Comparative Analysis of SNR for Image Sensors with Enhanced Dynamic Range

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Motivation

Dynamic range is synonymous to imager quality

- **True for conventional CCD or CMOS imagers**
- **Not necessarily true when dynamic range enhancement schemes are used, e.g.,**
  - **Well capacity adjusting (Decker'98)**
  - **Multiple sampling (Yadid-Pecht'97, Yang'98)**

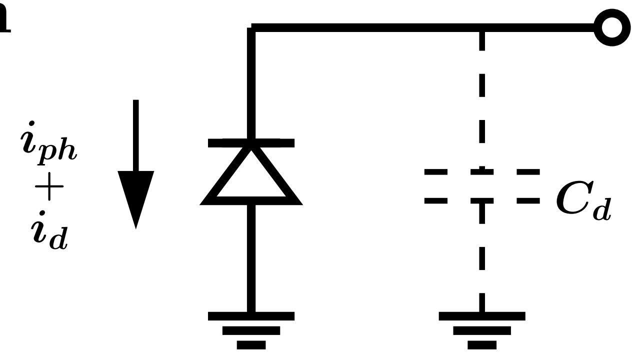
SNR plot is a better indicator of imager quality

Outline

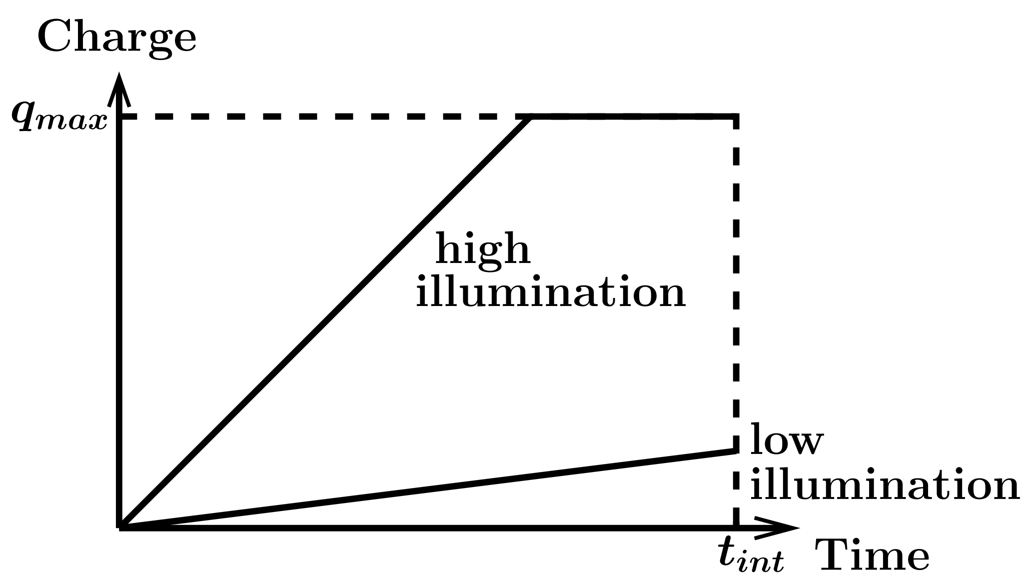
- **Dynamic range and SNR in integration mode**
- **Enhancing dynamic range by adjusting well capacity**
- **Enhancing dynamic range via multiple sampling**
- **Comparisons of the two enhancement schemes**

