Astro 500

Techniques of Modern Observational Astrophysics

Matthew Bershady
University of Wisconsin

Lecture Outline

Part II. Detectors *continued*

- S/N formulation
- S/N regimes
- DQE
- Photon propagation method

- NIR detectors
- MIR & FIR detectors

Signal

- Point source
  - We are measuring photon flux
  - $E(\gamma) = f(\gamma) A\ t$
- Resolved source
  - We are measuring surface brightness
  - $E(\gamma) = I(\gamma)\ A\ \Omega\ t$

A is telescope collecting area; *t* is exposure time

$S(\gamma)$

This ignores any inefficiencies in the measurement process

Signal-to-Noise (S/N)

total system efficiency

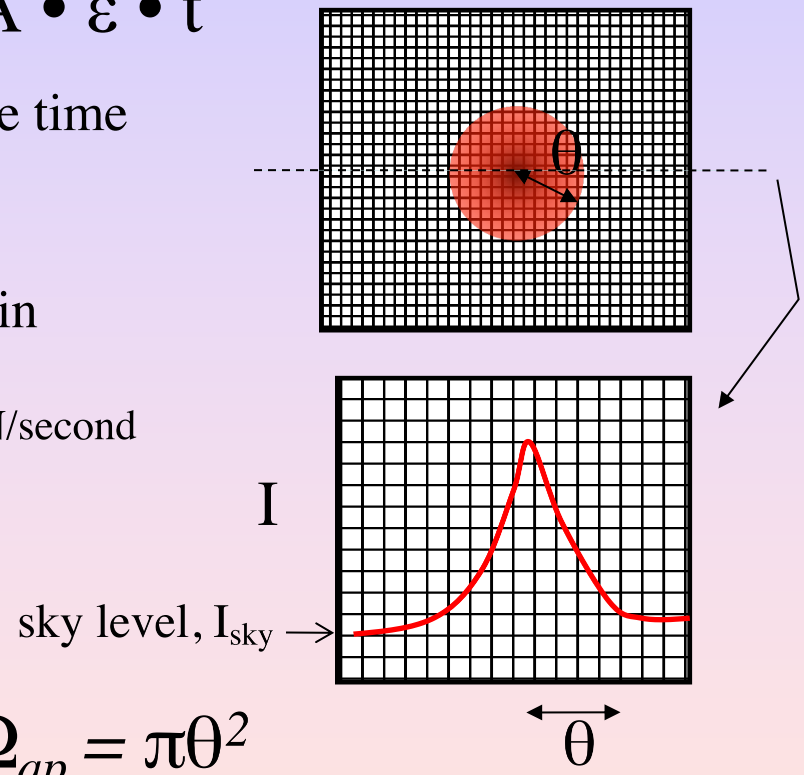
- Signal = $S_{obj} \bullet \varepsilon \bullet t = f_{\mathrm{obj}} \bullet A \bullet \varepsilon \bullet t$

exposure time

detected e-/second: $S_{obj} = S_{DET} \bullet \mathrm{gain}$

DN/second

- Consider the case where we count all the detected e- in a circular aperture with radius θ. In this case $\Omega_{ap} = \pi\theta^2$



Aside: how big an area do we want to integrate over?

Noise Sources

$\pi\theta^2$ must be in units that match I_{sky} (e.g., flux per unit solid angle)

$\pi\theta^2$ must be in pixel units

$\sqrt{S_{obj} \cdot \varepsilon \cdot t} = \sqrt{f_{obj} \cdot A \cdot \varepsilon \cdot t}$ $\Rightarrow$ shot noise from source

$\sqrt{I_{sky} \cdot A \cdot \pi\theta^2 \cdot \varepsilon \cdot t}$ $\Rightarrow$ shot noise from sky in aperture of circular radius r

$\sqrt{RN^2 \cdot \pi\theta^2}$ $\Rightarrow$ readout noise in aperture of circular radius r

$\sqrt{\left[RN^2 + (0.5 \times \text{gain})^2\right]} \cdot \sqrt{\pi\theta^2}$ $\Rightarrow$ more general RN

?

