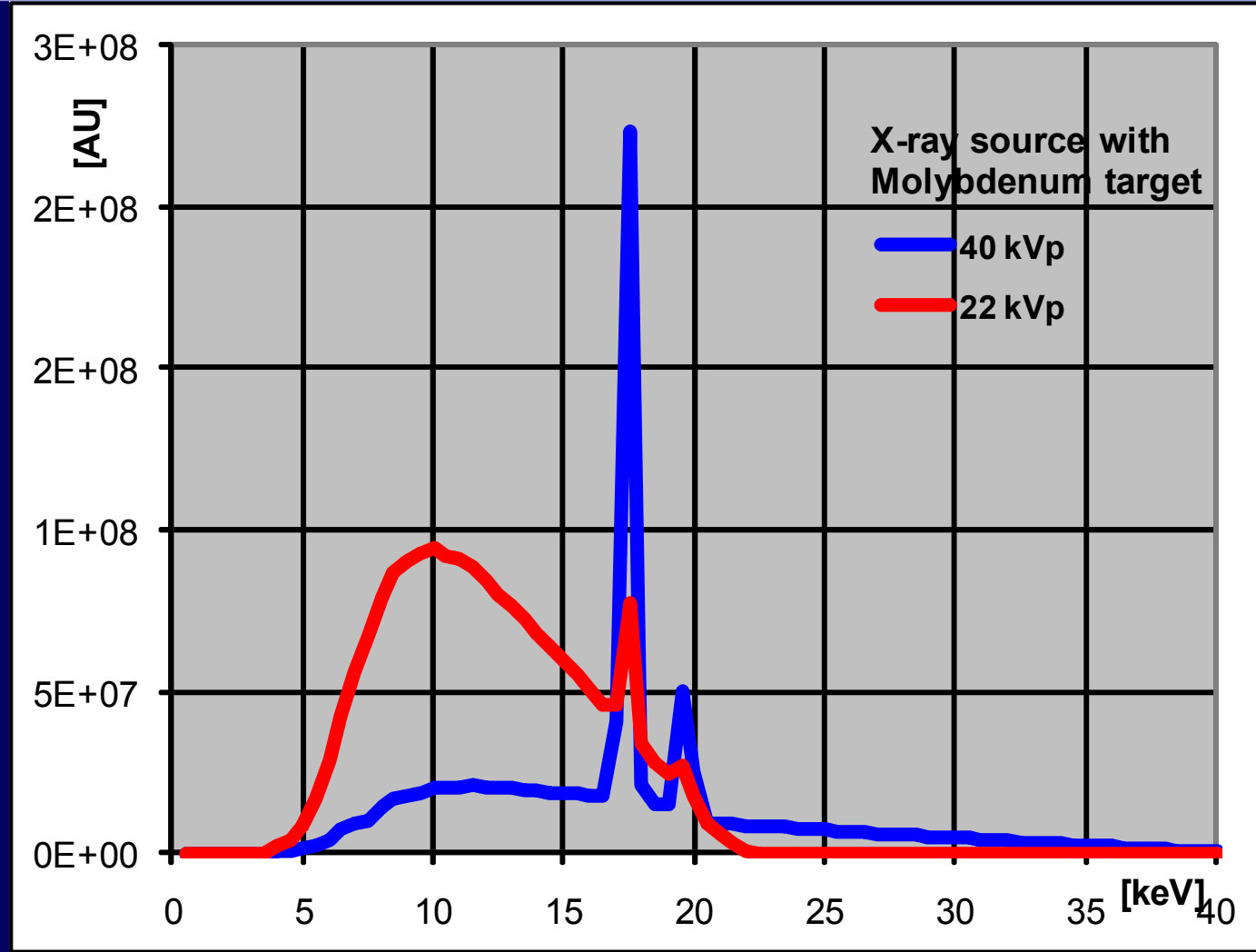
Set-up

- ⇒ Source: 22, 30 and 40kVp X-ray source voltages
- ⇒ Acquire 3 consecutive exposures with different energies
- ⇒ Classic DR detector
- ⇒ See references in abstract