Simplified Photocurrent to Output Sensor Model

Direct integration

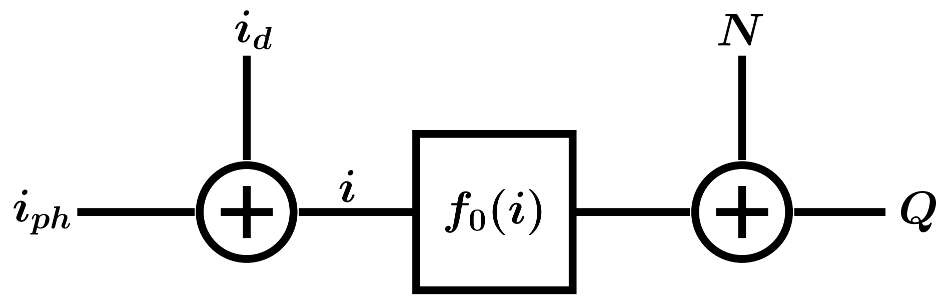


Charge collected vs. time

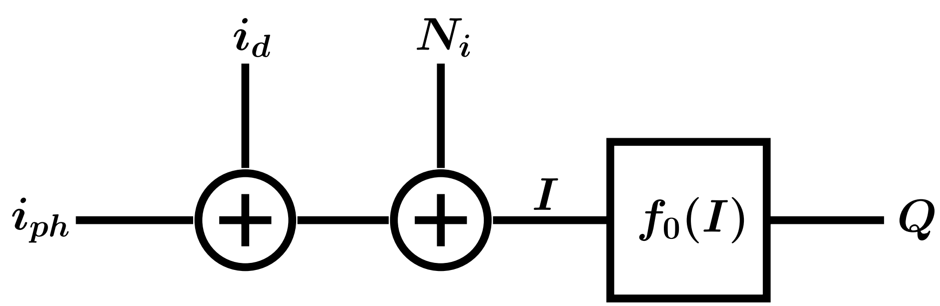


Sensor Noise Model

Sensor model



Equivalent model with input referred noise



Need N_i to compute SNR and DR

SNR and Dynamic Range in Integration Mode

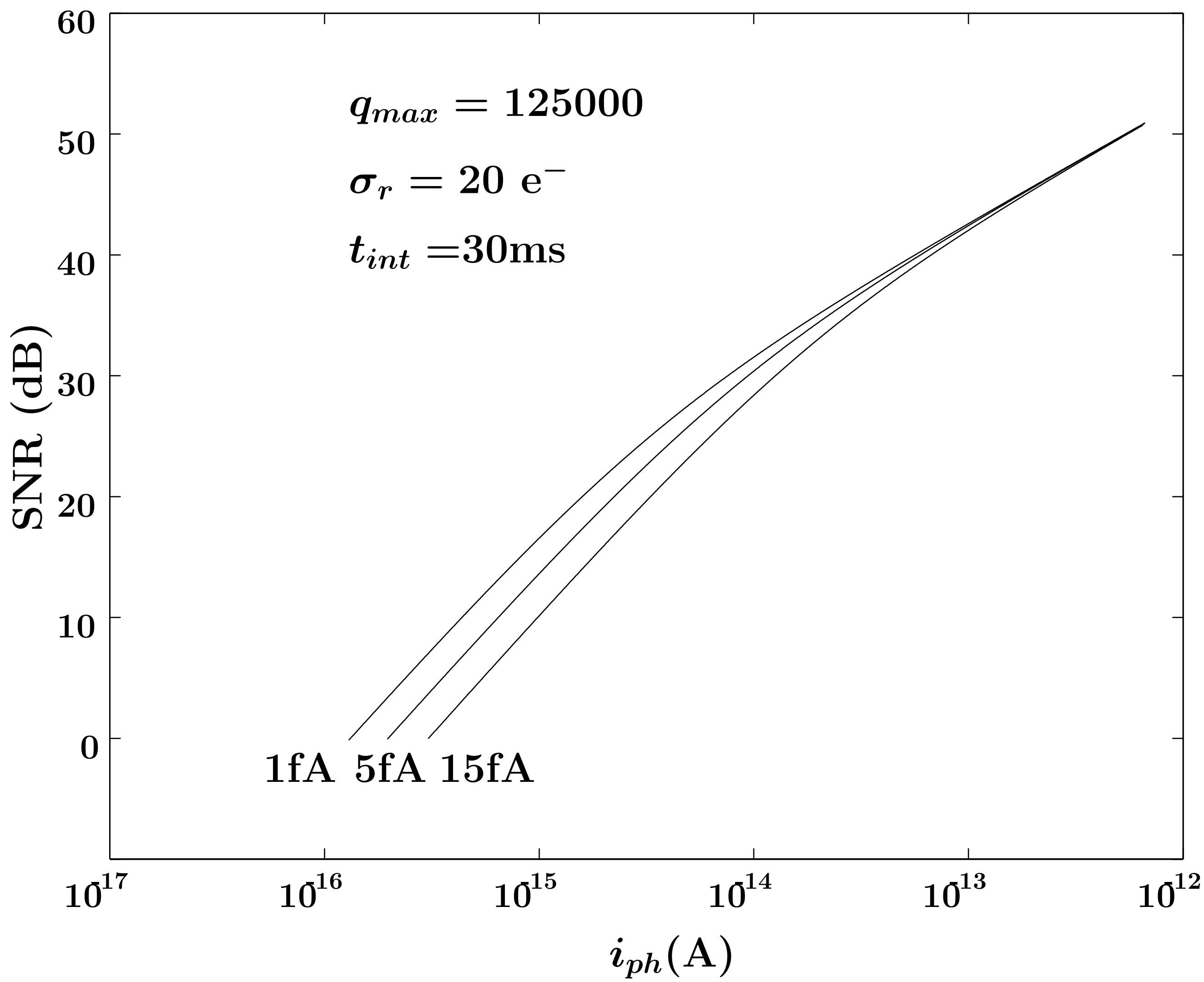
$$f_0(i + N_i) \approx f_0(i) + N_i f_0'(i)$$

$$\sigma_{N_i}^2 = \frac{\sigma_N^2}{f_0'(i)^2} = \frac{\sigma_N^2}{t_{int}^2}$$

$$\mathrm{SNR}(i_{ph}) = \frac{(i_{ph} t_{int})^2}{q(i_{ph} + i_d)t_{int} + \sigma_r^2} \text{ for } \quad i_{ph} \leq i_{max}$$

