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High Dynamic Range the pixel standpoint

Bart Dierickx
Caeleste CVBA
Antwerp, Belgium
www.caeleste.be
bart@caeleste.be

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1. Why do we need a wide dynamic range? √

   Examples of dynamic range scenes, extreme contrast scenes and what we would like to see in them

2. Dynamic range and S/N definitions √

   There is not a single definition for S, N, and even less for DR. We base the definitions on "noise equivalent contrast" (NEC)

3. Non-linear response √

   As a way to capture the highest possible dynamic range scenes. Derive which non-linear laws are optimal.

1. Why do we need a wide dynamic range?

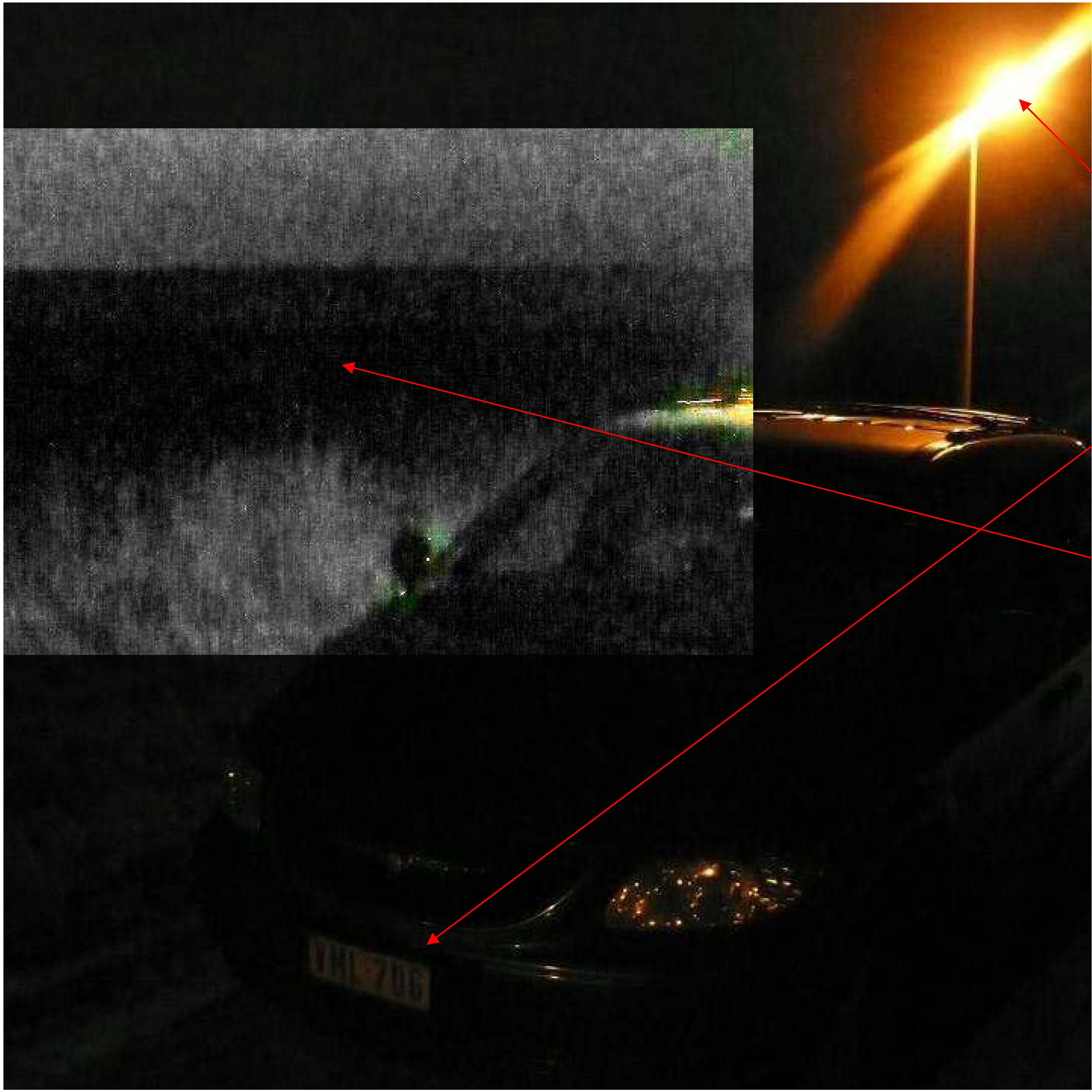
Wide dynamic range scenes
Extreme contrast scenes

Why do we need a wide dynamic range?

- To catch highlights
- To allow us to be lazy and not adjust camera speed to the scene
- To discriminate objects in any part (dark/bright) of the scene

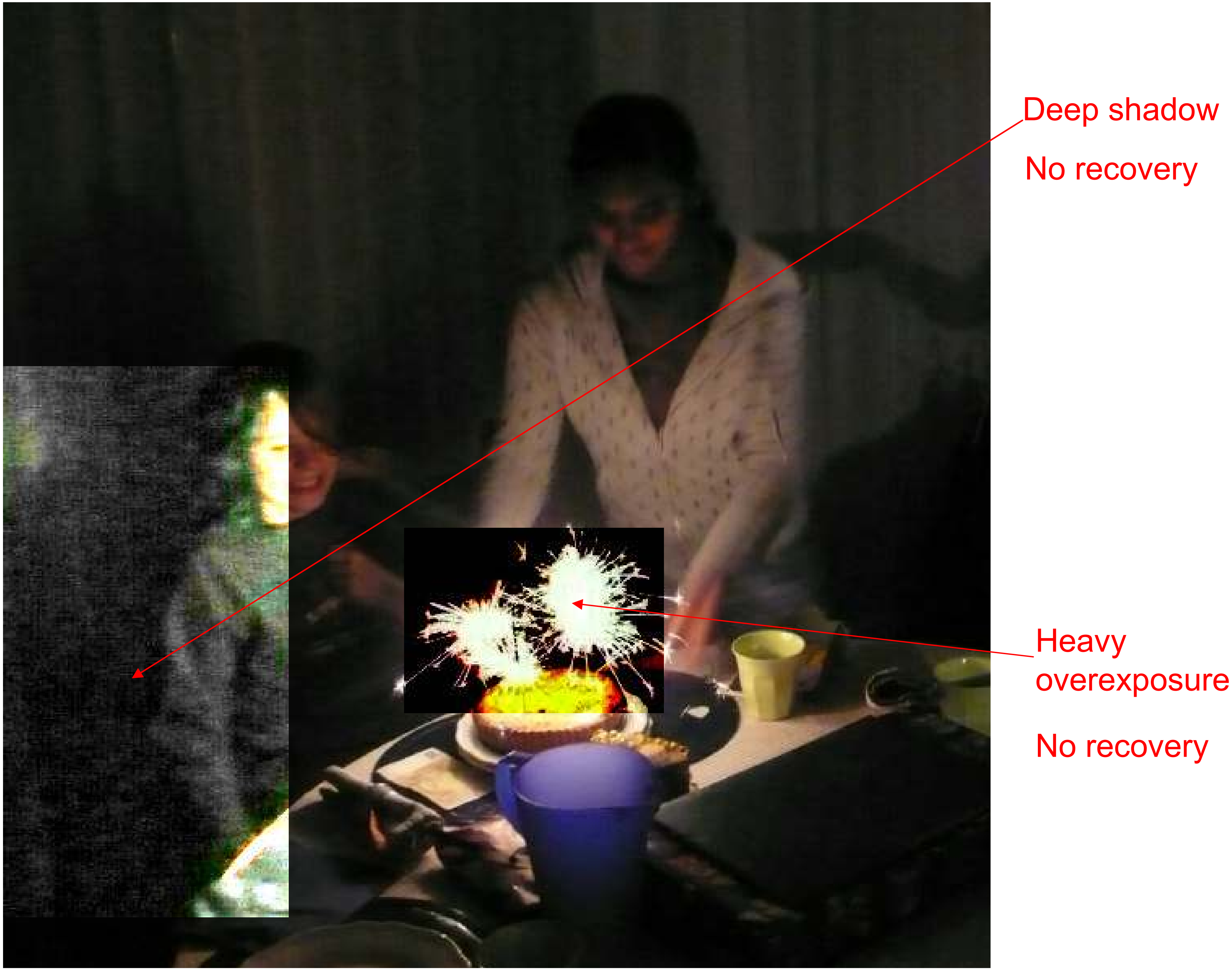
- Natural scenes
- Extreme contrast scenes

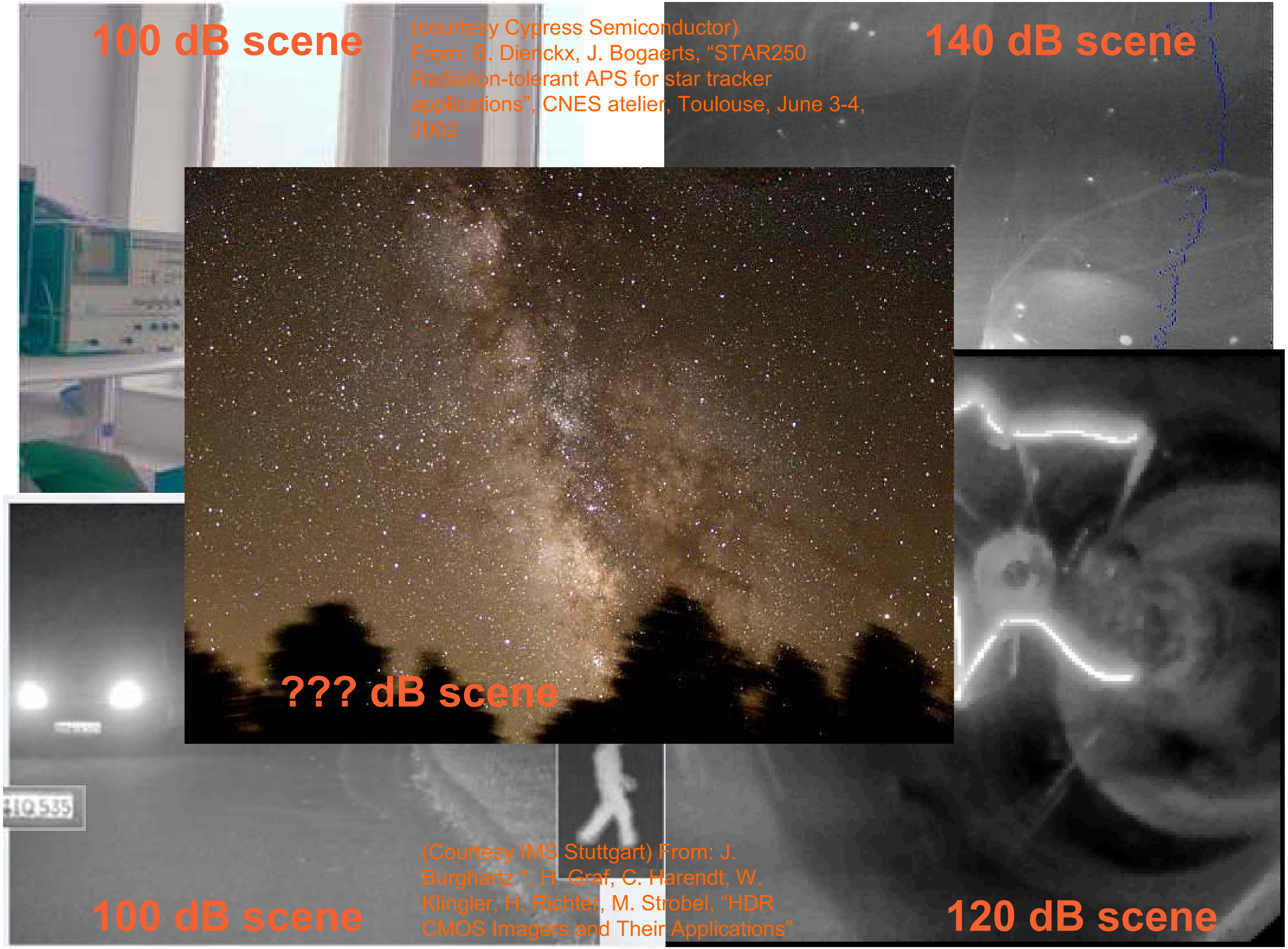

Highlight
Hidden in Shadow
Retro-reflection
Dark objects
Deep dark space
VML 706


High lights
Dark object
With some
contrast
Deep dark
background

Highlight
partly overexposed

In the shadow of a
shadowed scene


Deep shadow
No recovery
Heavy overexposure
No recovery


100 dB scene
(courtesy Cypress Semiconductor) From: B. Dierickx, J. Bogaerts, “STAR250 Radiation-tolerant APS for star tracker applications”, CNES atelier, Toulouse, June 3-4, 2002
140 dB scene
??? dB scene
(Courtesy IMS Stuttgart) From: J. Burghartz *, H. Graf, C. Harendt, W. Klingler, H. Richter, M. Strobel, “HDR CMOS Imagers and Their Applications”
100 dB scene
120 dB scene

… and while grabbing a wide dynamic range scene…

Don’t throw away the “sensitivity”

BTW what does sensitivity mean:
- High conversion ratio of light power to voltage?
- To see a faint signal in a limited exposure time?
- To see a faint signal in an unlimited exposure time?
- The ratio of the signal and the uncertainty thereof?