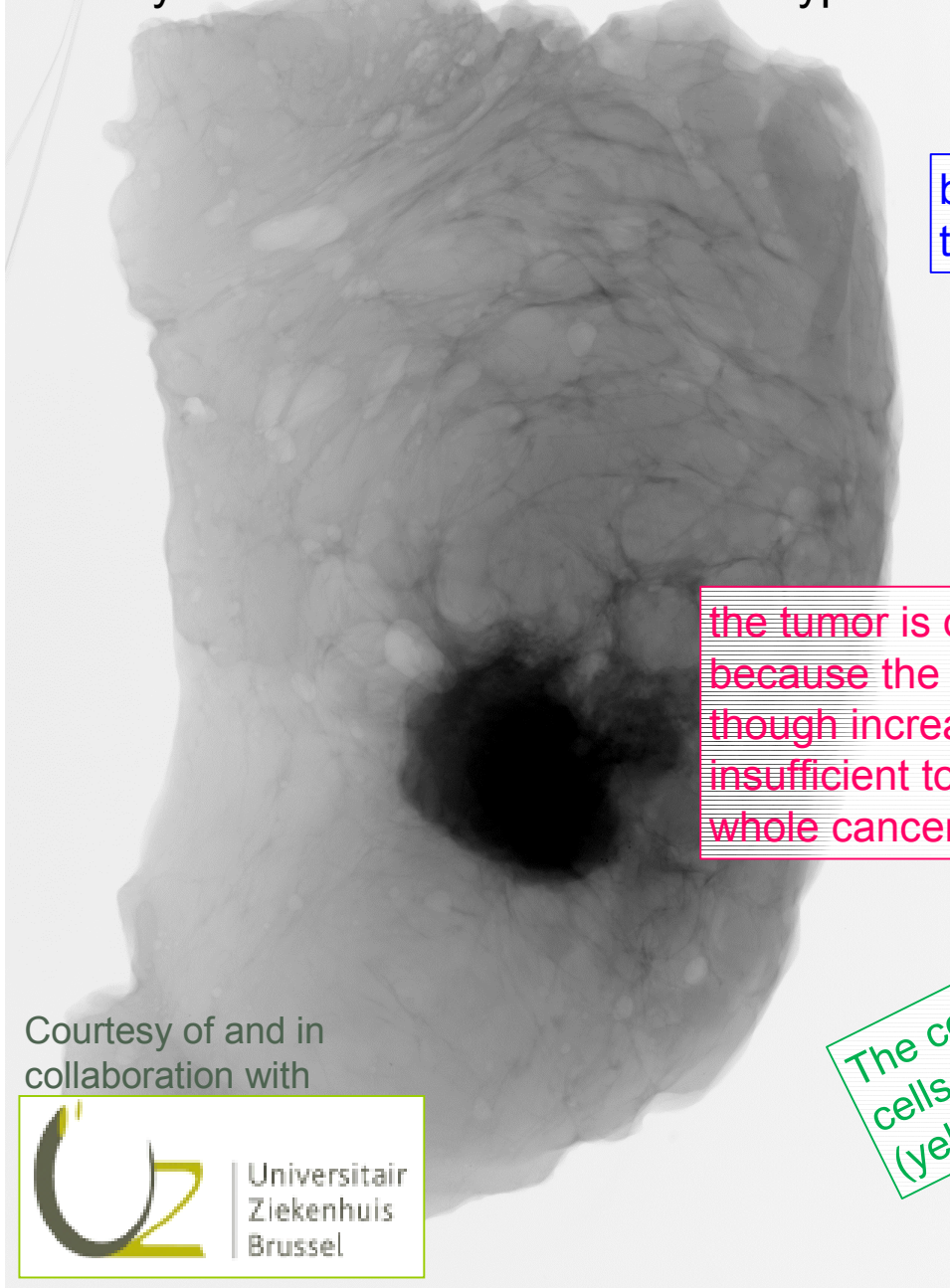
For display purposes

- ⇒ Inverse Beer's law to obtain a linear thickness/blackness relation
- ⇒ Normalization of the thickness/blackness of each spectral image, their average becoming the "luminance" of the displayed color image.
- ⇒ Code the ratio of the pixel values of the 3 images as "hue+saturation".

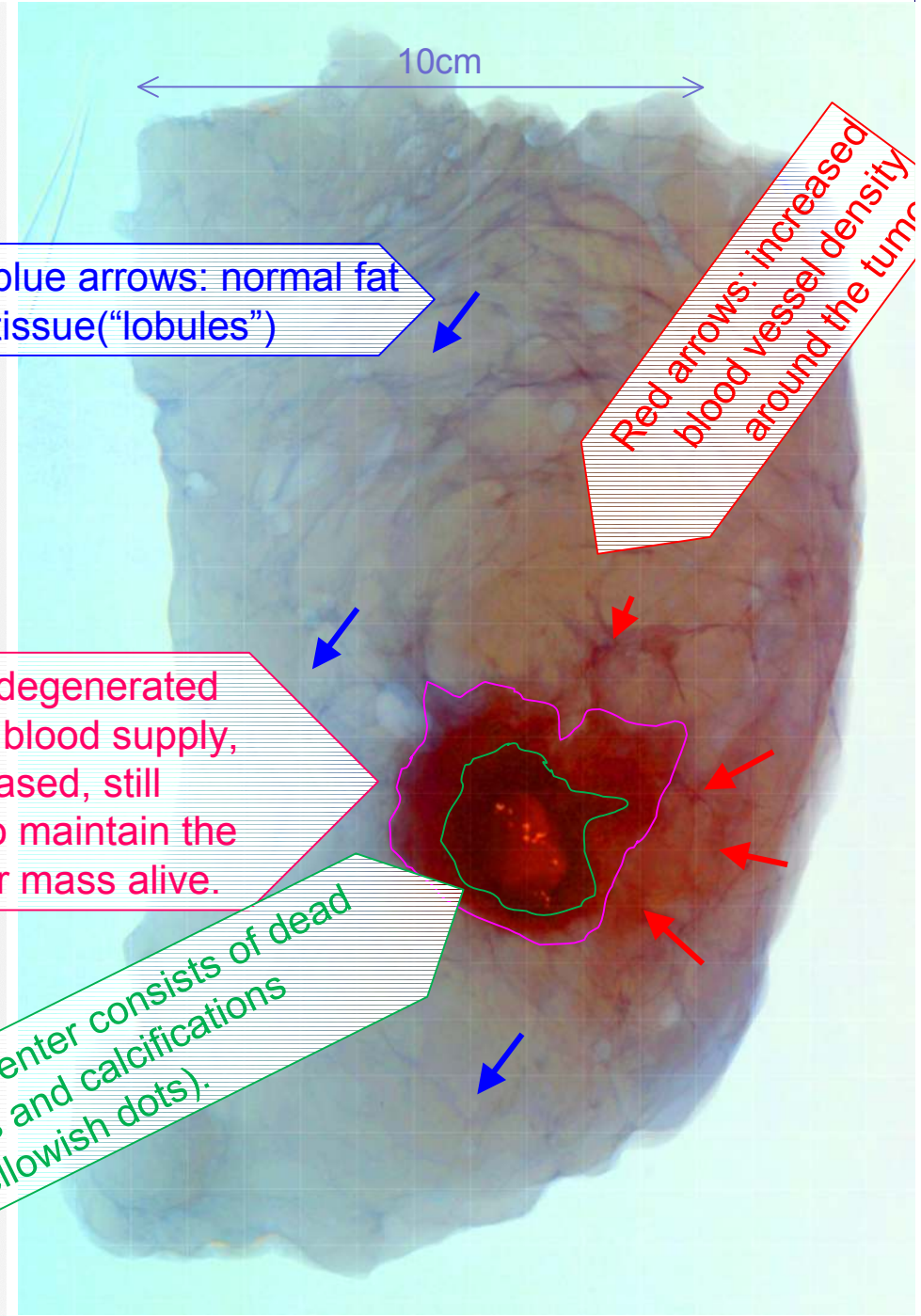
X-ray spectrum used in color mammography experiment



Breast carcinoma specimen
"Poorly differentiated invasive duct" type.



Courtesy of and in
collaboration with



blue arrows: normal fat
tissue("lobules")

Red arrows: increased
blood vessel density
around the tumor

the tumor is degenerated
because the blood supply,
though increased, still
insufficient to maintain the
whole cancer mass alive.

The center consists of dead
cells and calcifications
(yellowish dots).

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➔ Design of a photon counting demonstrator