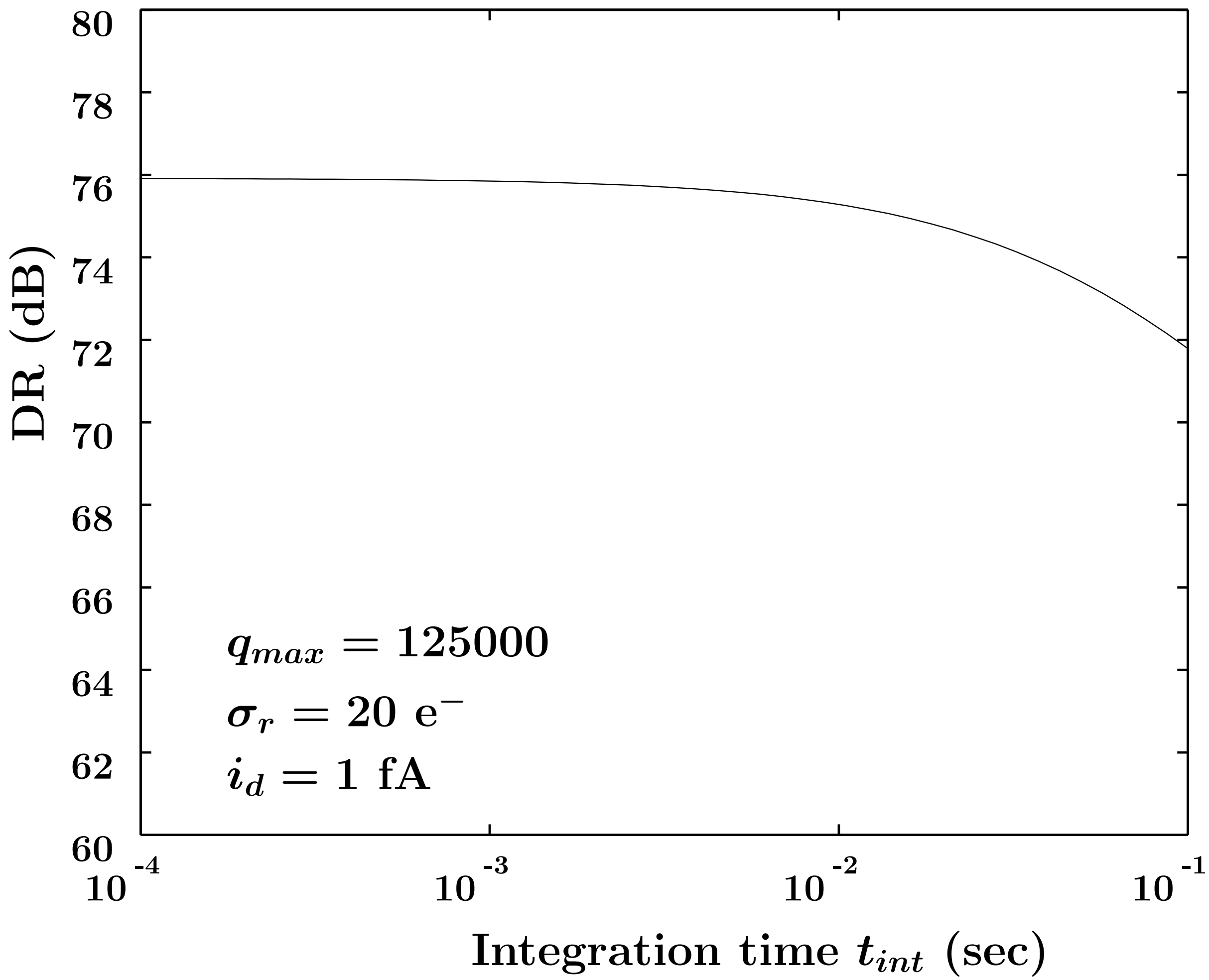
$$\mathrm{DR} = \frac{i_{max}}{i_{min}} = \frac{q_{max} - i_d t_{int}}{\sqrt{q i_d t_{int} + \sigma_r^2}}$$

Dynamic Range = Sensor Quality (Integration Mode)