2. dynamic range definitions

Dynamic Range definition?

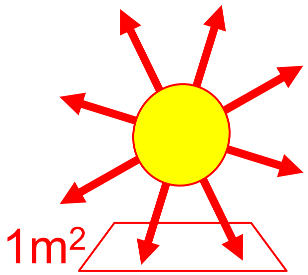
$DR_{wikipedia}$

Wikipedia: "Dynamic range is a term used frequently in numerous fields to describe the ratio between the smallest and largest possible values of a changeable quantity, such as in sound and light."

Applies to the scene, not to the sensor

- our "changeable quantity" is "P", "light" [W, W/m2, photons, lux…]
- "signal", "S", is the measurement result [V, ADC bits…]

prior definitions



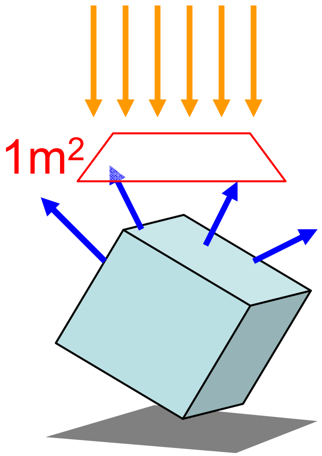
lamp
surface
(emittance)

Units:

W
Photons/s
Lumen
Candela

W/m²
Photons/s.m²
Lumen/m²=lux

For white light
Between 400-700nm
1W≈150…250Lumen



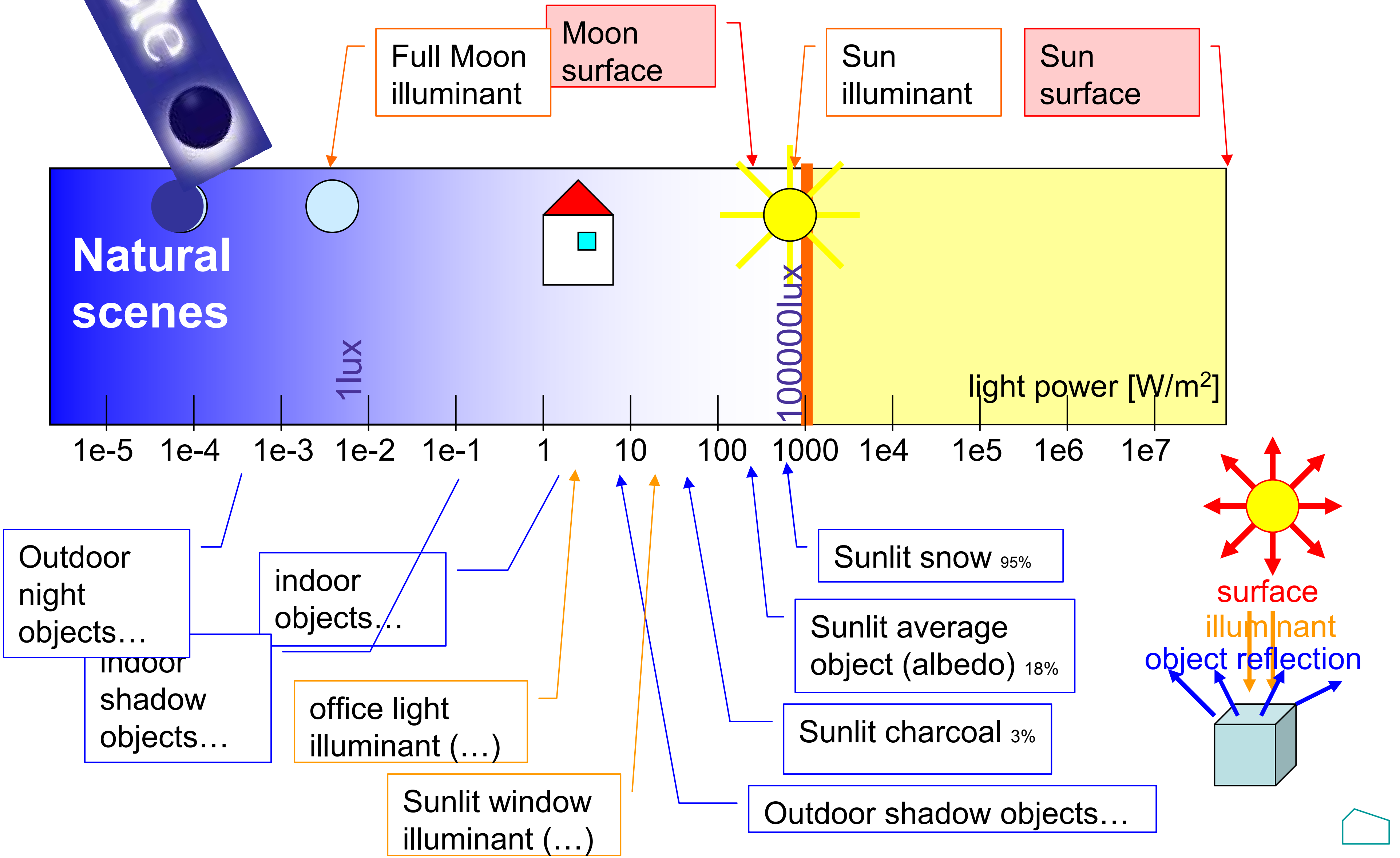
Illuminant
(illuminance)

object reflection
(emittance)

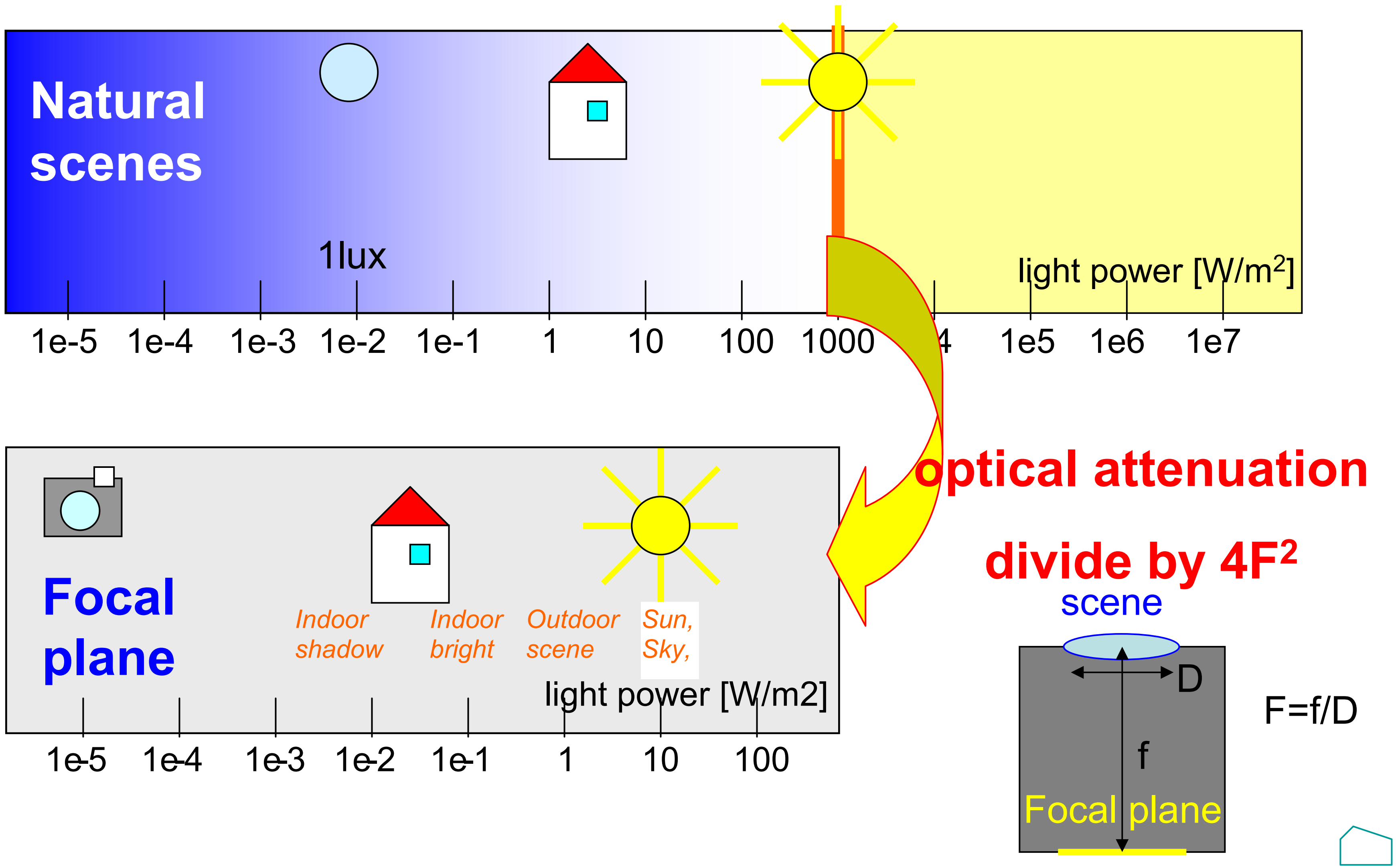
W/m²
Photons/s.m²
Lumen/m²=lux

For white light
Between 400-700nm
1lux*μm²≈4000photons/s
1lumen≈4E15photons/s
1W ≈ 8e17 photons/s

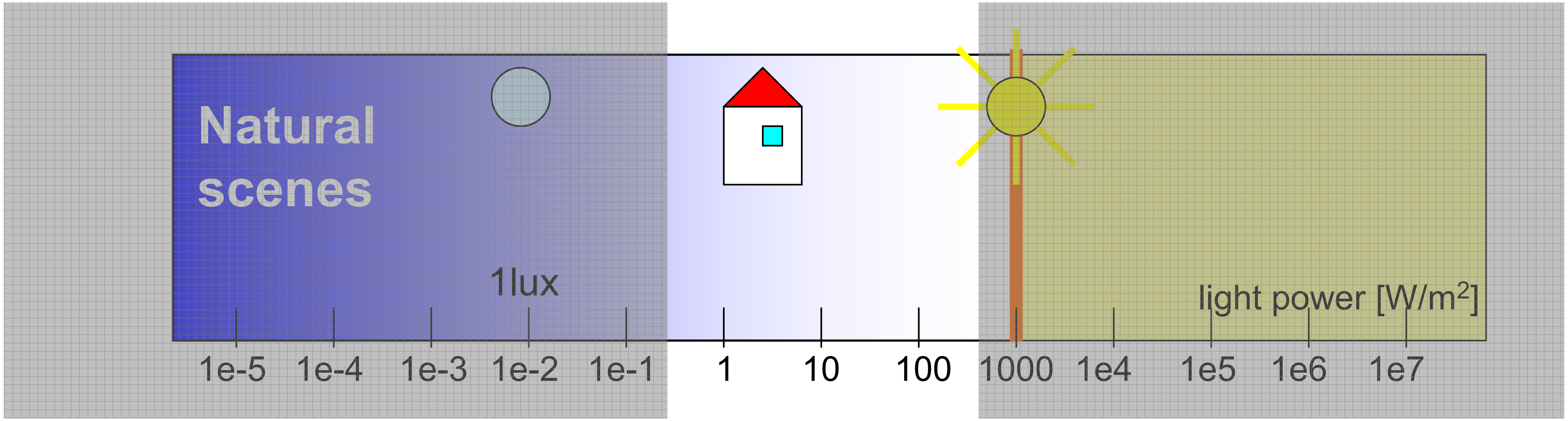
Natural scenes



From scene to focal plane



With a linear response sensor



Linear response sensor:

S/N or SNR = Dynamic Range?