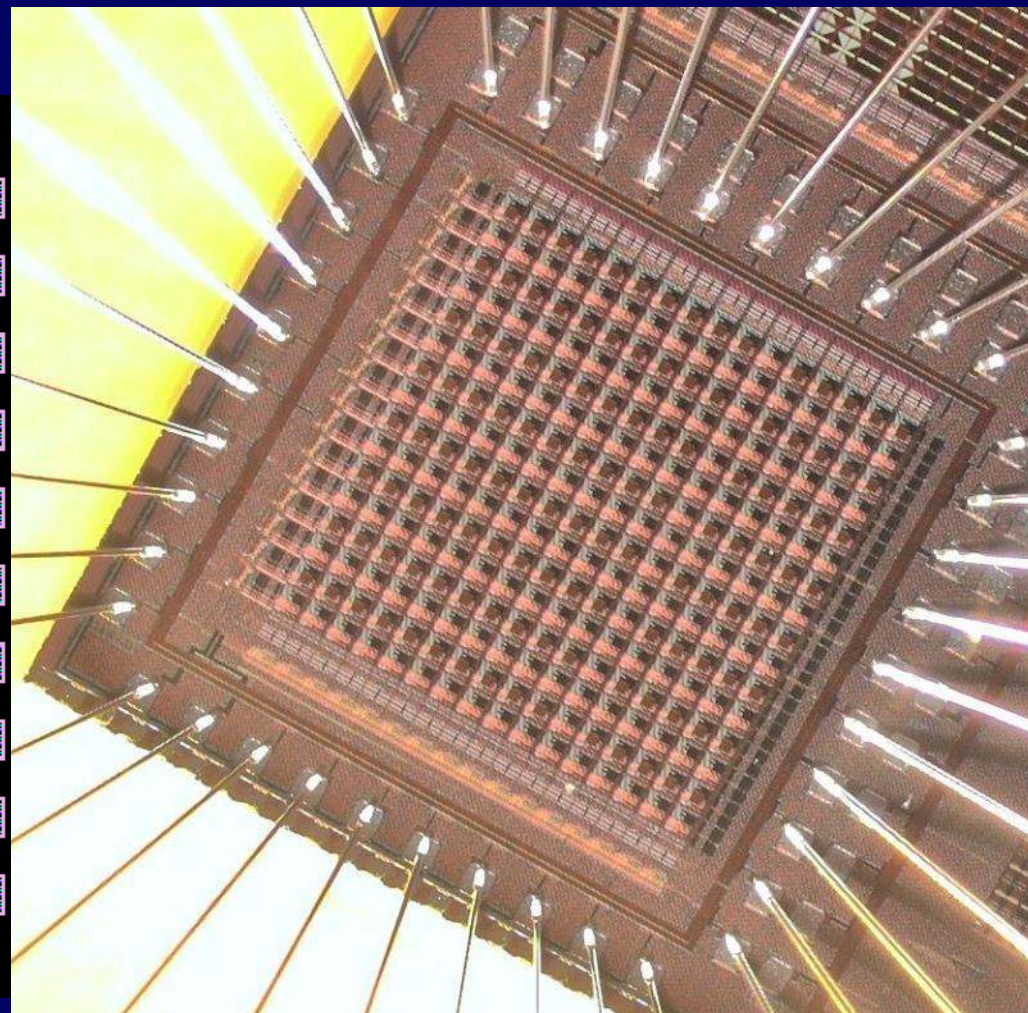
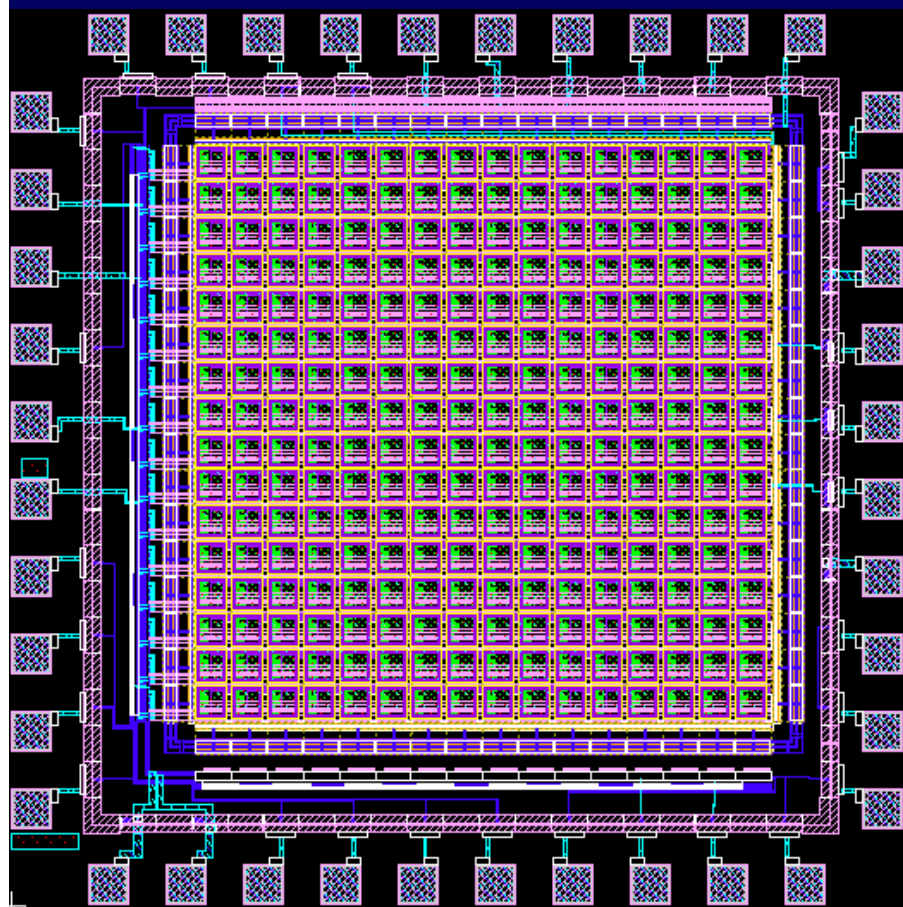
- ⇒ Specifications of the demonstrator array
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- ⇒ First measurement results

Specifications of a 2D XPC demonstrator

- 16x16 pixels
- 100 μ m pitch
- X/Y addressing scheme, slow scan
- 8 variant pixel electronics
- 5 photo diode types
- Each pixel contains
 - ⇒ Pulse shaper + comparator + counter + readout mux
- 0.18 μ m CMOS technology