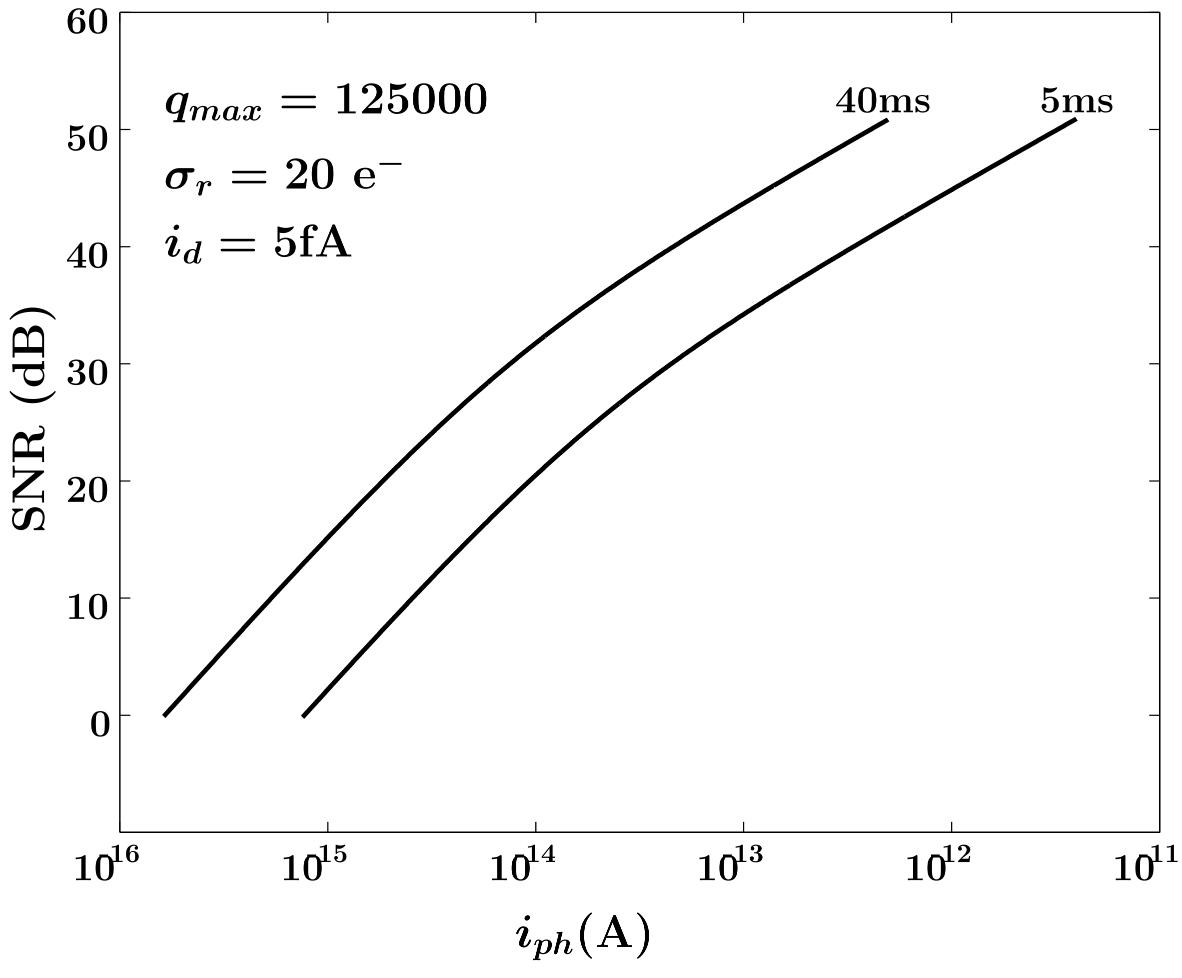


Shuttering Does Not Affect Dynamic Range

Dynamic range vs. integration time t_{int}



Shuttering Matches Dynamic Range to Scene Illumination



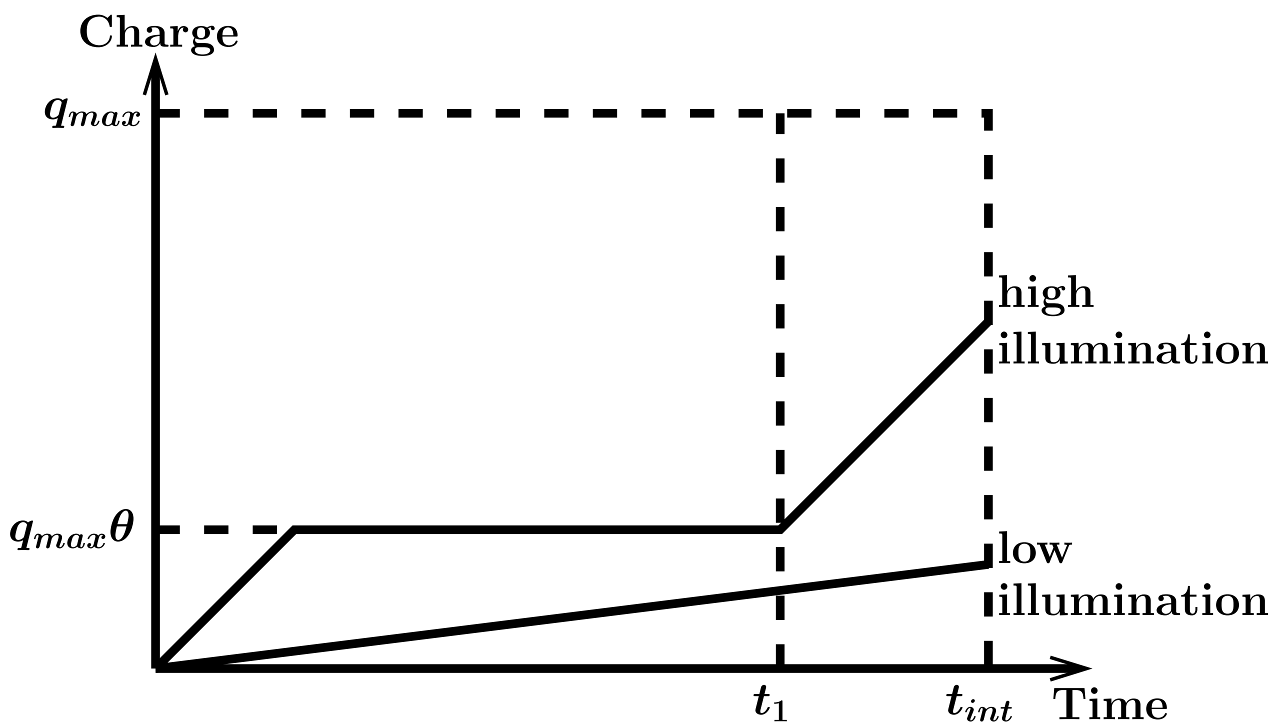
Outline

- Dynamic range and SNR in integration mode
- **Enhancing dynamic range by adjusting well capacity**
- Enhancing dynamic range via multiple sampling
- Comparisons of the two enhancement schemes