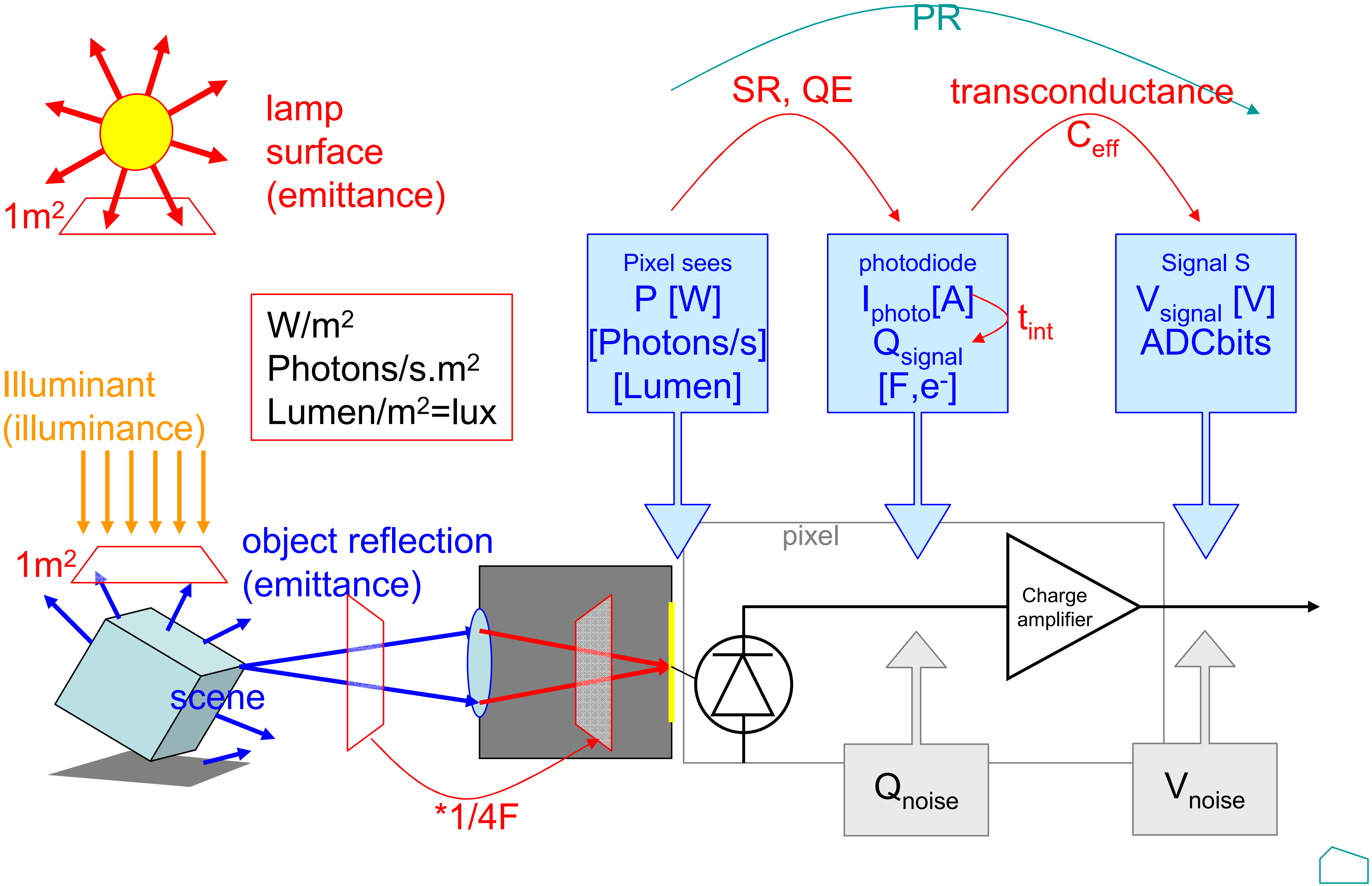
- typical: Between 1000: 1 = 60 dB — $S \approx 1V$, $N \approx 1mV_{RMS}$
- extreme high end: 10000:1 = 80 dB — $S \approx 2V$, $N \approx 200\mu V_{RMS}$

Dynamic range in sunlit scene: > 100 dB

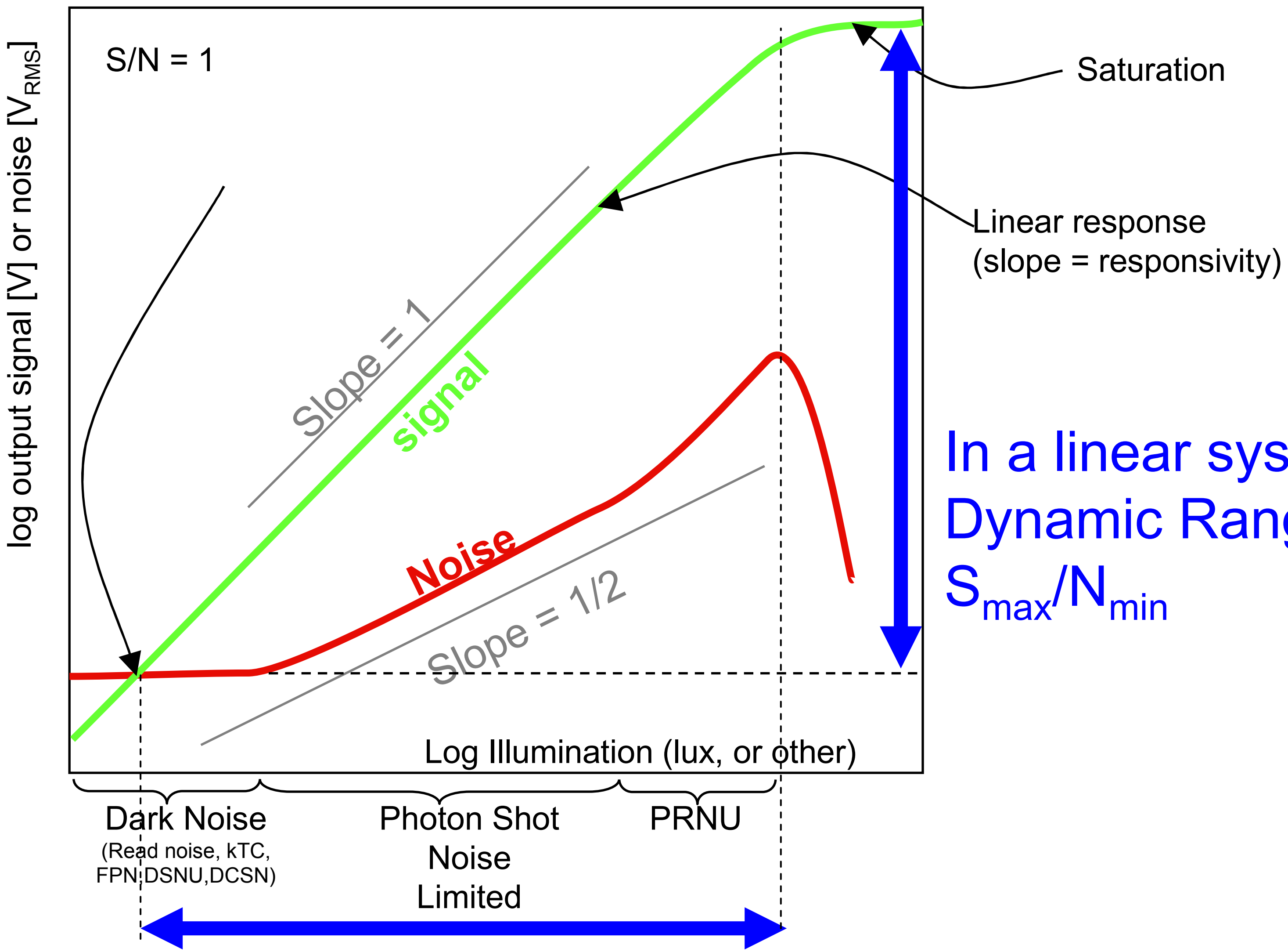
dynamic range definition, attempt 1

"DR is in light power domain what S_{max}/N_{min} is in voltage (signal) domain"

further definitions



DR = S/N ?



In a linear system Dynamic Range == S_{max}/N_{min}

Maybe there are S/N definitions suitable for non-linear systems?

- Signal, S, V_{signal} [V]
  - The maximum signal: S_{max}, V_{max}-V_{dark}
  - At the working point, referred to Dark: V-V_{Dark}
  - Linearized around working point
  - Take into account ∂V/∂Illumination or PR?
- Noise, N, V_{noise} [V_{RMS}]
  - At dark: N_{min}
  - Where S/N==1
  - At the working point

What is part of N?

- Spatial noises
  - Fixed Pattern Noise
  - Temperature dependent: Dark signal non-unifirmity (DSNU)
  - Signal dependent: Photo response non-uniformity (PRNU)
- Temporal noises
  - kTC, EMI, thermal and 1/f device noise, …
  - Temperature dependent: Dark current shot noise (DCSN)
  - Signal dependent: Photon Shot Noise (PSN)

Issue: some of these can be / are calibrated
→Maximal noise: all of these
→Minimal noise: only PSN and DCSN

Noise breakdown

in 6 orthogonal categories

	Temporal noise (variation of the signal of one pixel over time)	Spatial noise (variation signals of pixels within a frame, steady over time)
Noise that is invariant for temperature, integration time and illumination level	Temporal noise •kTC noise, reset noise •other pixel and circuit noise •EMI (random EMI, Row noise, Interference…) •ADC noise	Fixed pattern noise •Random FPN •Column/Row FPN •Other cosmetic flaws •EMI fixed interference patterns
Noise that depends on temperature and integration time	DCSN (dark current shot noise)	DSNU (Dark signal non-uniformity)
Noise that depends on the illumination level or signal level	PSN (photon shot noise)	Photo response non-uniformity •Random PRNU •Column PRNU •Other cosmetic flaws •Color PRNU

Dynamic Range definition?

$DR_{wikipedia}$

– *Wikipedia:* "Dynamic range is a term used frequently in numerous fields to describe the ratio between the smallest and largest possible values of a changeable quantity, such as in sound and light."

Applies to the scene, not to the sensor

The sensor should be able to catch that range

What does that mean?

DR, attempt 2

Generalized dynamic range definition, attempt 2

DR_{SNR1} = "ratio between highest and lowest light intensity for which S/N is greater than or equal to 1".

Dynamic Range definitions

Further attempts for definition

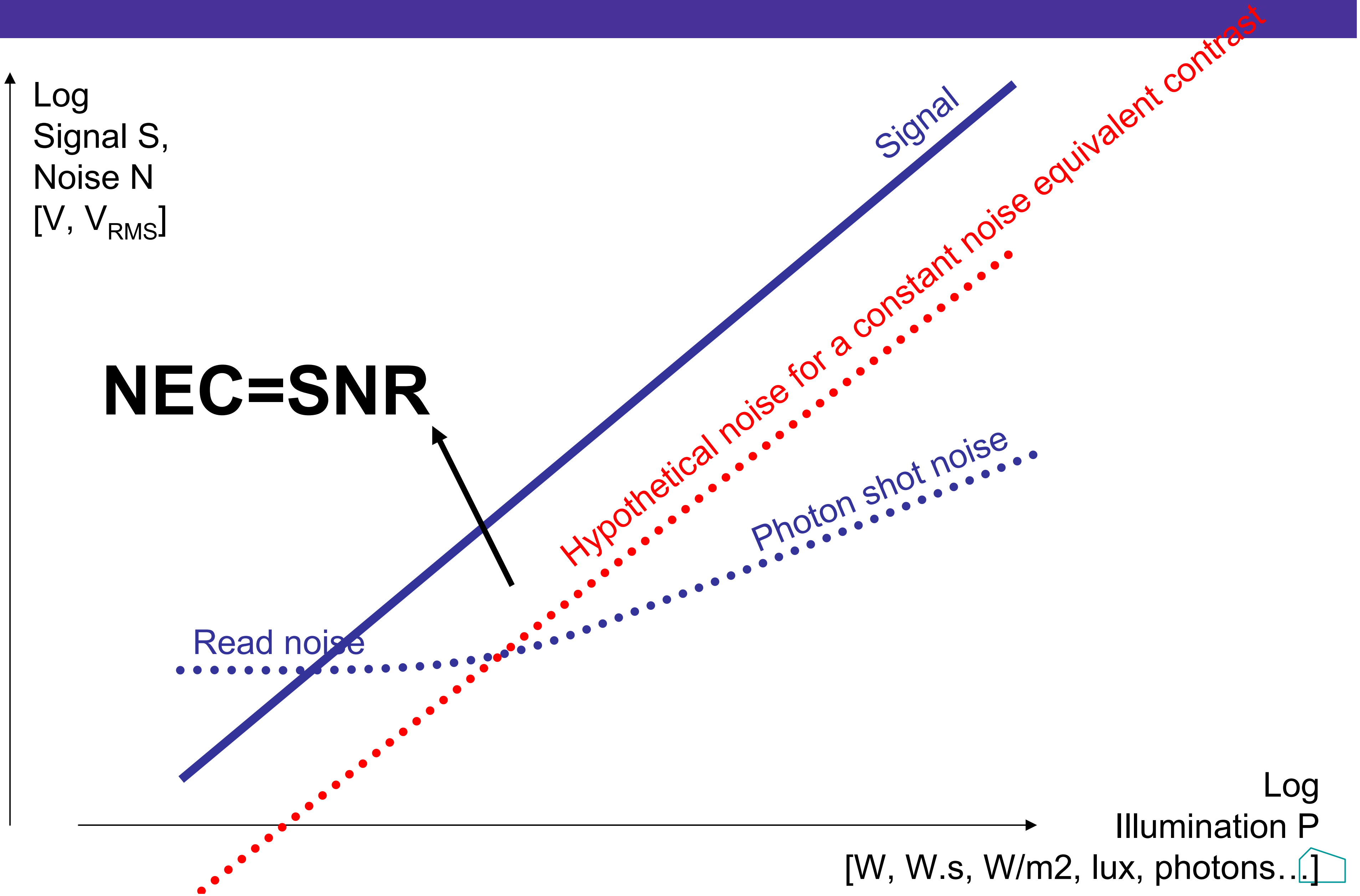
- The range of light intensity levels that can be captured by the image sensor within a single frame
- The range of illumination levels on a similar object within the same frame, for which the object is recognizable (=decent contrast, after image processing)
- The range of intensities that can be captured, for which the SNR has at least a certain value
- The range of intensities that can be captured for which the Noise Equivalent Contrast (NEC) has at least a certain value