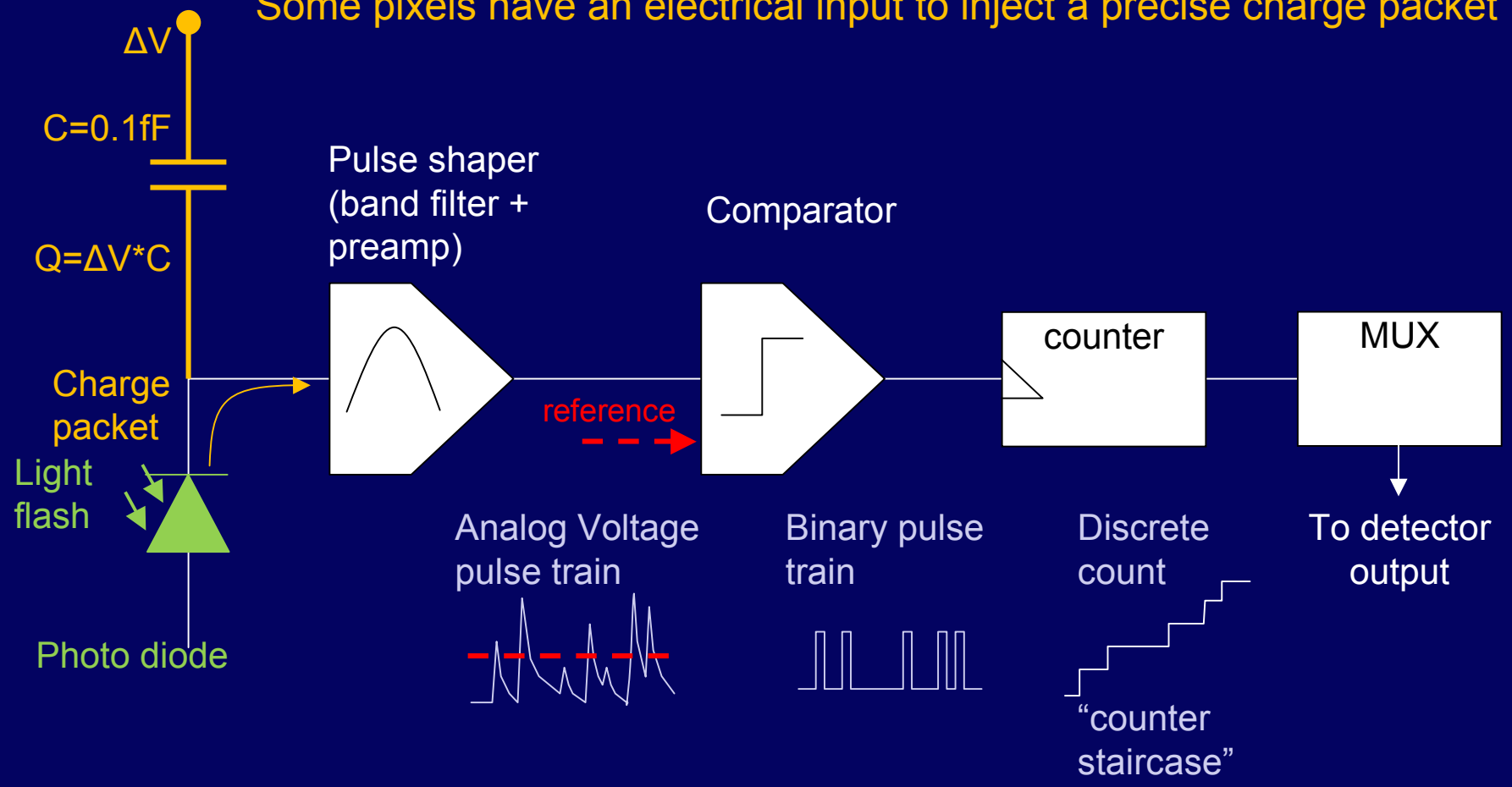
Patents pending

First generation of 2D photon counting pixel array

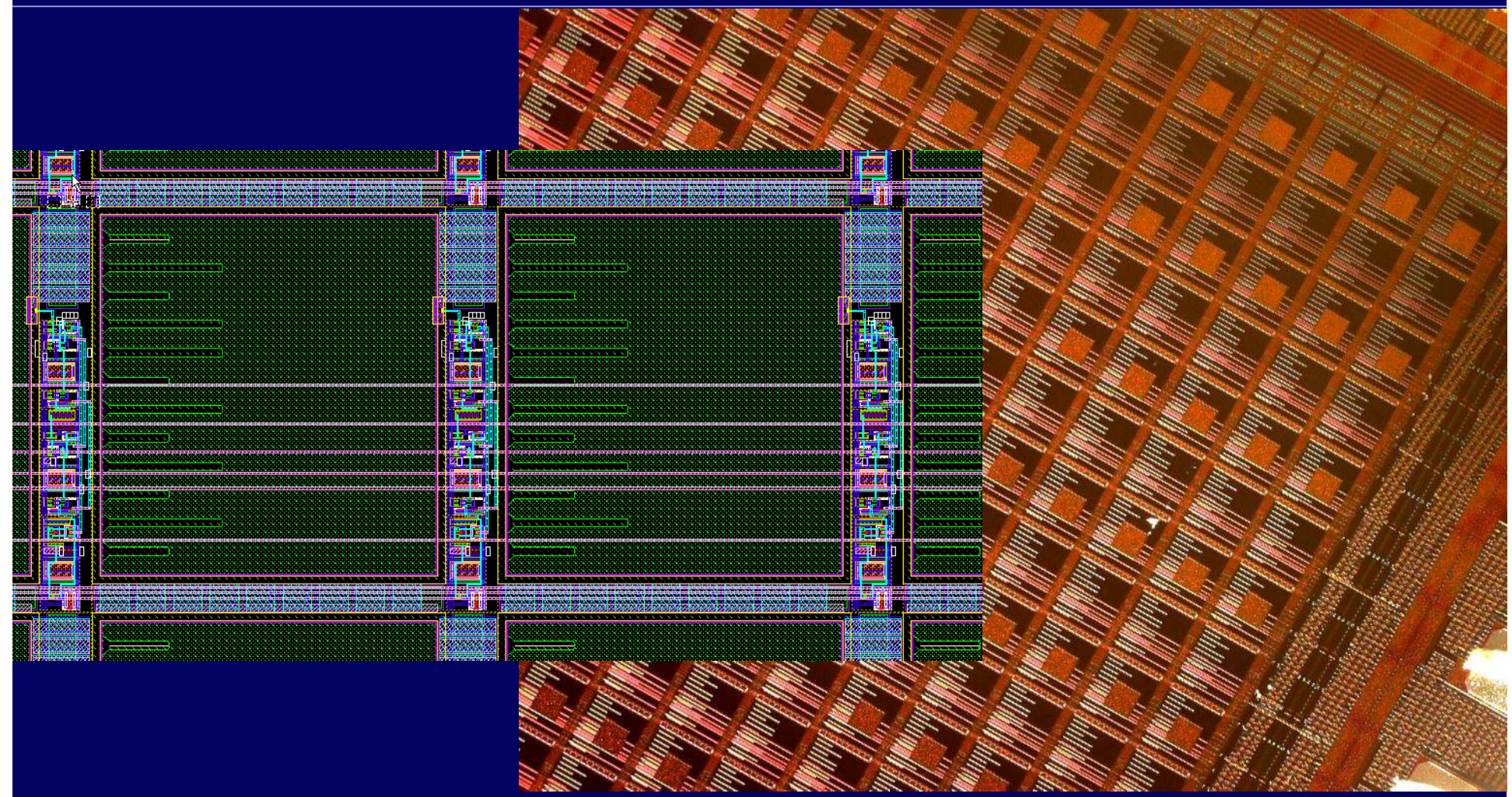


X-photon counting pixel general topology

Some pixels have an electrical input to inject a precise charge packet