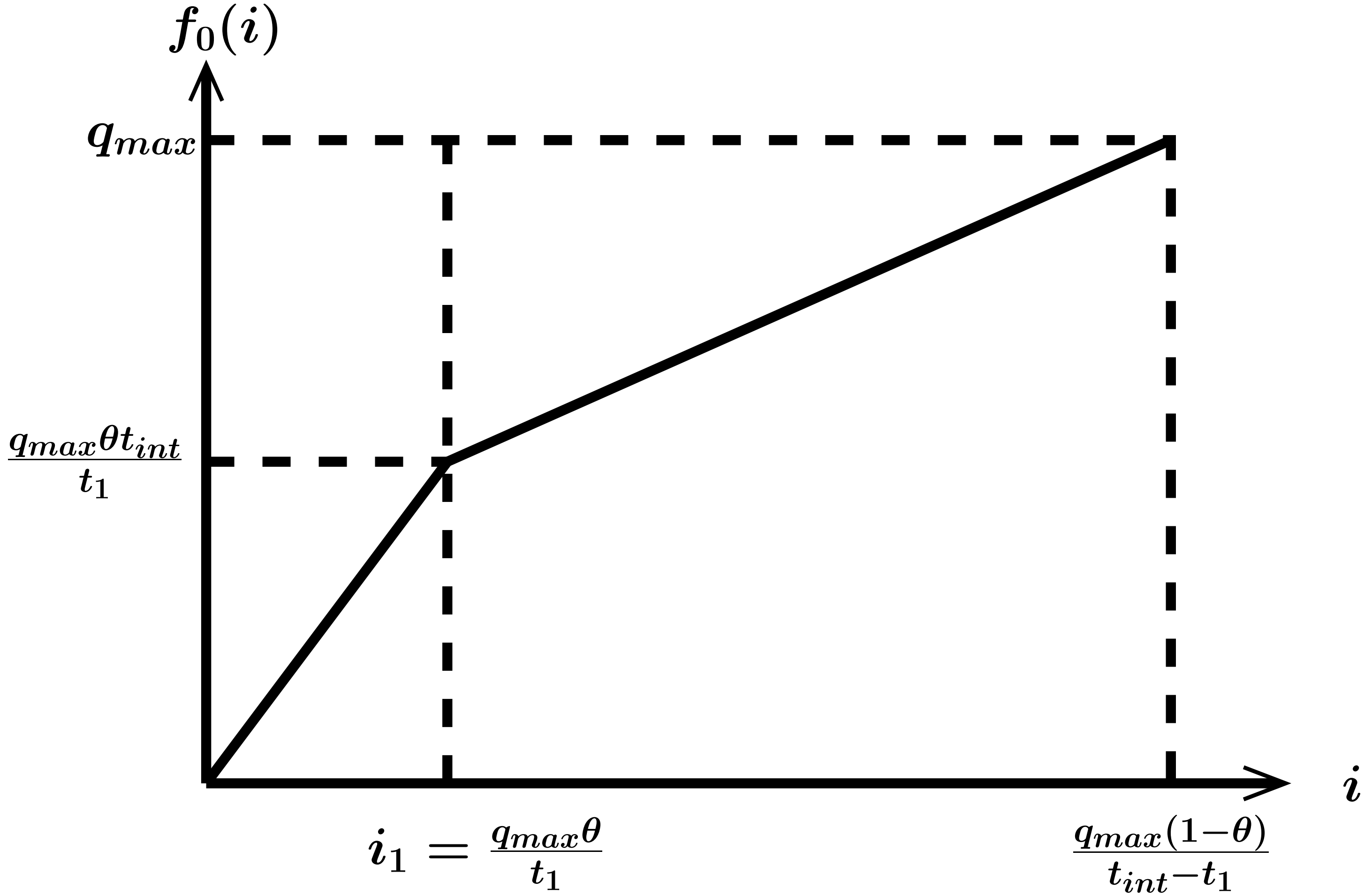
Enhancing DR by Adjusting Well Capacity

Compress the sensor's current versus charge response curve using a lateral overflow gate (Sayag'91, Decker'98)

Well capacity is monotonically increased to its maximum value



$f_0(i)$ for the Well Adjusting Scheme

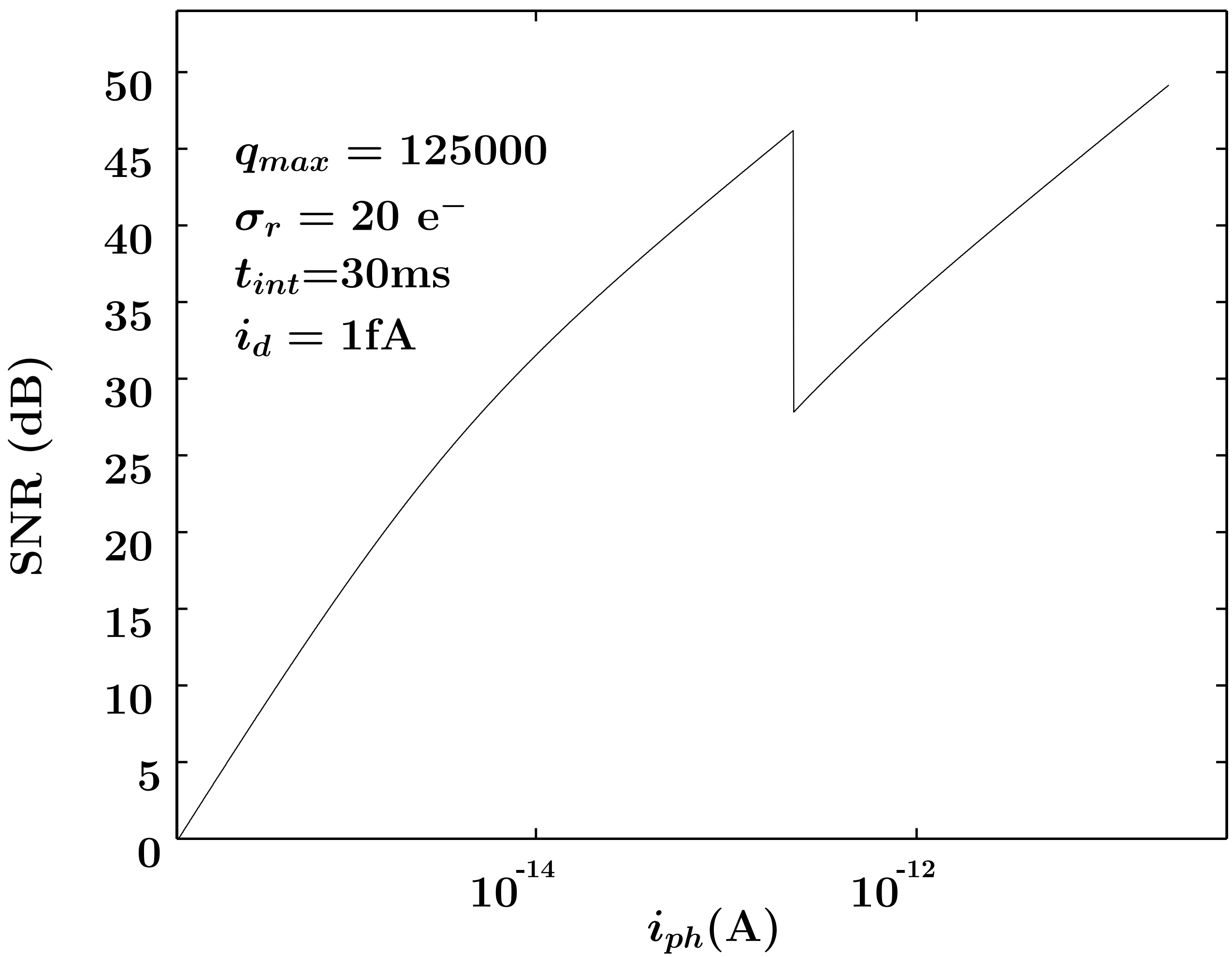


Dynamic Range and SNR for Well Adjusting

$$\mathrm{SNR}(i_{ph}) = \begin{cases} \frac{i_{ph}^2 t_{int}^2}{q(i_{ph}+i_d)t_{int}+\sigma_r^2} & \text{if } 0 \le i_{ph} < \frac{q_{max}\theta}{t_1} - i_d \\ \frac{i_{ph}^2 (t_{int}-t_1)^2}{q(i_{ph}+i_d)(t_{int}-t_1)+\sigma_r^2} & \text{if } \frac{q_{max}\theta}{t_1} - i_d \le i_{ph} < \frac{q_{max}(1-\theta)}{t_{int}-t_1} - i_d \end{cases}$$