Ratios between the measured quantity and the uncertainty on that measurement

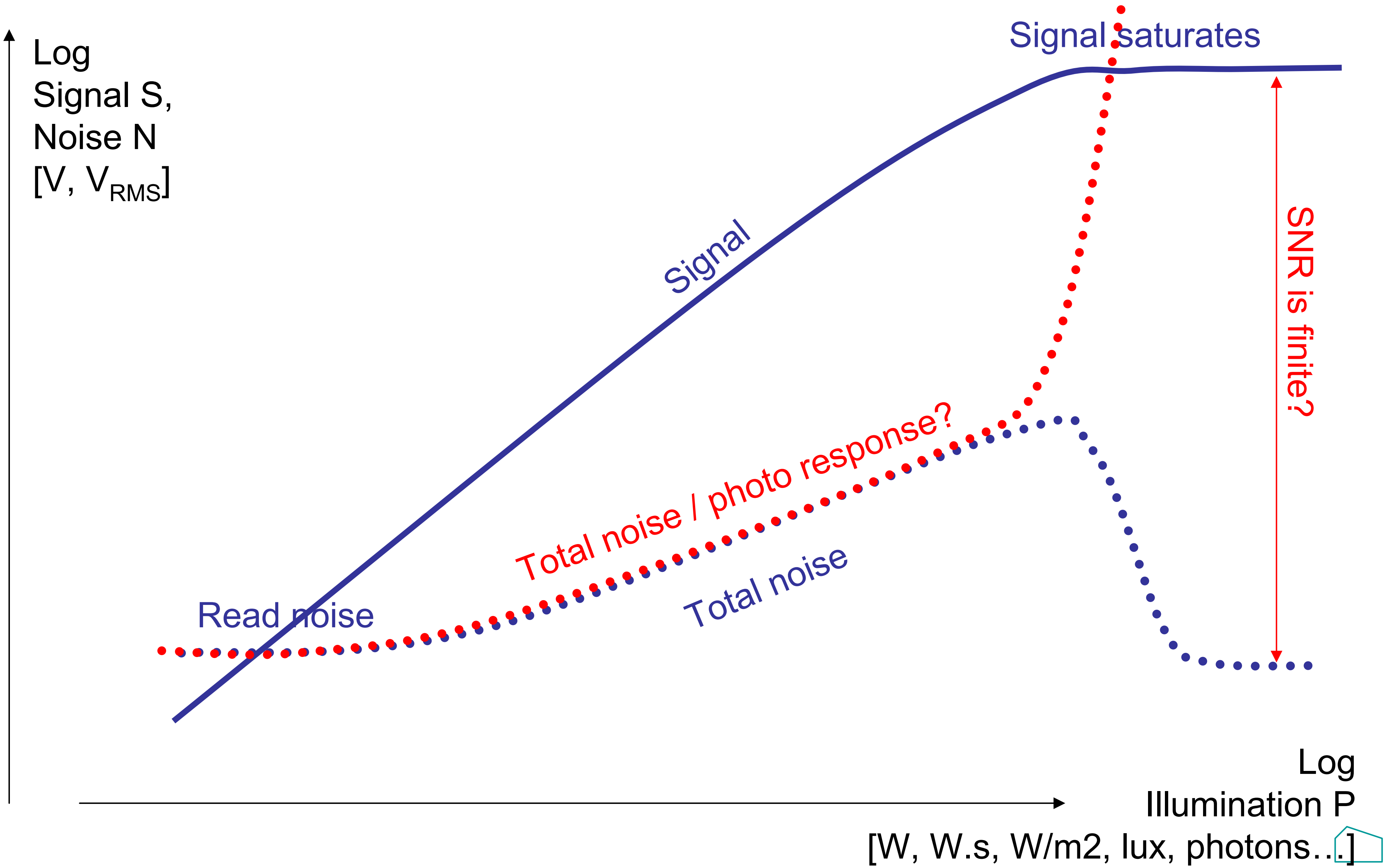
definition	**Symbol**	**Unit**	**How to obtain**
Signal to Noise Ratio	S/N_{max} SNR_{max}	1	sensor signal voltage range / sensor signal noise in the dark
Differential or small-signal signal to noise ratio	dS/dN dSNR	1	signal voltage / signal noise at that same signal level
Noise equivalent contrast ratio	NEC	1	The ability to discriminate between nearby grey levels *=1/(dSNR)*PR (where PR=photo response)*
Dynamic range	DR_{max}	1	Saturation *intensity* divided by noise equivalent *intensity* In a linear system this is the same as SNR_{max}.
Generalized dynamic range	DR_{SNR1}	1	the ratio between upper and lower *intensities* for which dSNR≥[value]
Generalized dynamic range	DR_{NEC10}	1	the ratio between upper and lower *intensities* for which NEC ≥ [value]
Linear dynamic range	LDR_x	1	DR_x with largest intensity for which dVolt/dIntensity is linear
ADC bits		1	Number of (useful) bits in the sensor's digital output
bits		1	Number of bits after image processing

Disclaimer: these suffixes are a clarification for this course. They are not used in practice.

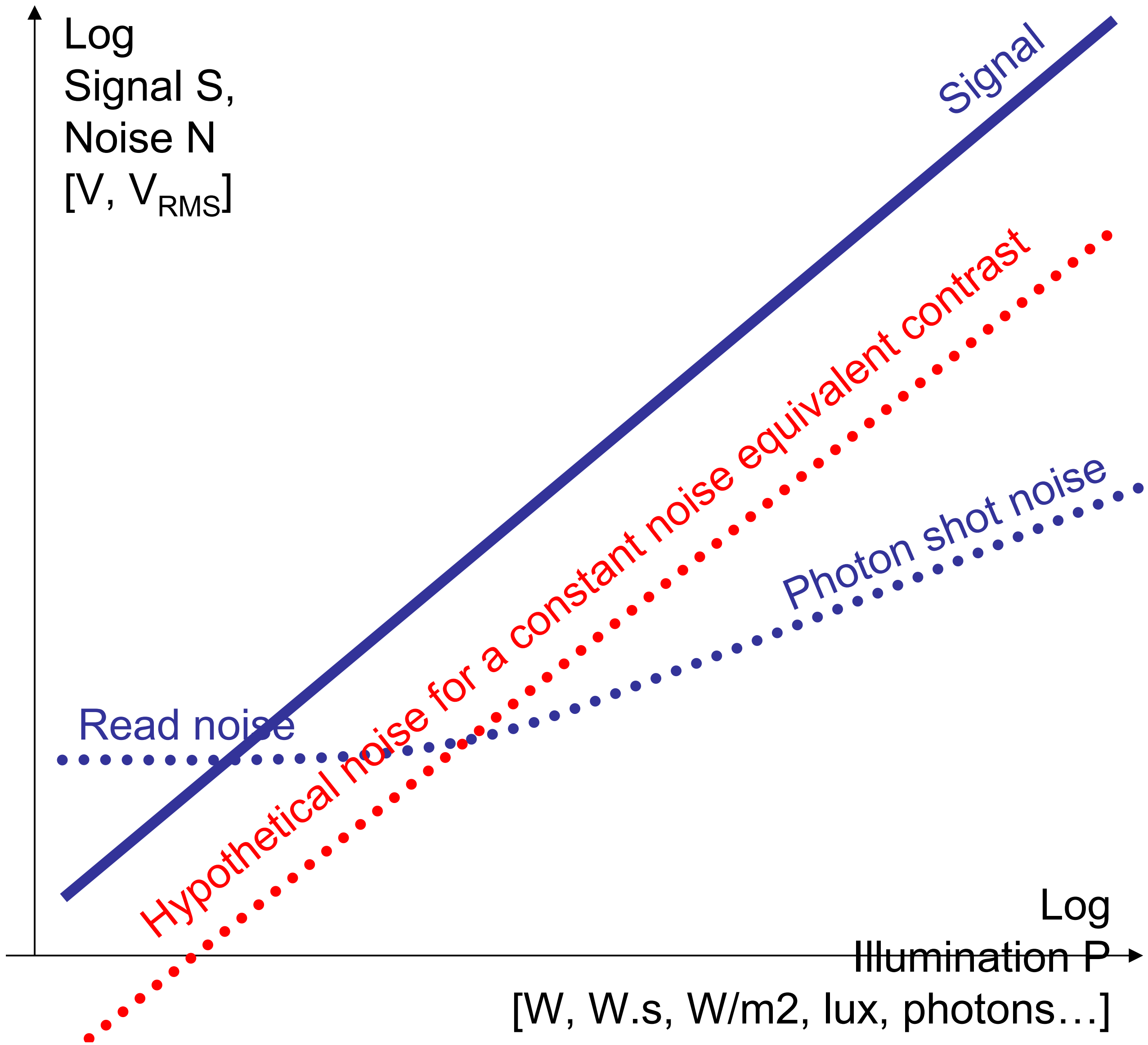
Constant N.E.Contrast - linear



In a non-linear system SNR≠NEC



Noise Equivalent Contrast - general



$$NEC = \frac{P}{NEP}$$

$$NEP = \frac{N}{Photoresponse} = \frac{N}{\left(\frac{\partial S}{\partial P}\right)}$$

$$NEC = \frac{P}{NEP} = \frac{P \cdot \frac{\partial S}{\partial P}}{N}$$

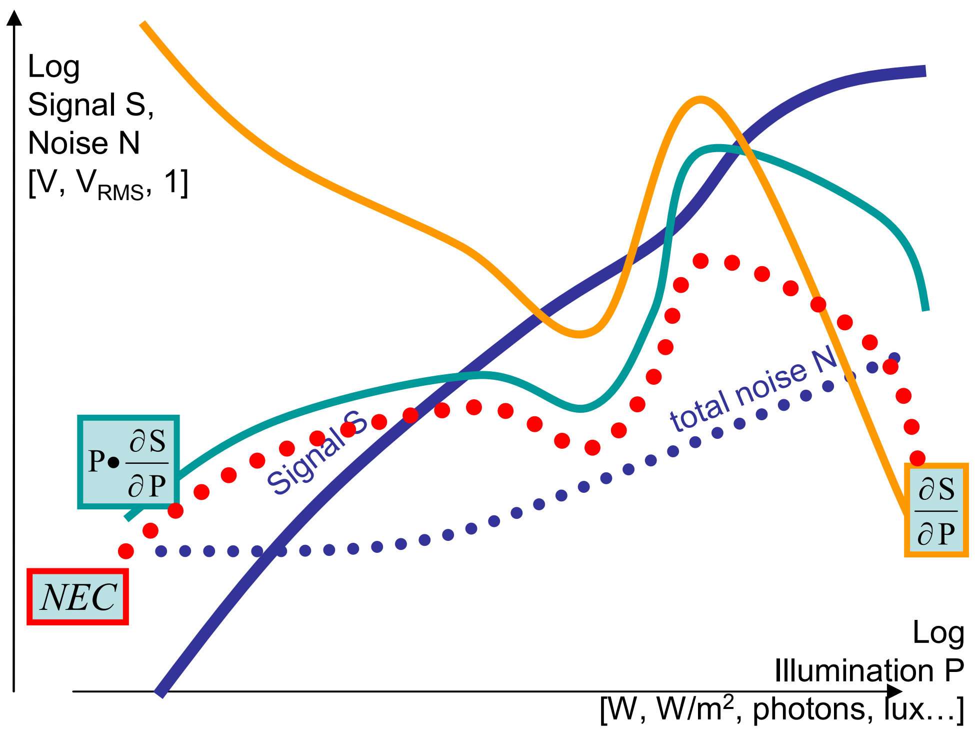
Noise Equivalent Contrast – non-linear

$$V_{signal} = S$$
$$V_{noise} = N$$

$$NEC = \frac{P}{NEP}$$

$$NEP = \frac{N}{Photoresponse} = \frac{N}{\left(\frac{\partial S}{\partial P}\right)}$$

$$NEC = \frac{P}{NEP} = \frac{P \cdot \frac{\partial S}{\partial P}}{N}$$



(In a linear system NEC == S/N)

Relation between NEC and Wide DR

- Goal: reach a constant or minimal NEC over the largest possible [dynamic range]$_{\text{wikipedia definition}}$

- Unproven underlying hypothesis: the largest range is obtained when NEC is just large enough, i.e. constant

$$NEC = \frac{P}{NEP} = \frac{P \cdot \frac{\partial S}{\partial P}}{N} = \text{constant}$$

In search for a constant NEC

- Exercise of thought:
  - Obtain the constant NEC by exploiting non-linear response
    - Increase DR by sacrificing NEC where it is sufficient
  - Non-linear response is obtained by
    - A non-linear transconductance, gain or $C_{effective}$
    - A non-linear integration time t_{int}
  - In the presence of noise of following kinds
    - A fixed amount in charge or light (as kTC…)
    - A fixed amount in voltage (other read noise, circuit noise)
    - Proportional to the √power (photon shot noise, PSN)
    - Proportional to the √integration time (dark current shot noise, DCSN)
    - Proportional to the power (photo response non-uniformity, PRNU)
    - Proportional to the integration time (Dark signal non-uniformity, DSNU)

$$V_{signal} = \frac{t_{int} \cdot I_{photo}}{C_{eff}}$$

Spare slide

Is ISO a potential measure for dynamic range?