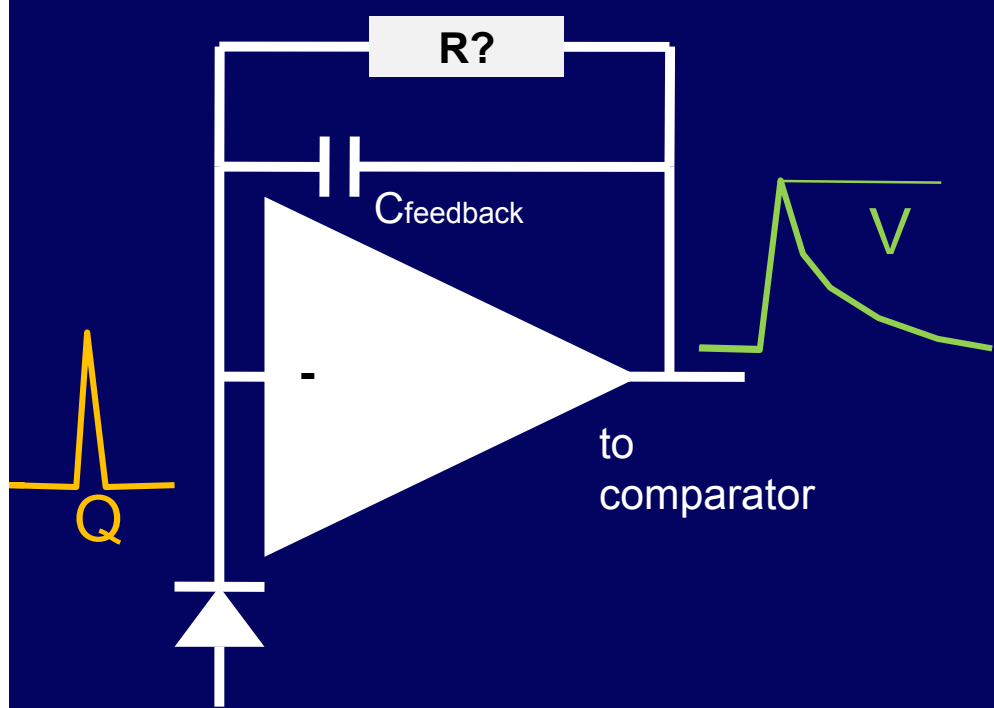


First generation of 2D photon counting pixel array, detail

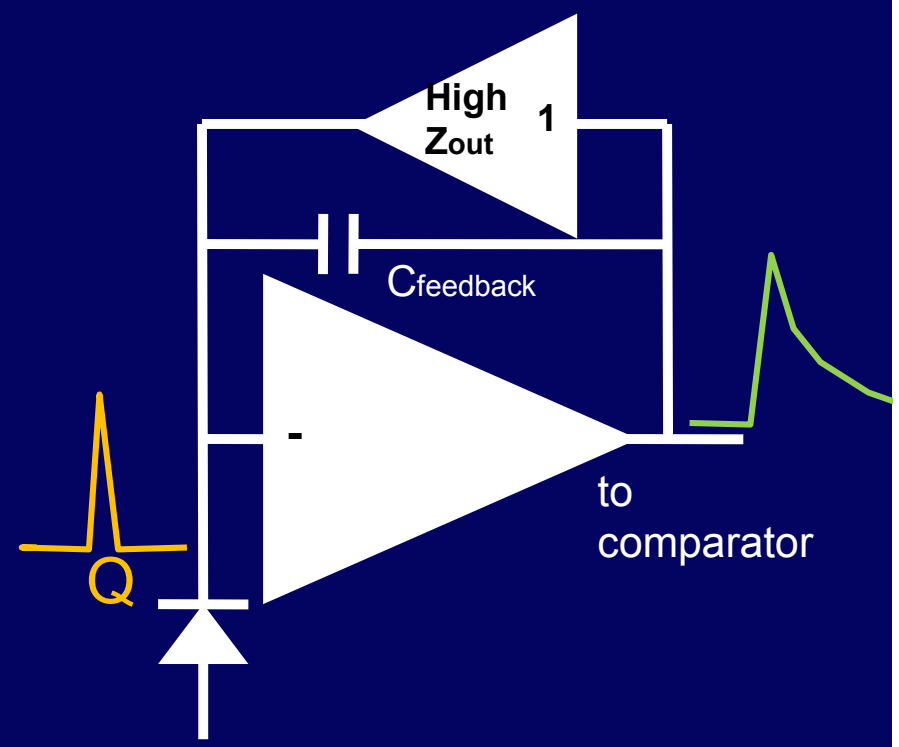


Pulse shaper: Current pulse to Voltage pulse

CTIA with very low feedback C and bandpass filter
 Integration = low pass
 Resistive feedback = highpass