$$\mathrm{DRF} = \frac{1-\theta}{1-\frac{t_1}{t_{int}}}$$

SNR vs. i_{ph} for the Well Capacity Adjustment Scheme

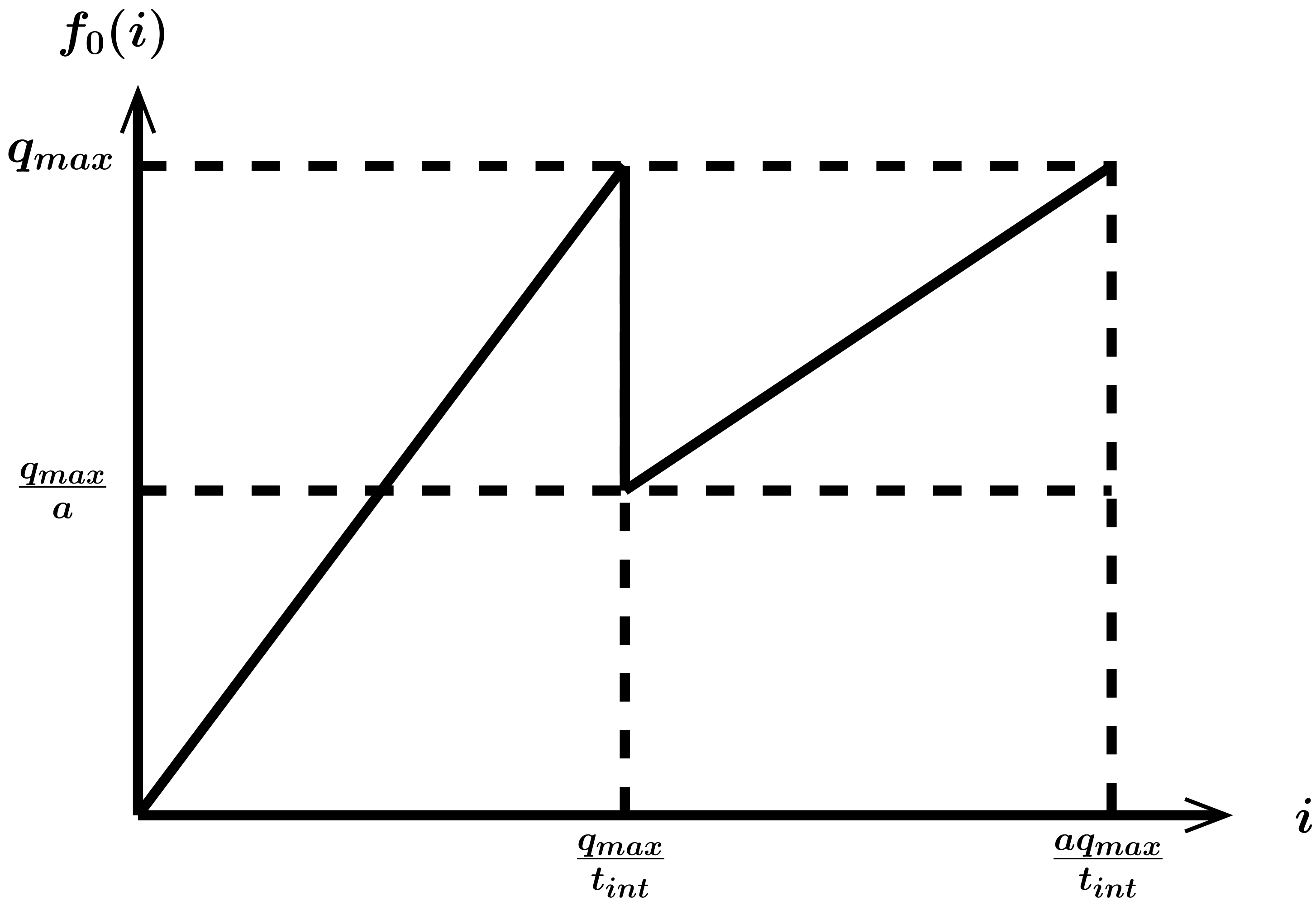


Enhancing DR by Multiple Sampling

Dual sampling is the simplest case of multiple sampling (Yadid-Pecht'97)

- **A scene is imaged twice, at a short and long integration times**
- **Two sampled images are combined into a high DR image**