method	Formula	Border conditions
MMS Bristol's	ISO = 0.2 [W.s/m^2] / (t_{int}[s] * P[W/m^2])	White light, P is average of scene, 50% of saturation
Basler's	100 ISO corresponds to 0.1 Lux*sec	Where the average P is at 18% of a linear grey scale
Michael Kriss'	ISO Speed = 0.8/H	at a signal-to-noise ratio of 30
Interpreting ISO12232	ISO == (1.92 lx.s)/Lf.t Lf [lx] = focal plane luminance	at 18%...50% of saturation - *the level of saturation itself is a parameter that one may change*
Kodak's "saturation based" ISO	ISO = (15.4 * f^2) / (Ls * t)	Ls[lx] = scene luminance 18/106 saturation *(18/170 for professional photography)*
Kodak's "noise based" ISO	ISO = 10 / H H = exposure in [lx.s]	SNR is either **40** (excellent image) or **10** (acceptable image), all noises included

Does not account for color information	Does not account for image processing
Does not account for effect of resolution on subjective perception	Does not account for dynamic range

3. non-linearity

non-linear response as a way to increase the sensor's capability to capture a wide dynamic range scene

non-linear response as a way to exploit the fact that the noise level depends on the scene contents

“dynamic range > 80 dB cannot be reached with a linear response sensor” – so what?

$$V_{signal} = \frac{Q_{signal}}{C_{eff}}$$

$$V_{noise} = \frac{Q_{noise}}{C_{eff}}$$

$$V_{signal} = \frac{t_{\text{int}} \bullet I_{photo}}{C_{eff}}$$

Modulation of the integration time

- Multiple slope response (piece-wise linear slopes)
- Non Destructive Readout

Modulation of the time constant

- Logarithmic response
- Lin-log

Modulation of the integration capacitance

- CCD with two wells
- Overflow MOSFET capacitors
- Adding multiple shorter integration periods
- Smart reset pixels

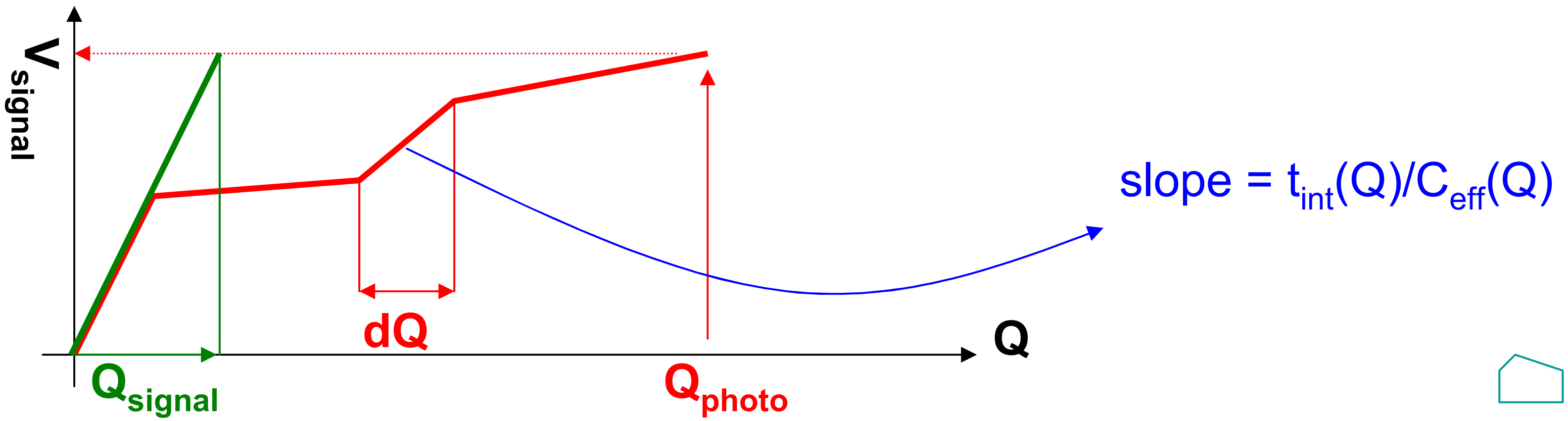
Non-linear version of $V_{signal}(Q)$

$$V_{signal} = \frac{t_{\text{int}} \cdot I_{photo}}{C_{eff}} \quad \text{(linear)}$$

$$V_{signal} = \sum \frac{t_{\text{int}} \cdot I_{photo}}{C_{eff}} = \frac{Q_{photo}}{t_{\text{int max}}} \cdot \sum \frac{t_{\text{int}}(Q)}{C_{eff}(Q)}$$

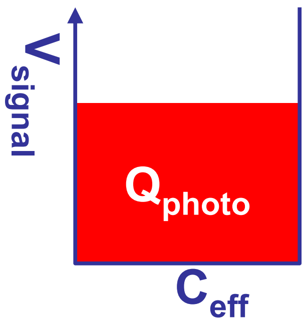
$$V_{signal} = \frac{1}{t_{\text{int max}}} \cdot \int_0^{Q_{photo}} \frac{t_{\text{int}}(Q)}{C_{eff}(Q)} dQ$$

•**We assume that the total photo charge is cut in pieces**
•**Each piece may have a different integration time or integration capacitor.**
•**Think on a charge accumulation axis, not on a time axis**



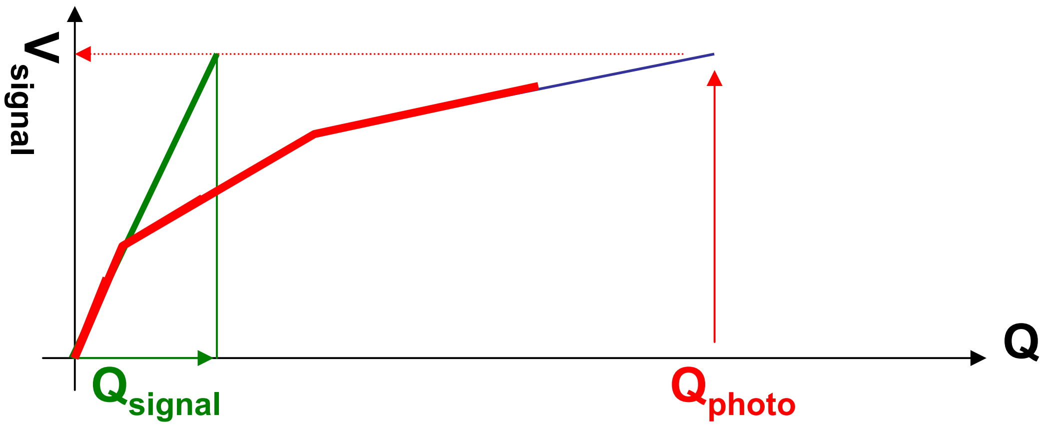
Non-linear version of $V_{signal}(Q)$ (2)

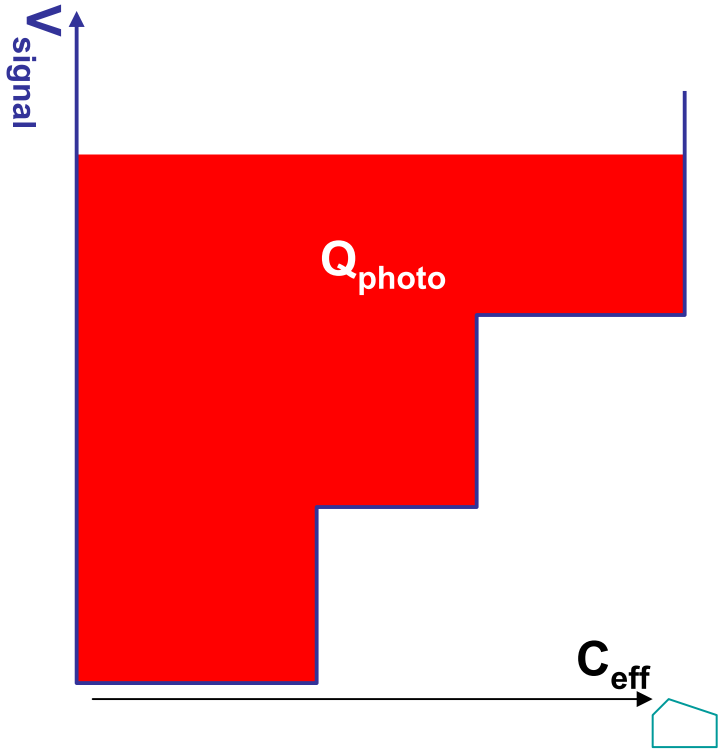
$$V_{signal} = \frac{t_{int} \cdot I_{photo}}{C_{eff}} \quad \text{(linear)}$$



$$V_{signal} = \sum \frac{t_{int} \cdot I_{photo}}{C_{eff}} = \frac{Q_{photo}}{t_{int\,max}} \cdot \sum \frac{t_{int}(Q)}{C_{eff}(Q)}$$

slope = $t_{int}(Q)/C_{eff}(Q)$





Is non-linearity mandatory?

Non-linearity (non-linear response) is *not* essential.
(e.g. *Non-Destructive Readout* is a linear method)

It may be considered as a feature of the acquisition process, helping to catch the wide range of intensities in the image

It *may* do so by taking noise levels (NEC!) into account

In a post-processing step the non-linearity may be linearized

Formula for NEC in charge domain

$$NEC = \frac{P}{NEP} = \frac{P \cdot \frac{\partial S}{\partial P}}{N}$$

$P \sim Q_{photo}$ total photo charge during frame time
Q_{signal} charge integrated during t_{int}
$N \sim Q_{noise}$ uncertainty on Q_{signal}
$Q_{signal}/Q_{photo}=t_{int}/t_{intmax}$

$V_{signal} = S$
$V_{noise} = N$

$$\Rightarrow NEC = \frac{Q_{photo} \cdot \frac{\partial Q_{signal}}{\partial Q_{photo}}}{Q_{noise}}$$

$$\frac{\partial Q_{signal}}{\partial Q_{photo}} = \frac{\partial t_{\mathrm{int}}}{\partial P} \cdot \frac{P}{t_{\mathrm{int\,max}}} = \frac{\partial t_{\mathrm{int}}}{\partial Q_{photo}} \cdot \frac{Q_{photo}}{t_{\mathrm{int\,max}}}$$

$$\Rightarrow NEC = \frac{Q_{photo} \cdot \frac{\partial t_{\mathrm{int}}}{\partial Q_{photo}} \cdot \frac{Q_{photo}}{t_{\mathrm{int\,max}}}}{Q_{noise}}$$

NEC does not depend on C_{eff} in charge domain

Formula for NEC in voltage domain

$$NEC = \frac{P}{NEP} = \frac{P \cdot \frac{\partial S}{\partial P}}{N}$$

$$V_{signal} = \int \frac{t_{int} \cdot I_{photo}}{C_{eff}} = \int \frac{t_{int} \cdot P \cdot SR}{C_{eff}}$$

$$V_{signal} = S$$

$$V_{noise} = N$$

SR=Spectral Response [A/W]

$$\frac{\partial S}{\partial P} = SR \cdot \left(\frac{t_{int}}{C_{eff}} + \frac{\frac{\partial t_{int}}{\partial P} \cdot P}{C_{eff}} - \frac{t_{int} \cdot P \cdot \frac{\partial C_{eff}}{\partial P}}{C_{eff}^{\ 2}} \right)$$

When one lets integration time depend on P or Q_{photo}

$$NEC = \frac{P}{N} \cdot \frac{\partial S}{\partial P} = \frac{SR \cdot \left(\frac{t_{int} \cdot P}{C_{eff}} + \frac{\frac{\partial t_{int}}{\partial P} \cdot P^2}{C_{eff}} - \frac{t_{int} \cdot P^2 \cdot \frac{\partial C_{eff}}{\partial P}}{C_{eff}^{\ 2}} \right)}{N}$$

When one lets C_{eff} depend on P or Q_{photo}

Keep NEC constant… in the presence of a fixed noise charge

t_{int} varies

$$NEC = \frac{\frac{\partial t_{\text{int}}}{\partial Q_{photo}} \cdot \frac{Q_{photo}^2}{t_{\text{int}\max}}}{Q_{noise}}$$

$$Q_{noise} = constant$$

$$\frac{\partial t_{\text{int}}}{\partial Q_{photo}} \sim \frac{1}{Q_{photo}^2}$$

$$t_{\text{int}}(Q_{photo}) \sim \frac{1}{Q_{photo}}$$

C_{eff} varies

$$NEC = \frac{Q_{signal}}{Q_{noise}} = \frac{Q_{photo}}{Q_{noise}}$$

No solution

i.e. there is no $C_{eff}(P)$ law that results in a constant NEC when noise a fixed charge. (This does not prohibit the use of C_{eff} modulation in general)

Keep NEC constant… in the presence of kTC noise

t_{int} varies

$$NEC = \frac{\frac{\partial t_{int}}{\partial Q_{photo}} \cdot \frac{Q_{photo}^2}{t_{int\,max}}}{Q_{noise}}$$

$$Q_{noise} = \text{constant (!)}$$

$$\frac{\partial t_{int}}{\partial Q_{photo}} \sim \frac{1}{Q_{photo}^2}$$

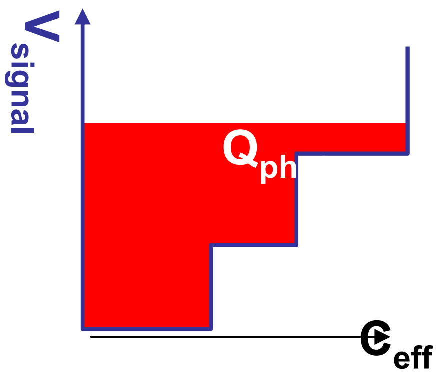
$$t_{int}(Q_{photo}) \sim \frac{1}{Q_{photo}}$$