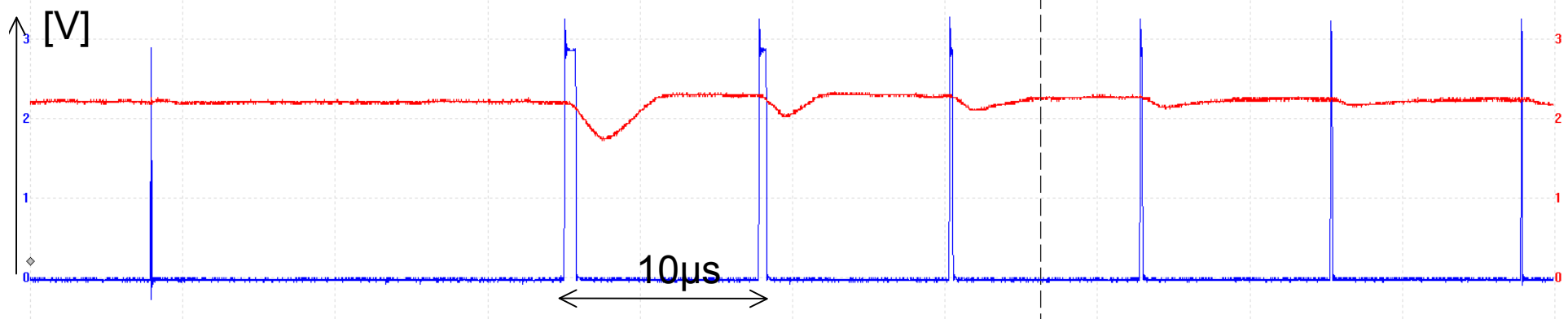


Theoretical pulse shaper with resistive feedback



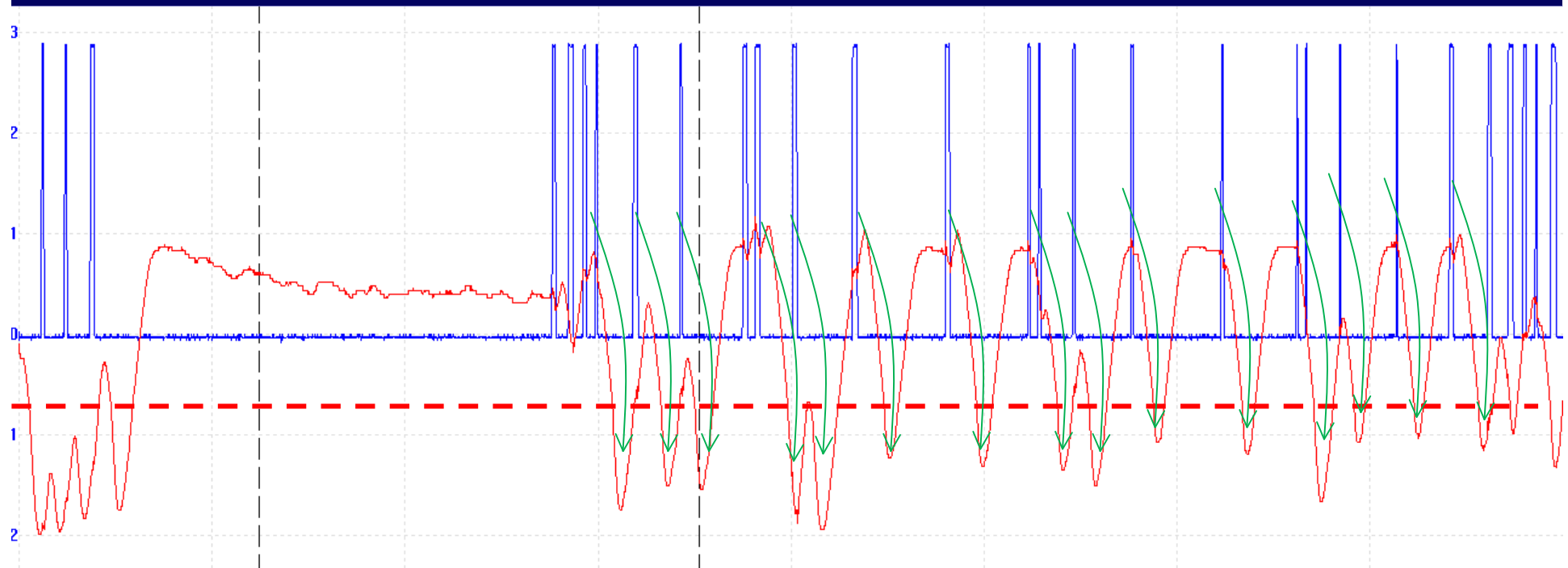
Practical pulse shaper with High Z_{out} OTA in unity feedback

Results: pulse shaper output



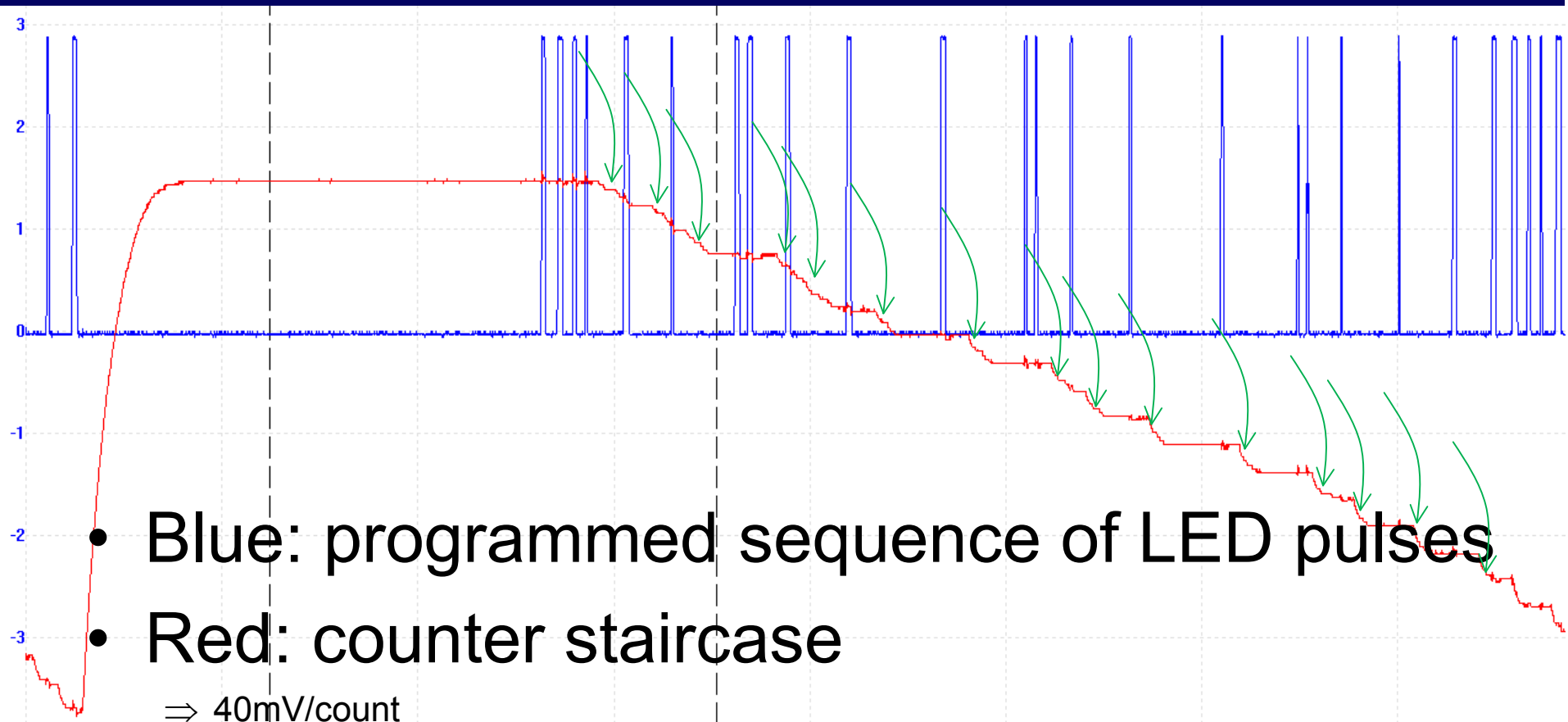
- Blue: sequence of pulses generated by a blue LED
 - ⇒ “emulates” the flash of a scintillator
 - Red: oscilloscope traces of pulse shaper response
- #visible photons/pulse programmed by pulse duration
- ⇒ 10000, 5000, 2500 etc electrons
 - ⇒ Raw estimate, difficult to calibrate