$f_0(i)$ for Dual Sampling

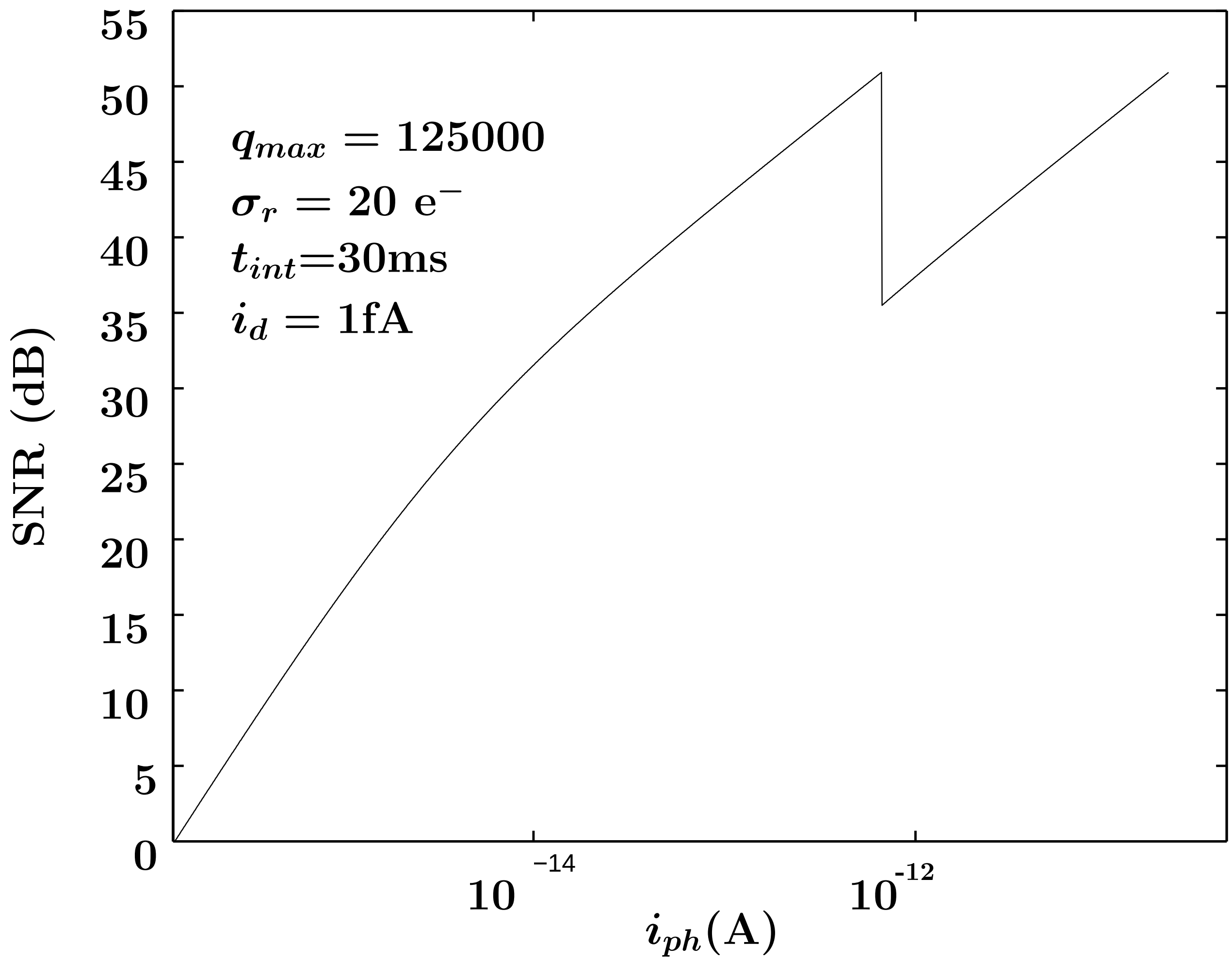


Dynamic Range and SNR for Dual Sampling

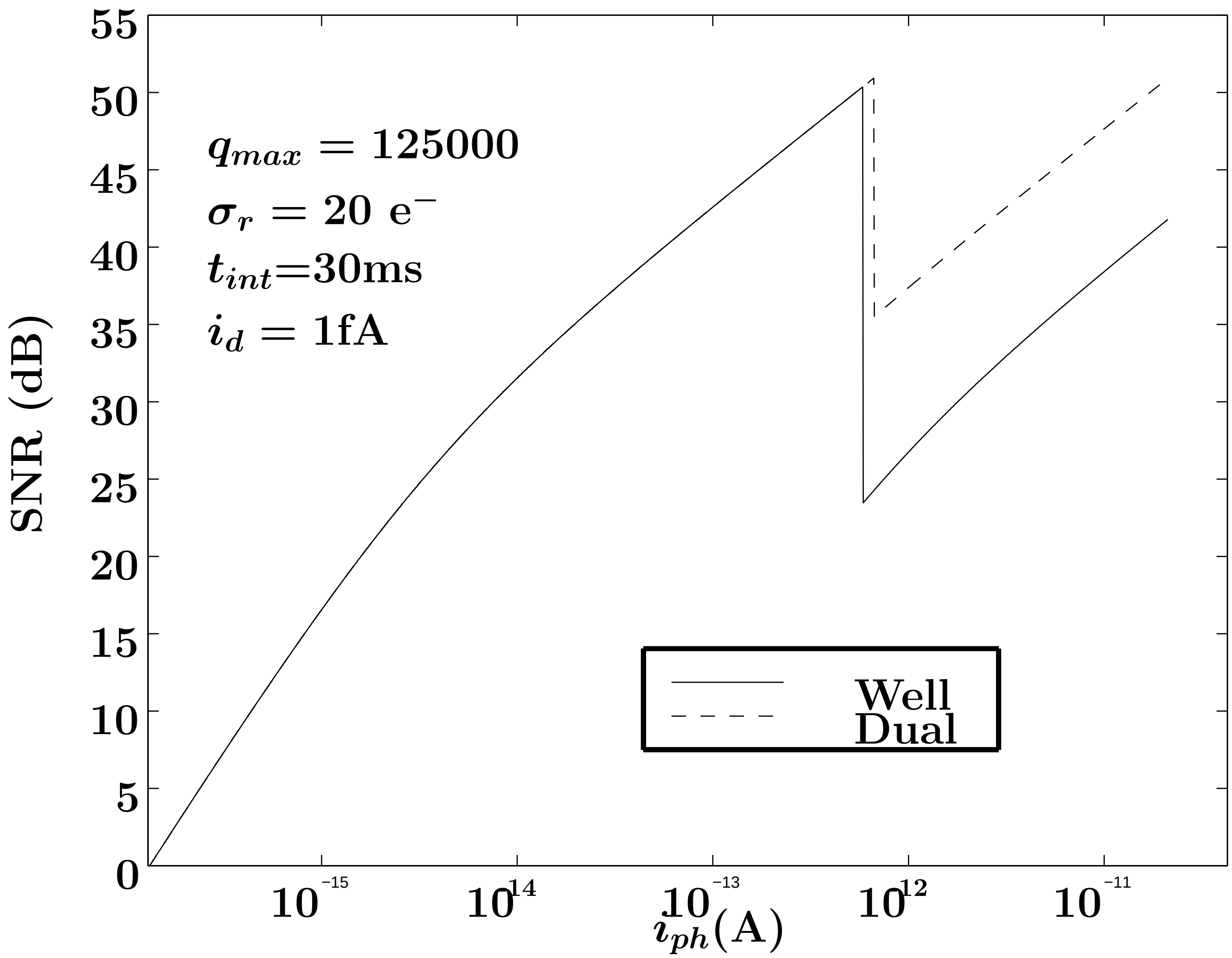
$$\mathrm{SNR}(i_{ph}) = \begin{cases} \frac{i_{ph}^2 t_{int}^2}{q(i_{ph}+i_d)t_{int}+\sigma_r^2} & \text{if } 0 \le i_{ph} < \frac{q_{max}}{t_{int}} - i_d \\ \frac{i_{ph}^2 (\frac{t_{int}}{a})^2}{q(i_{ph}+i_d)\frac{t_{int}}{a}+\sigma_r^2} & \text{if } \frac{q_{max}}{t_{int}} - i_d \le i_{ph} < \frac{aq_{max}}{t_{int}} - i_d \end{cases}$$