C_{eff} varies

$$NEC = \frac{Q_{photo}}{Q_{noise}}$$

$$Q_{noise} = \sqrt{kTC_{eff}} \sim \sqrt{C_{eff}}$$

$$C_{eff} \sim Q_{photo}^2$$



Keep NEC constant… in the presence of photon shot noise

t_{int} varies

$$NEC = \frac{\frac{\partial t_{int}}{\partial Q_{photo}} \cdot \frac{Q_{photo}^{\;2}}{t_{int\max}}}{Q_{noise}}$$

$$Q_{noise} \sim \sqrt{Q_{signal}} \sim \sqrt{Q_{photo} \cdot t_{int}}$$

$$\frac{\partial t_{int}}{\partial Q_{photo}} \sim \frac{\sqrt{Q_{photo}} \cdot \sqrt{t_{int}}}{Q_{photo}^{\;2}}$$

$$t_{int}(Q_{photo}) \sim \frac{1}{Q_{photo}}$$

C_{eff} varies

$$NEC = \frac{Q_{photo}}{Q_{noise}}$$

$$Q_{noise} \sim \sqrt{Q_{photo}}$$

No solution

i.e. there is no $C_{eff}(P)$ law that results in a constant NEC when noise is exclusively PSN. This does not prohibit the use of C_{eff} modulation in general

Keep NEC constant… when dominated by PRNU

t_{int} varies

$$NEC = \frac{\frac{\partial t_{int}}{\partial Q_{photo}} \cdot \frac{Q_{photo}}{t_{int\,max}}^{2}}{Q_{noise}}$$

$$Q_{noise} \sim Q_{signal} \sim Q_{photo} \cdot t_{int}$$

$$\frac{\partial t_{int}(Q)}{\partial Q_{photo}} \sim \frac{t_{int}(Q)}{Q_{photo}}$$

Always fulfilled

C_{eff} varies

$$NEC = \frac{Q_{photo}}{Q_{noise}}$$

$$\mathrm{PRNU} = \frac{Q_{noise}}{Q_{photo}} = \mathrm{constant}$$

Always fulfilled

i.e. for any relation $C_{eff}(P)$, NEC is constant for systems dominated by PRNU

Keep NEC constant in the presence of a fixed voltage noise

t_{int} varies

$$NEC = \frac{SR \cdot \left(\frac{\frac{\partial t_{int}}{\partial P} \cdot P^2}{C_{eff}} \right)}{N}$$

$$V_{noise} = constant \sim \frac{\partial t_{int}}{\partial P} \cdot P^2$$

$$\frac{\partial t_{int}}{\partial P} \sim \frac{1}{P^2}$$

$$t_{int}(P) \sim \frac{1}{P}$$

C_{eff} varies

$$NEC = \frac{SR \cdot \left(\frac{t_{int} \cdot P^2 \cdot \frac{-\partial C_{eff}}{\partial P}}{C_{eff}^{\;2}} \right)}{N}$$

$$V_{noise} = constant \sim \frac{P^2 \cdot \frac{\partial C_{eff}}{\partial P}}{C_{eff}^{\;2}}$$

$$\frac{\partial C_{eff}}{\partial P} \sim \frac{C_{eff}^{\;2}}{P^2}$$

$$C_{eff} \sim P$$

Keep NEC constant…
when dominated by dark current shot noise

t_{int} varies

$$NEC = \frac{\frac{\partial t_{int}}{\partial Q_{photo}} \cdot \frac{Q_{photo}{}^2}{t_{int\max}}}{Q_{noise}}$$

$$Q_{noise} \sim \sqrt{t_{int}}$$

$$\frac{\partial t_{int}}{\partial Q_{photo}} \sim \frac{\sqrt{t_{int}}}{Q_{photo}{}^2}$$

$$t_{int}(Q_{photo}) \sim \frac{1}{Q_{photo}{}^2}$$

C_{eff} varies

$$NEC = \frac{Q_{photo}}{Q_{noise}}$$

$$Q_{noise} \sim constant$$

No solution

Keep NEC constant…
when dominated by DSNU

t_{int} varies

$$NEC = \frac{\frac{\partial t_{int}}{\partial Q_{photo}} \cdot \frac{Q_{photo}^{2}}{t_{int\,max}}}{Q_{noise}}$$

$$Q_{noise} \sim t_{int}$$

$$\frac{\partial t_{int}}{\partial Q_{photo}} \sim \frac{t_{int}}{Q_{photo}^{2}}$$

No solution

C_{eff} varies

$$NEC = \frac{Q_{photo}}{Q_{noise}}$$

$$Q_{noise} \sim constant$$

No solution

Summary of "keep NEC constant"

Nature of noise

Noise sources that persist after calibration in high end imagers

$$NEC = \frac{SR \cdot \left(\frac{\frac{\partial t_{int}}{\partial P} \cdot P^2}{C_{eff}} \right)}{N}$$

$$NEC = \frac{Q_{photo} \cdot \frac{\partial Q_{signal}}{\partial Q_{photo}}}{Q_{noise}}$$

$$NEC = \frac{SR \cdot \left(\frac{t_{int} \cdot P^2 \cdot \frac{-\partial C_{eff}}{\partial P}}{C_{eff}^{\ 2}} \right)}{N}$$

$$NEC = \frac{Q_{photo}}{Q_{noise}}$$

Nature of noise	Noise source	t_{int} varies	C_{eff} varies
Constant $charge_{RMS}$	kTC noise	$t_{int} \sim 1/Q$	$C_{eff} \sim Q^2$
Constant $voltage_{RMS}$	EMI, read noise, ADC...	$t_{int} \sim 1/Q$	$C_{eff} \sim Q$
~√power	PSN	$t_{int} \sim 1/Q$	No solution
$\sim\sqrt{t_{int}}$	DCSN	$t_{int} \sim 1/Q^2$	No solution
~power	PRNU	always	always
$\sim t_{int}$	DSNU	No solution	No solution

interpretation

One can define a $t_{int}(Q)$ or $C_{eff}(Q)$ law to obtain a constant and optimal NEC for most common noise signatures

The relations t_{int}~1/Q and C_{eff}~Q found are essentially “logarithmic responses”

$$V_{signal} = \frac{1}{t_{\text{int}\max}} \cdot \int_0^{Q_{photo}} \frac{t_{\text{int}}(Q)}{C_{eff}(Q)} dQ \sim \int_0^{Q_{photo}} \frac{1}{Q} dQ$$

$$V_{signal} \sim \log_n(Q_{photo}) + Cte$$

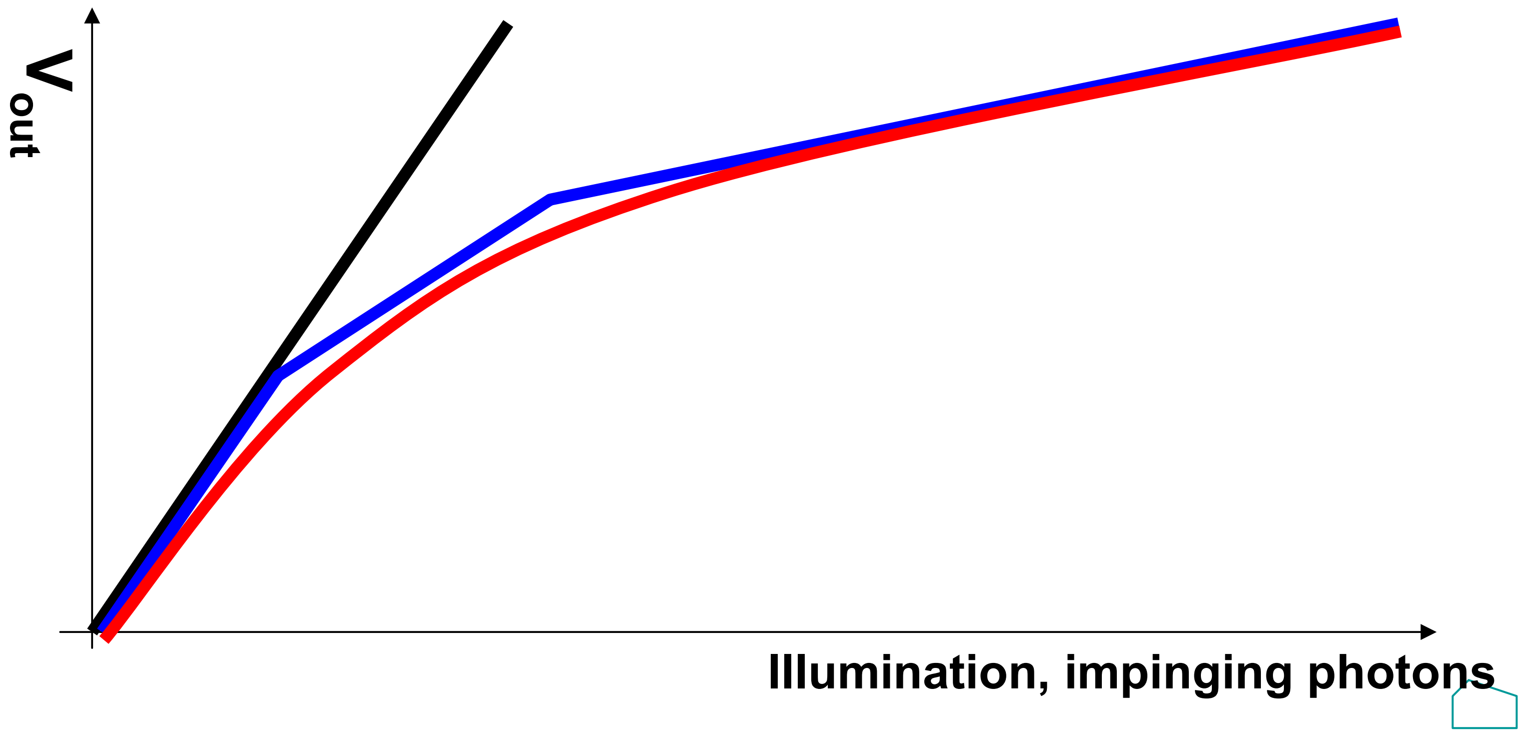
For t_{int}~1/P² and C_{eff}~P²:

$$V_{signal} \sim \int_0^{Q_{photo}} \frac{1}{Q^2} dQ$$

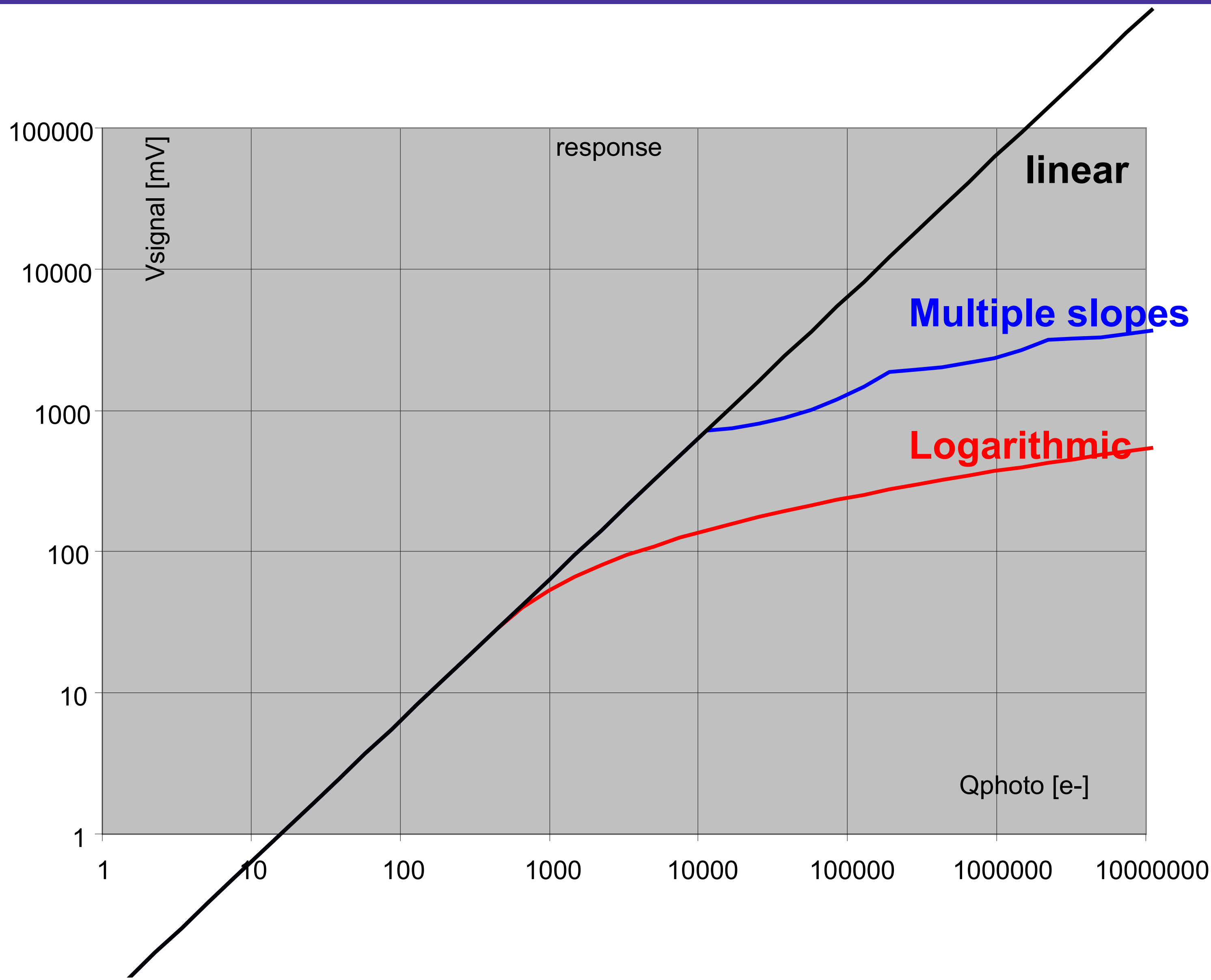
$$V_{signal} \sim \frac{1}{Q_{photo}} + Cte$$

illustration

- Linear response
- Logarithmic response for NEC≈10
- Approximation multiple slopes for NEC≥10