$\sqrt{\text{Dark} \cdot \pi\theta^2 \cdot t}$ $\Rightarrow$ shot noise in dark current in aperture of circular radius r

In general: replace $\pi\theta^2$ with Ω_{ap} where Ω_{ap} is the solid angle of your measurement aperture.

$S_{obj} \cdot \varepsilon = \text{e}^- / \sec$ from the source

If I_{sky} is in units of photon flux per pixel, then $I_{sky} \cdot \varepsilon = \text{e}^- / \sec / \text{pixel}$ from the sky and $S_{sky} = I_{sky} \cdot A \cdot \pi\theta^2 = I_{sky} \cdot n_{pix}$

If I_{sky} is in units of photon flux per unit solid angle $d\Omega$ (e.g., $\text{arc}\sec^{-2}$), then $S_{sky} = I_{sky} \cdot \pi\theta^2$ but express $\pi\theta^2$ in the same units of solid angle.

RN = read noise (as if RN^2 e^- had been detected)

Dark = $\text{e}^- / \sec / \text{pixel}$

NB $\longrightarrow$ Ω_{ap} must have suitable units (pixels for RN and Dark and typically arcsec^2 for I_{sky}).

S/N for object measured in aperture with radius θ:

n_{pix}= # of pixels in the aperture = $\pi\theta^2$

Noise from the dark current in aperture with angle Ω_{ap}solid expressed in pixels

$$\frac{\text{Signal}}{\text{Noise}} = \frac{\overbrace{f_{obj} \cdot A \cdot \varepsilon \cdot t}^{S_{obj}}}{\left[\underbrace{f_{obj} \cdot A \cdot \varepsilon \cdot t}_{} + \underbrace{I_{\text{sky}} \cdot A \cdot \Omega_{ap} \cdot \varepsilon \cdot t}_{S_{sky}} + \underbrace{\left(RN + \frac{\text{gain}}{2} \right)^2 \cdot n_{pix}}_{} + \overbrace{\text{Dark} \cdot t \cdot n_{\text{pix}}}^{} \right]^{\frac{1}{2}}}$$

Noise from object *e*- in aperture

Noise from sky *e*- in aperture with solid angle Ω_{ap}

Readnoise in aperture with angle Ω_{ap}solid expressed in pixels

All the noise terms added in quadrature

Note: always calculate in *e*-   *why?*

What is ignored in this S/N eqn?

Telescope diameter

- Explicit inclusion of collecting aperture (i.e., $A \propto D_{tel}^2$)
- Break-out of terms that go into total system efficiency (starting from the top of the atmosphere)

- o Bias level/structure correction and errors
- o Flat-fielding correction and errors
- o Charge Transfer Efficiency (CTE) 0.99999/pixel transfer
- o Non-linearity when approaching full well
- o Scale changes in focal plane
- o Interpolation errors and correlation

S/N regimes

- Two basic regimes:
  1. Photon-limited (shot-noise from source+sky photons)
  2. Detector-limited (read-noise)
- In photon-limited case, two important sub-regimes
  a. Source-limited
  b. Sky-limited

S/N regimes: limiting cases

Let's assume CCD with Dark=0, well sampled read noise.

$$S/N = \frac{f_{obj} \cdot A \cdot \varepsilon \cdot t}{\left[f_{obj} \cdot A \cdot \varepsilon \cdot t + I_{\mathrm{sky}} \cdot A \cdot \Omega_{ap} \cdot \varepsilon \cdot t + (RN)^2 \cdot n_{pix} \right]^{\frac{1}{2}}}$$

Note: seeing or source-size comes in with Ω_{ap} and $\mathrm{n}_{\mathrm{pix}}$ terms

1a. Bright Sources: $(S_{obj}\, \varepsilon\, t)^{1/2}$ dominates noise term

$$\mathrm{S/N} \approx \frac{S_{obj}\, \varepsilon\, t}{\sqrt{S_{obj}\, \varepsilon\, t}} = \sqrt{S_{obj}\, \varepsilon\, t} \propto t^{\frac{1}{2}}$$