$$\mathrm{DRF} = \frac{\frac{aq_{max}}{t_{int}} - i_d}{\frac{q_{max}}{t_{int}} - i_d} \approx a, \quad \text{for small } i_d$$

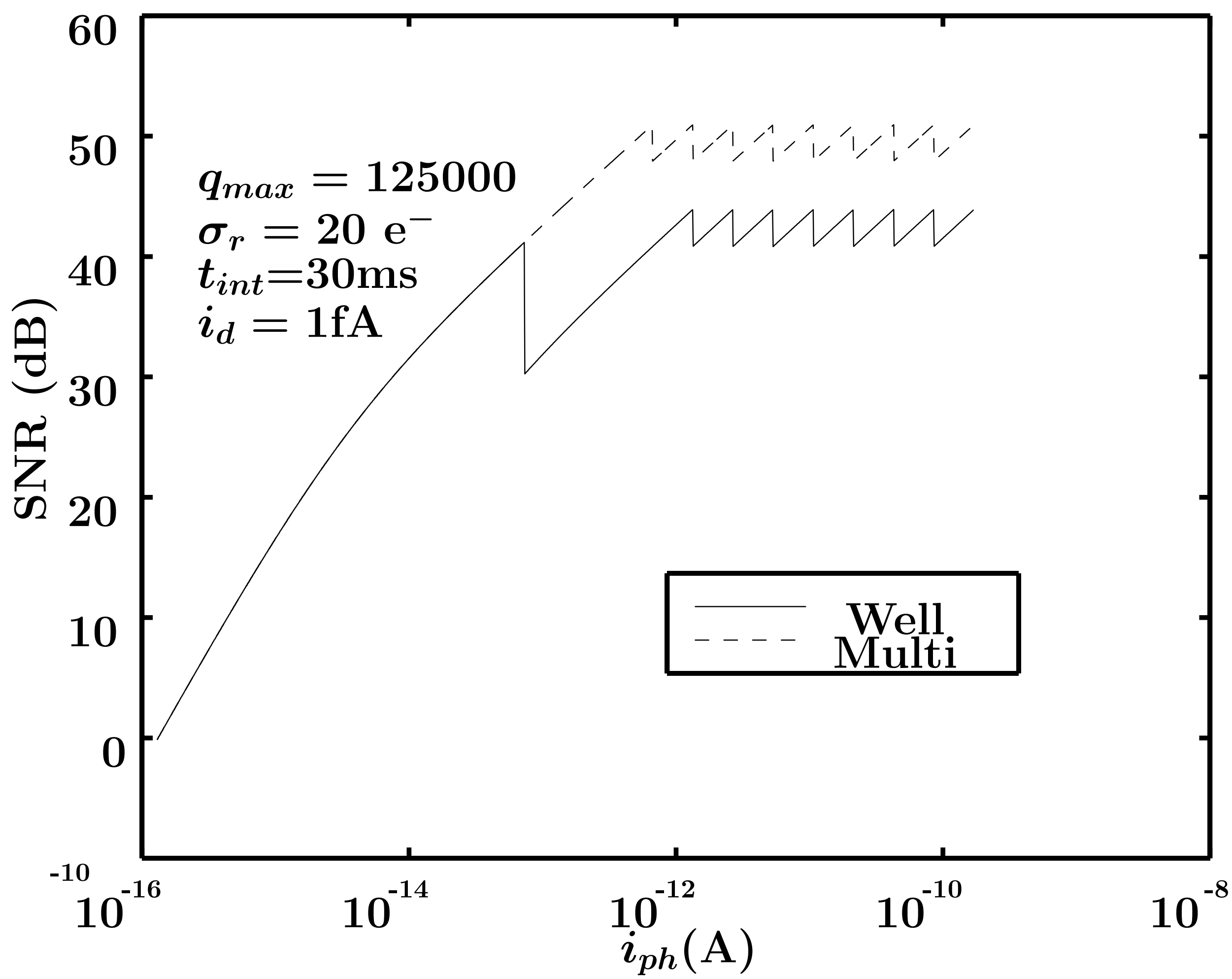
SNR vs. i_{ph} for Dual Sampling



SNR vs. i_{ph} for Both Well Adjusting and Dual Sampling



SNR vs. i_{ph} for Well Adjusting and Multiple Sampling



Conclusion

Dynamic Range as a measure of imager quality

- Good for conventional CCD and CMOS imagers
- Does not tell the full story when dynamic range enhancement schemes are used

SNR plot is a better indicator of imager quality

Multiple sampling achieves higher SNR than well adjusting