Result NEC≥10

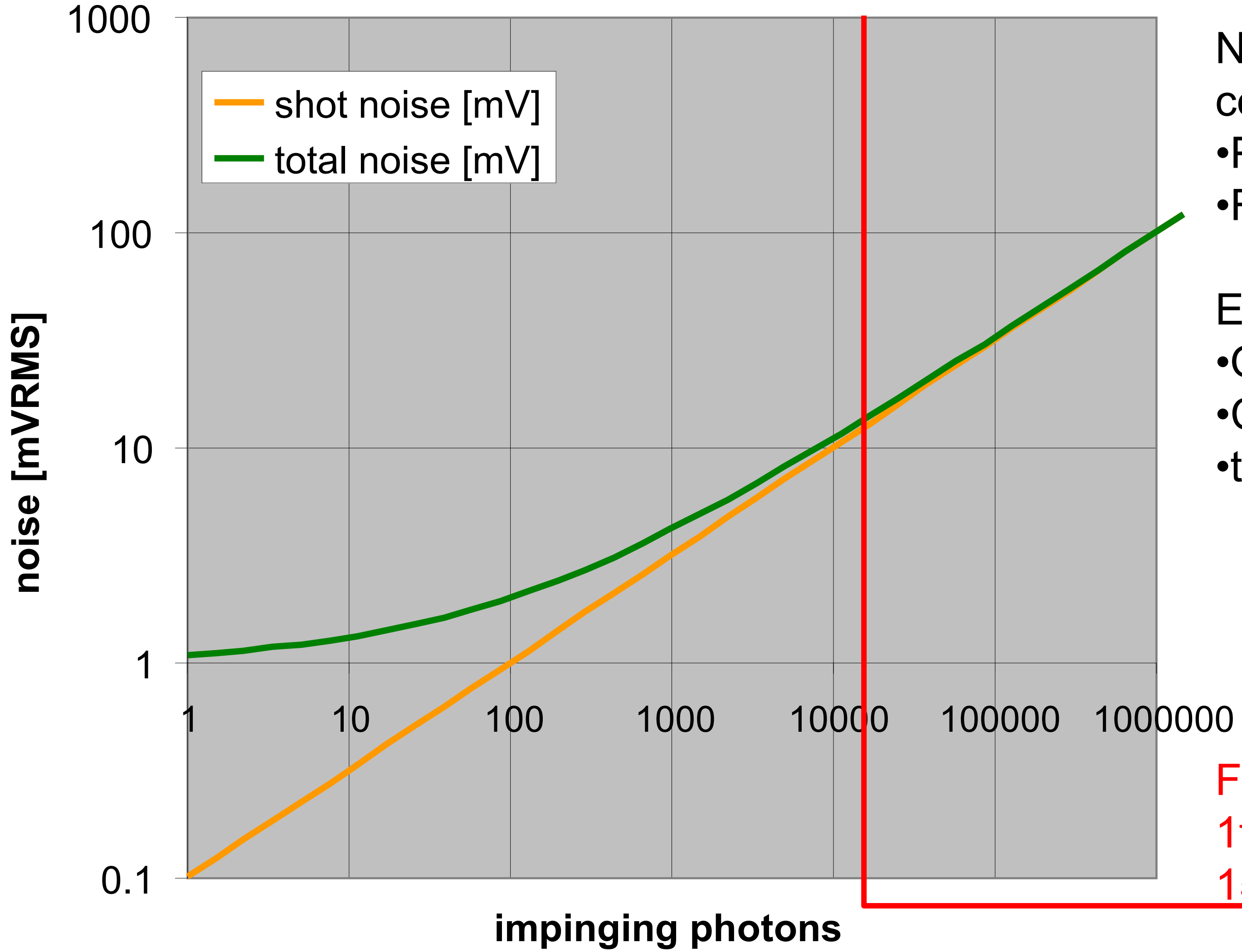


Noise sources considered:
- PSN
- Read noise $1mV_{RMS}$

Essential pixels specs
- QE = 40%
- C_{eff}=1fF
- t_{int}=not specified

Full well limit≈ 1fF*1V≈6000e^- 15000photons

Linear response



Noise sources considered:

- PSN
- Read noise 1mV$_{RMS}$

Essential pixels specs

- QE = 40%
- C_{eff}=1fF
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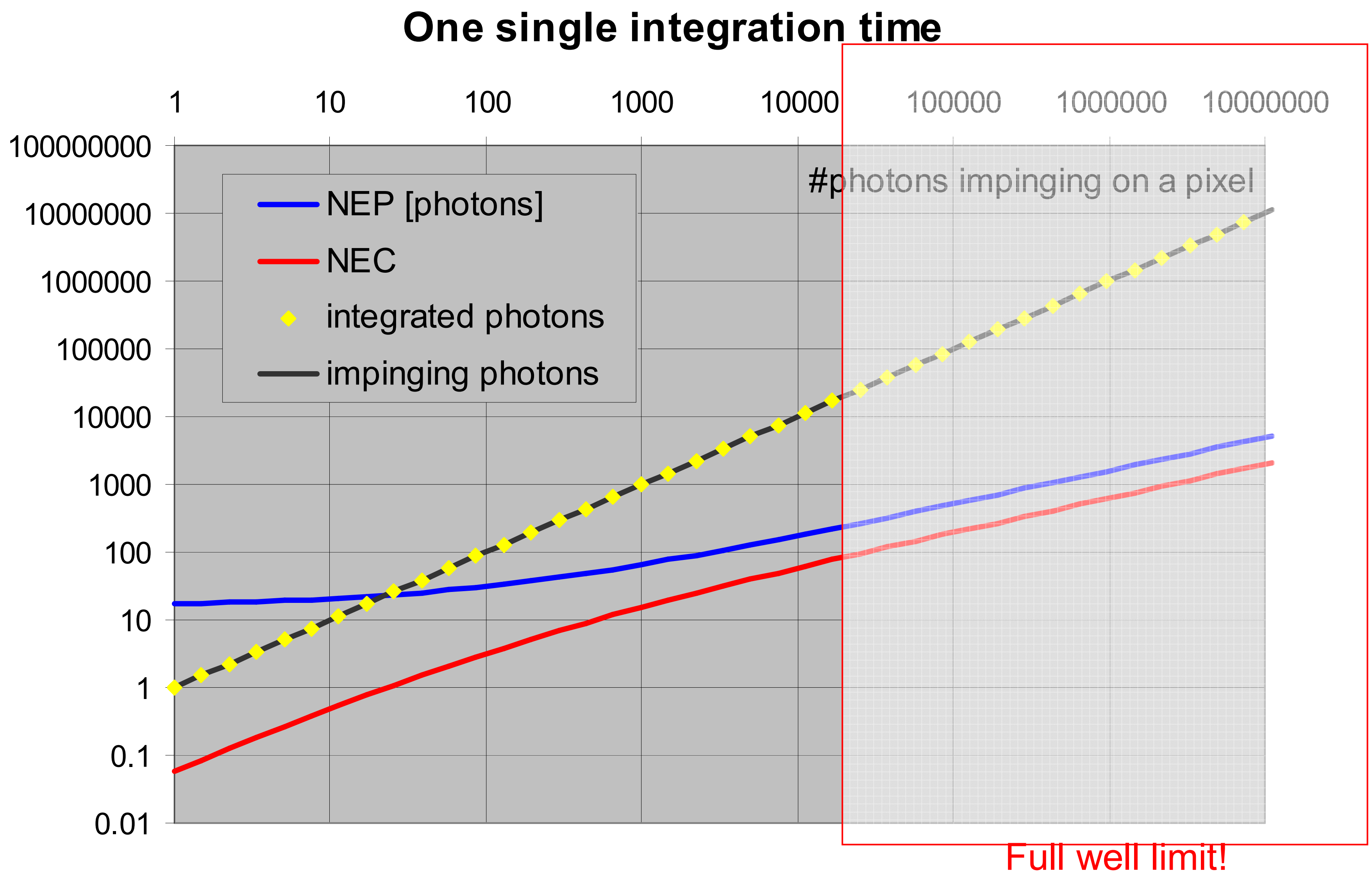
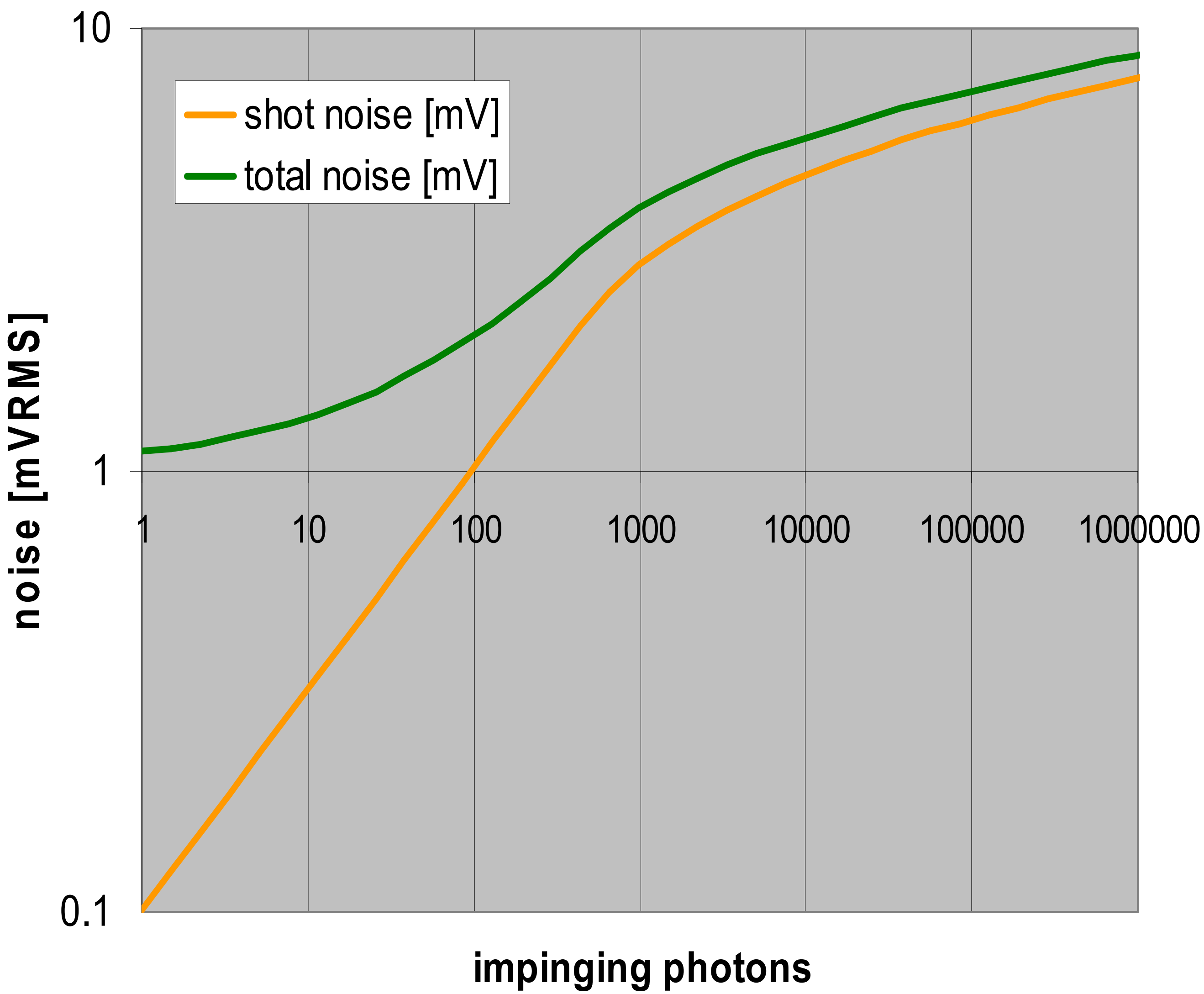
Full well limit≈
1fF*1V≈6000e^{-}
15000photons