Pulse shaper output and counter staircase

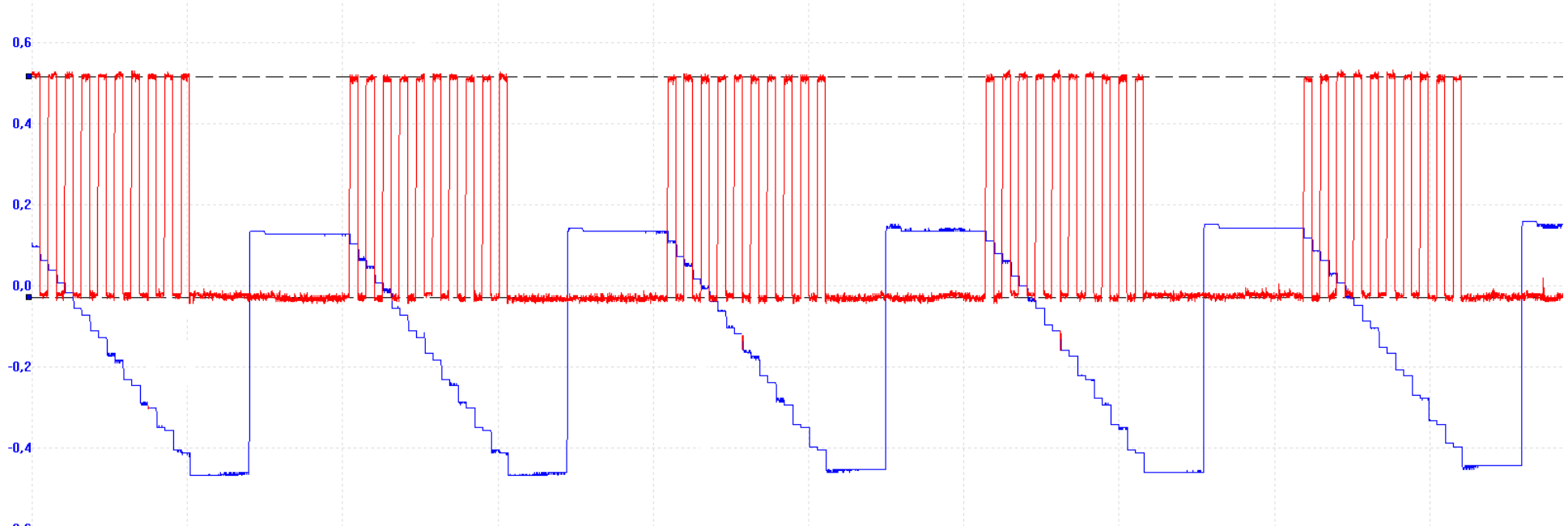


- **Blue: programmed sequence of pulses**
 - ⇒ Blue LED; variable pulse width
 - ⇒ Pulse interval between $1\mu\text{s}$ and $100\mu\text{s}$
- **Red: pulse shaper, input to comparator**

Pulse shaper output and counter staircase

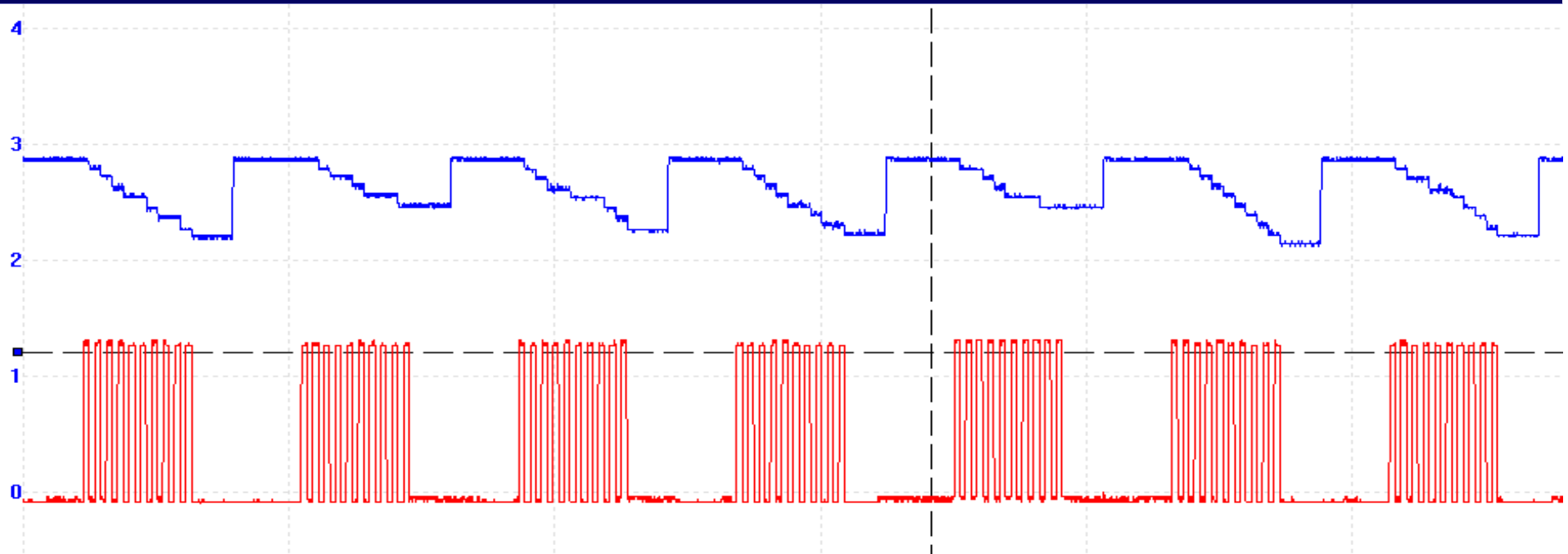


Counting performance: large packets



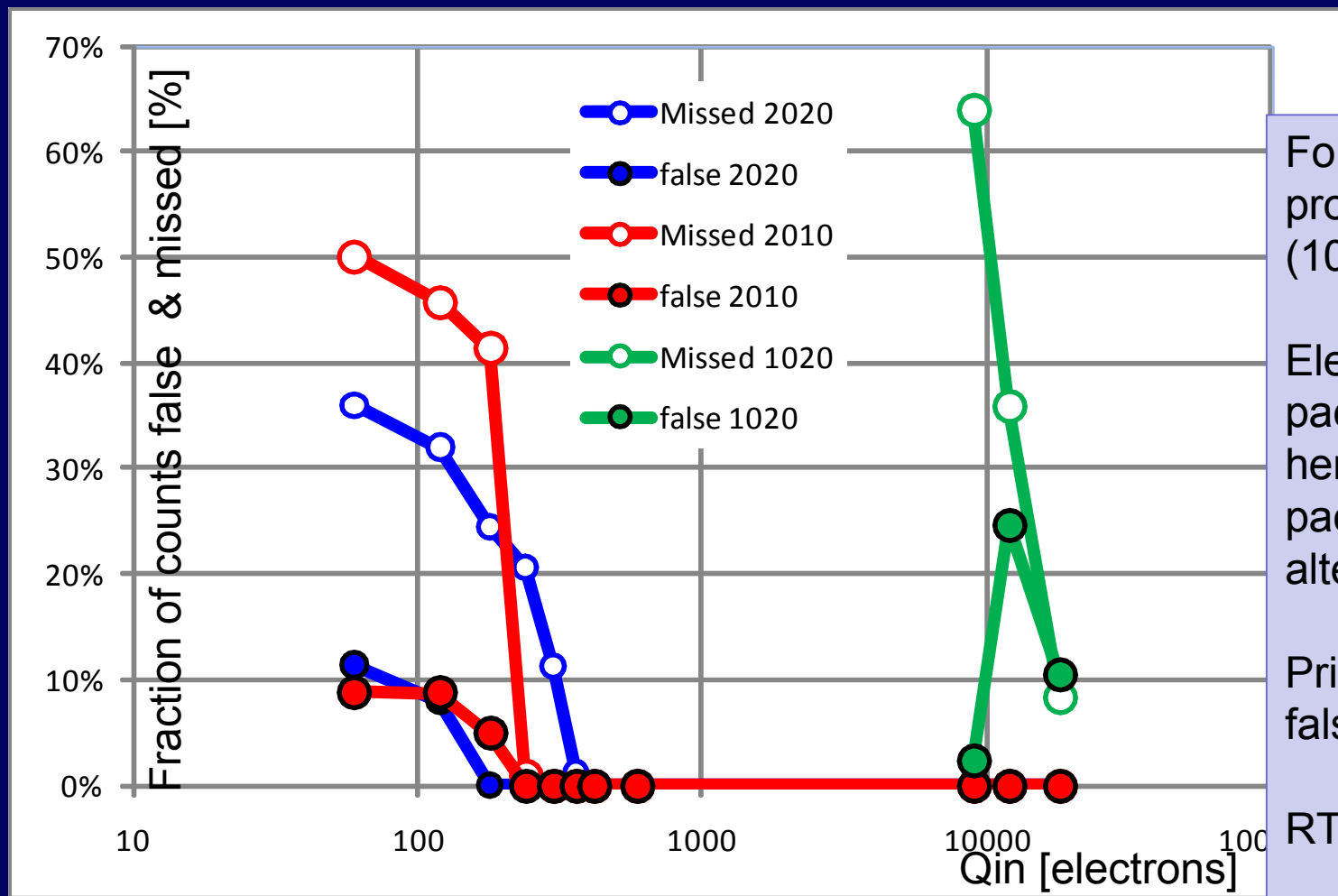
- 9000e⁻/charge packet
 - ⇒ applied by capacitive input (1.5V * 0.1fF)
 - ⇒ 10kHz bursts separated by “dark”
- No false counts, no missed counts