Linear response



Ideal response yielding NEC≈10

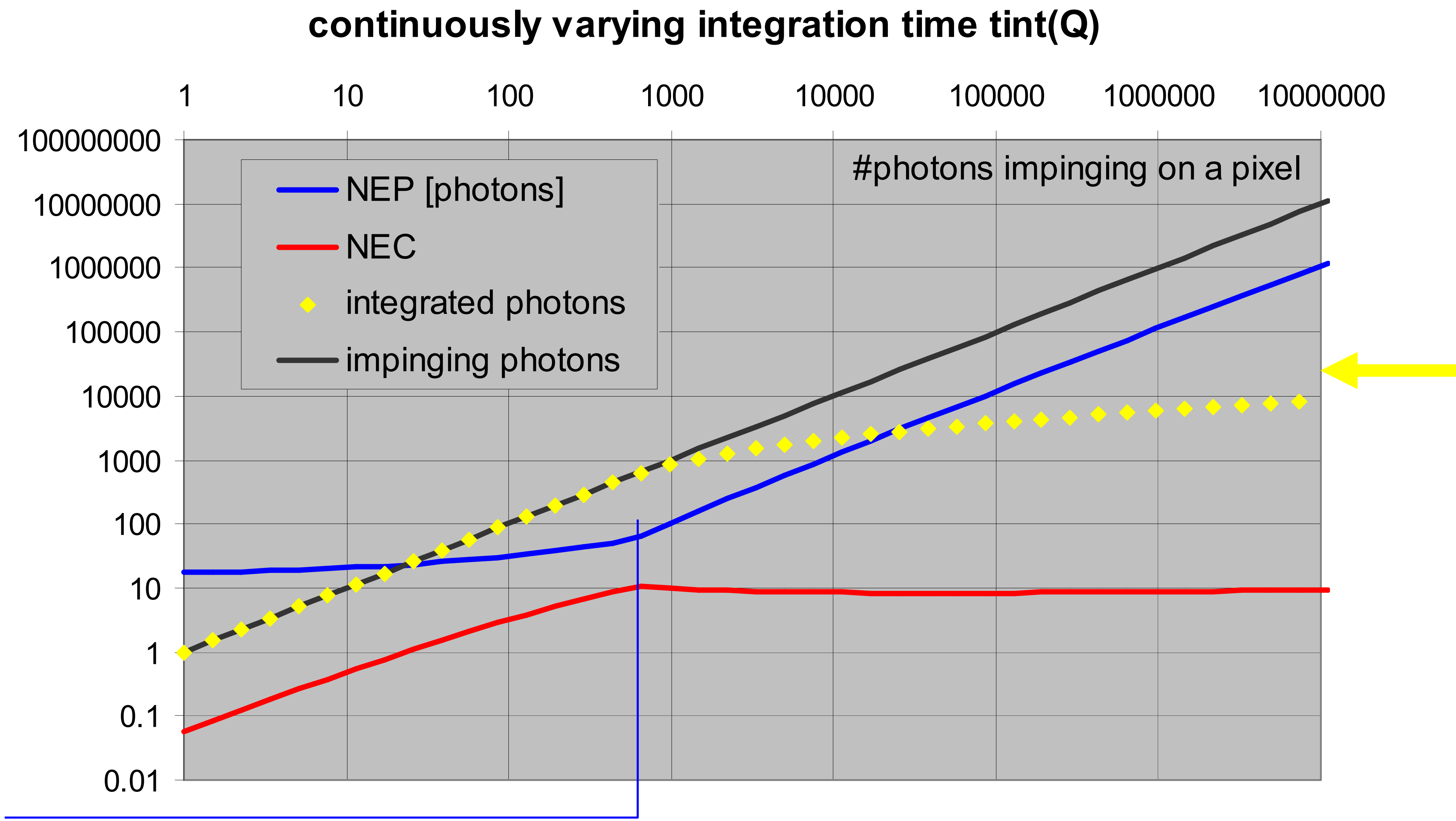


Noise sources considered:
- PSN
- Read noise $1mV_{RMS}$

QE = 40%
C_{eff}=1fF
t_{int}=not specified

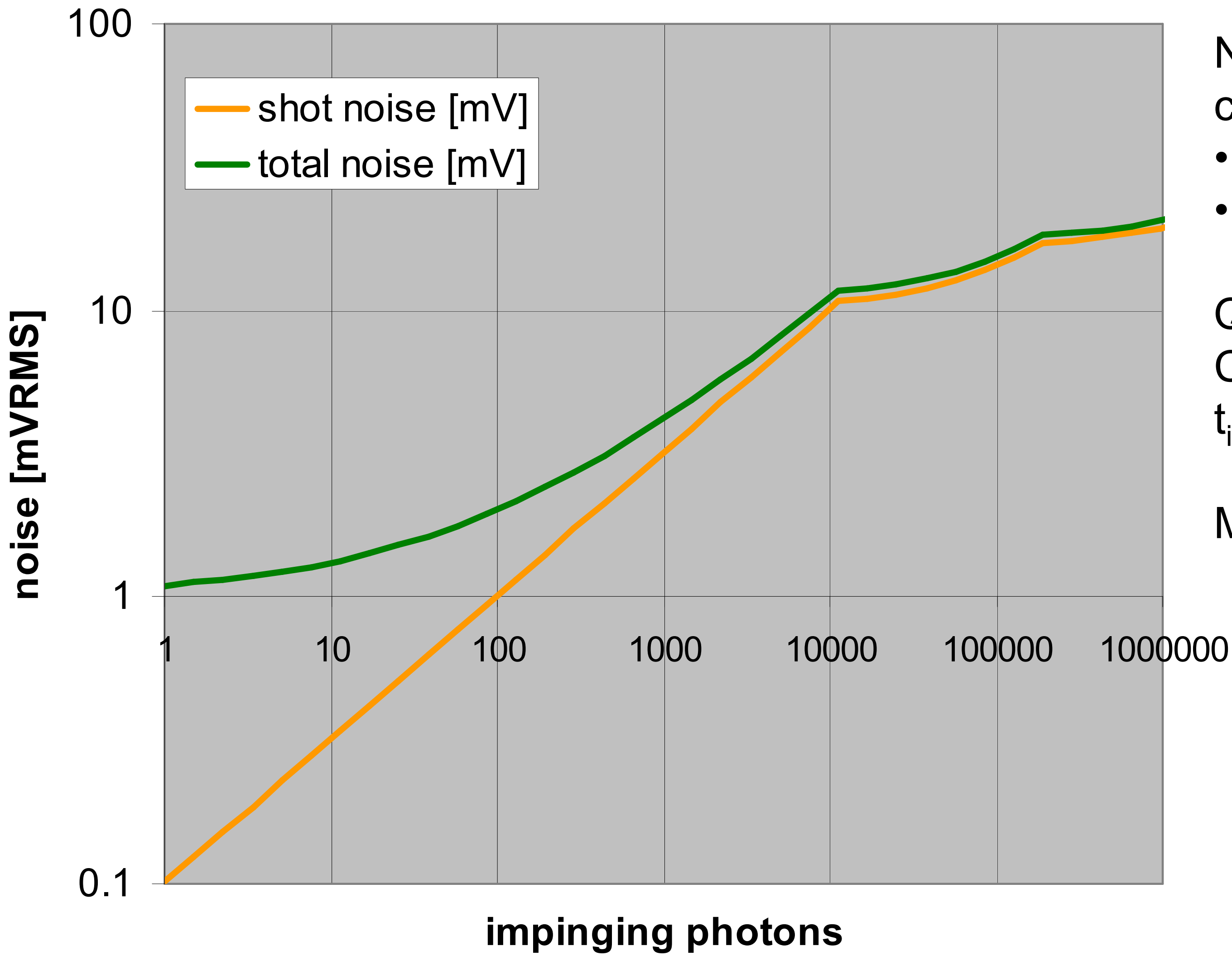
(Logarithmic) response realized by continuously reducing the integration time during the charge acquisition, to have NEC≡10

Logarithmic response NEC≈10



$t_{int} > t_{intmax}$? **NEP is limited to linear case**

Multiple slopes methods NEC>10

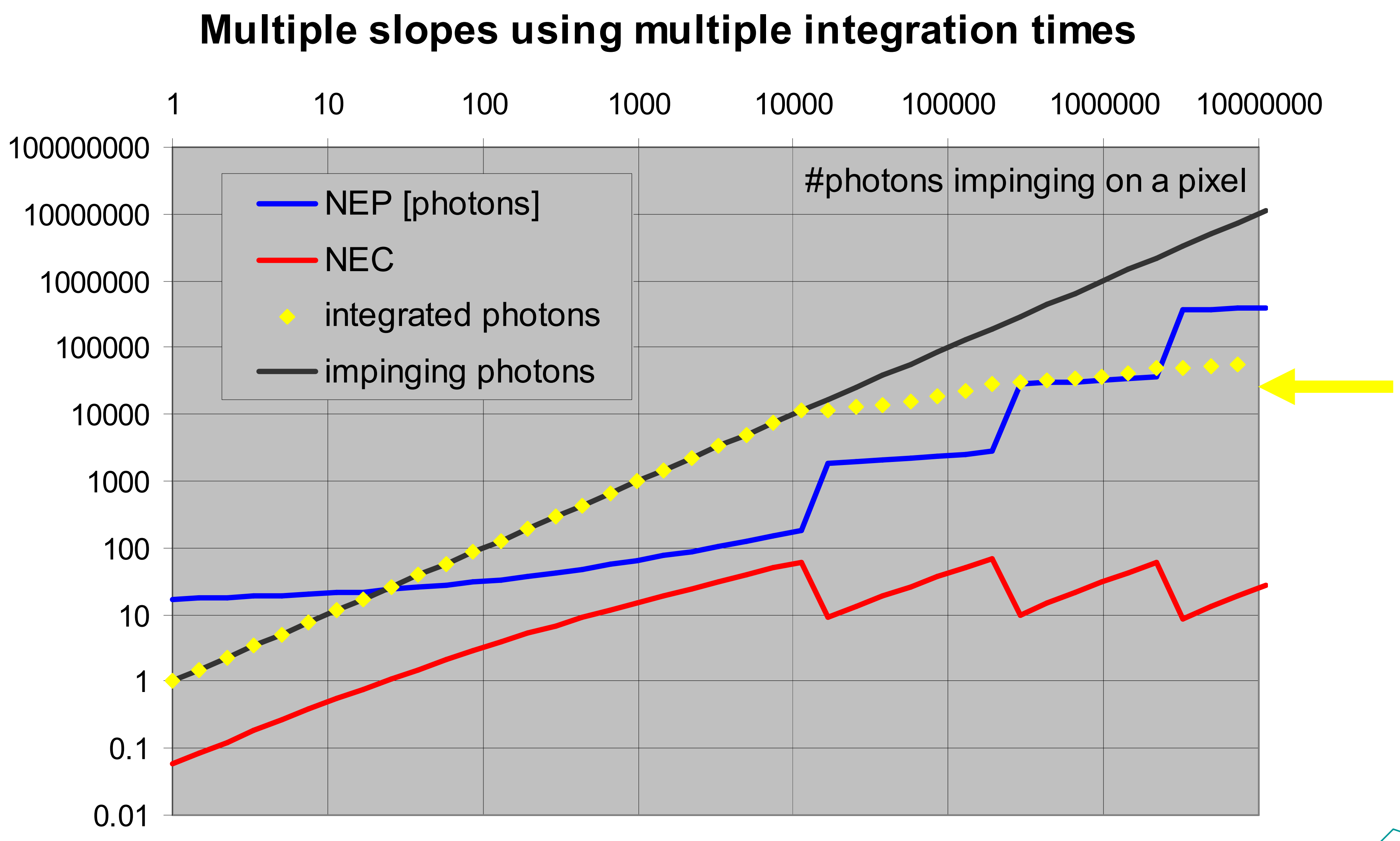


Noise sources considered:
- •PSN
- •Read noise $1mV_{RMS}$

QE = 40%
C_{eff}=1fF
t_{int}=not specified

Multiple slopes
- •1st slope starts at 10000 photons (4000 electrons)
- •Consecutive slopes have factor 10 lower integration time
- •New slope starts only when NEC≥10 is assured

Multiple slopes methods NEC>10



Conclusions

Was there something you might want to remember?

- High (wide) dynamic range is a property of the scene. The sensor has to accommodate.
- How to accommodate: yielding a sufficient NEC in all parts of the image/scene
- The logarithmic response follows naturally when assuming a typical noise signature, and aiming for a constant, minimal NEC
- Piece-wise approximation (multiple slopes) of the ideal logarithmic response is not as good.
- How to implement? ☺ the next presentations

Thank you

Abbreviations and symbols

C_{eff}	charge to voltage transconductance
D	lens aperture
DCSN	dark current shot noise
DSNU	dark signal non uniformity
EMI	electro-magnetic interference
f	focal length
F	f-number F=f/D
FPN	fixed pattern noise
N	Noise, uncertainty on S
NEC	noise equivalent contrast [%]
NEP	noise equivalent power [W…]
P	optical power [W, photons/s, …]
PR	photo response [V/W, V.m²/W.s]
PRNU	PR non-uniformity

Q_{noise}	uncertainty on Q_{signal} [F, e^-]
Q_{photo}	(maximum) photo charge [F, e^-]
Q_{signal}	actual photo charge, due to electronic shutter
QE	quantum efficiency [electrons/photon]
RMS	root-mean-square, subscript denoting that the value is a distribution
S	Signal, normally equal to V_{signal}
SR	spectral response [A/W]
t_{int}	integration time, electronic shutter time
t_{intmax}	maximum available integration time
V_{noise}	uncertainty on V_{signal}, = N