Counting performance near the noise threshold



- 120 e-/packet = $0.02\text{V} * 0.1\text{fF}$
- Missed counts: pulses not seen
- False counts: counting in absence of pulses

Counting pixel performance



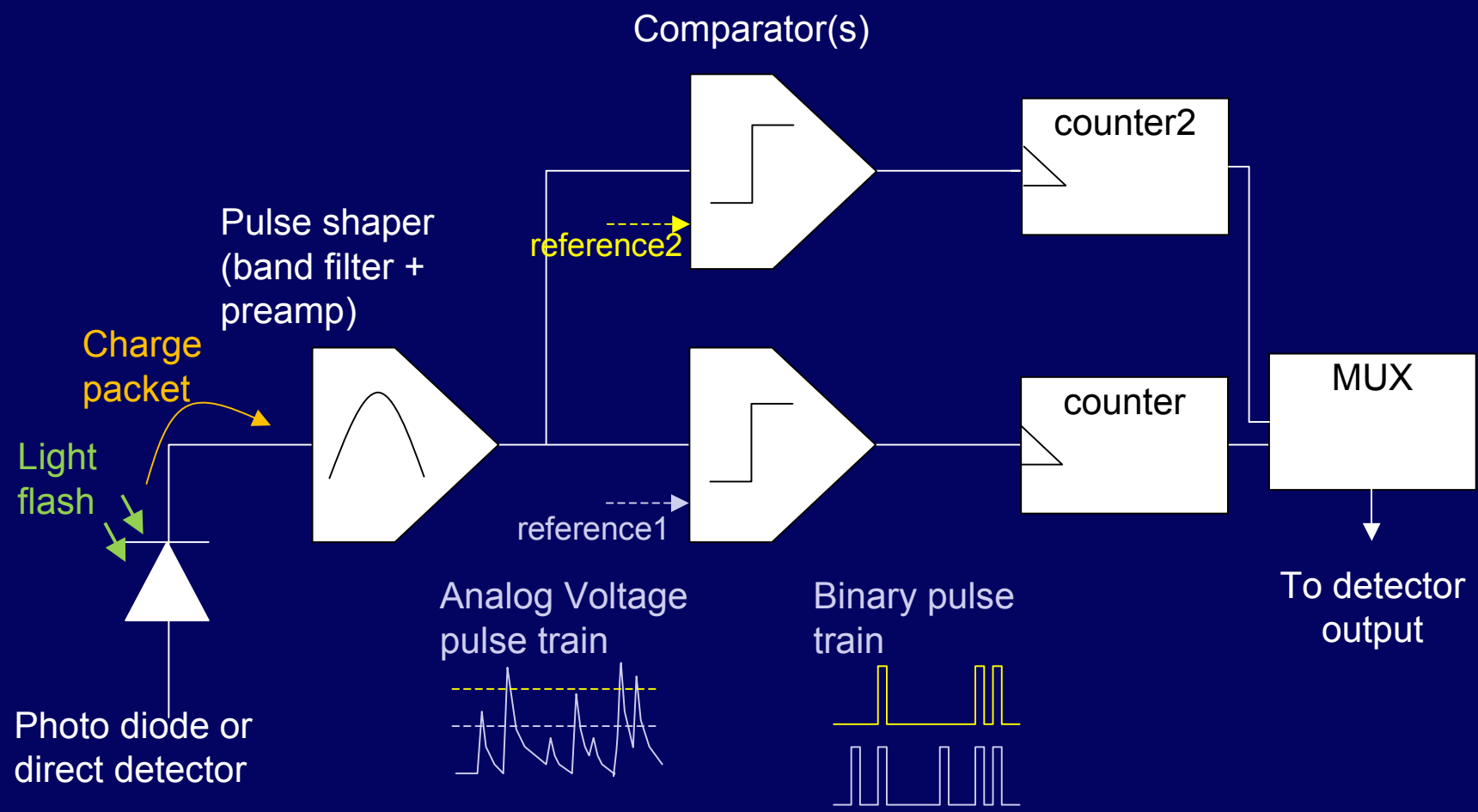
For 3 types of prototype pixels (1020, 2010, 2020)

Electrical charge packet injection, here bursts of 10 packets @10kHz alternated with rest

Priority given to low false counts

RT, Dark.

Color X-ray photon counting pixel concept



What stops us from manufacturing large 2D arrays?

Pixel Topology

- ⇒ Circuit complexity
- ⇒ Hybrid constructions both direct and indirect

Noise & accuracy of the comparator threshold

- ⇒ device noise (thermal noise, MOSFET 1/f noise etc.) and variability
- ⇒ electromagnetic interference, crosstalk

Manufacturing yield

- ⇒ High transistor count compared to classic integrating pixel topology
- ⇒ Near future large arrays (larger than 1dm²) with good yield

Maximum count speed

- ⇒ Counter speed limited by: scintillator decay time, photodiode charge collection time and the readout circuit speed

Conclusions

X-ray photon counting

- ⇒ Applies to both direct and indirect X-ray
- ⇒ Color X-ray is enabled by photon counting

Demonstration of miniature 2D array of photon counting pixels

- ⇒ Not yet multiple energy discrimination (color X-ray)
- ⇒ Promising results; “decent” counting capabilities down to $60e^-$ per pulse (= per X-photon)

- **Next?**

- ⇒ Large 2D arrays
- ⇒ Color X-ray by multiple comparators per pixel

Thank you

Acknowledging for the
color X-ray experiments