S/N limiting cases (*contd*)

$$S/N = \frac{f_{obj}\cdot A\cdot\varepsilon\cdot t}{\left[f_{obj}\cdot A\cdot\varepsilon\cdot t + I_{\rm sky}\cdot A\cdot\Omega_{ap}\cdot\varepsilon\cdot t + (RN)^2\cdot n_{pix}\right]^{\frac{1}{2}}}$$

$I_{sky,pix} = I_{sky}\,\Omega_{ap}/n_{pix}$, i.e., this is the sky flux per pixel

<u>1b. Sky Limited:</u> $(\sqrt{I_{sky,pix}\,\varepsilon t} > 3\times RN)$ *

$$\mathrm{S/N} \propto \frac{S_{obj}\,\varepsilon t}{\sqrt{I_{sky}\,A\Omega_{ap}\varepsilon t}} \propto t^{\frac{1}{2}}$$

Note: seeing comes in with Ω_{ap} or n_{pix} term

<u>2. Read-noise Limited:</u> $(\sqrt{I_{sky,pix}\,\varepsilon t} < 3\times RN)$ *

$$\mathrm{S/N} \propto \frac{S_{obj}\,\varepsilon t}{RN\sqrt{n_{pix}}} \propto t$$

What does this imply about exposure time?

*Why 3? How about 1?

S/N regimes: limiting cases

Again, let's assume CCD with Dark=0, well sampled read noise.

$$S/N = \frac{f_{obj}\cdot A\cdot\varepsilon\cdot t}{\left[f_{obj}\cdot A\cdot\varepsilon\cdot t + I_{\text{sky}}\cdot A\cdot\Omega_{ap}\cdot\varepsilon\cdot t + (RN)^2\cdot n_{pix}\right]^{\frac{1}{2}}}$$

But now let's take into account the explicit dependencies not just on time but on collecting area *A* and measurement aperture Ω_{ap}.

S/N limiting cases (*contd*)

1a. Bright Sources:

$$S/N \approx \frac{S_{obj}\,\varepsilon\,t}{\sqrt{S_{obj}\,\varepsilon\,t}} \propto (A\ \varepsilon\ t)^{\frac{1}{2}} \propto (\varepsilon\ t)^{\frac{1}{2}} D_{\text{tel}}$$

1b. Sky Limited:

$$S/N \propto \frac{S_{obj}\,\varepsilon\,t}{\sqrt{I_{sky}\,\Omega_{ap}\varepsilon\,t}} \propto \left(A\ \varepsilon\ t/\Omega_{ap}\right)^{\frac{1}{2}} \propto (\varepsilon\ t)^{\frac{1}{2}} D_{\text{tel}}/\theta_{ap}$$

Could choose 1

2. Read-noise Limited: $(\sqrt{I_{sky}\,\varepsilon\,t} < 3 \times RN)$

$$S/N \propto \frac{S_{obj}\,\varepsilon\,t}{\sqrt{n_{pix}RN^2}} \propto \varepsilon\ t\left(D_{\text{tel}}^2/\theta_{ap}\right)$$

D_{tel}: telescope diameter
θ_{ap}: measurement aperture radius

DQE

- DQE is often defined as the *effective quantum efficiency* of a CCD relative to an ideal detector with no read-noise. In the source-limited regime, ignoring dark-current:

$$DQE \quad = \quad QE \,/\, \left[1 + \frac{RN^2}{QE \cdot S_{obj} \cdot t} \right]$$

  where QE is the CCD quantum efficency.
- This can be generalized for any noise-regime, and including dark-current.
- A related concept is the *effective system efficiency*, $\mathrm{DQE}_{\mathrm{sys}}$, of which CCD QE is only one part.

How are these quantities formulated?

S/N regimes (recap)

$$S/N = \frac{S_{obj} \cdot \varepsilon \cdot t}{\left[S_{obj} \cdot \varepsilon \cdot t + I_{\text{sky}} \cdot \Omega_{ap} \cdot \varepsilon \cdot t + (RN)^2 \cdot n_{pix}\right]^{\frac{1}{2}}}$$

1. Photon Limited:

$$\text{S/N} \propto t^{\frac{1}{2}}$$

2. Read-noise Limited:

$$\text{S/N} \propto t$$

What does this imply about exposure time?

Photon propagation

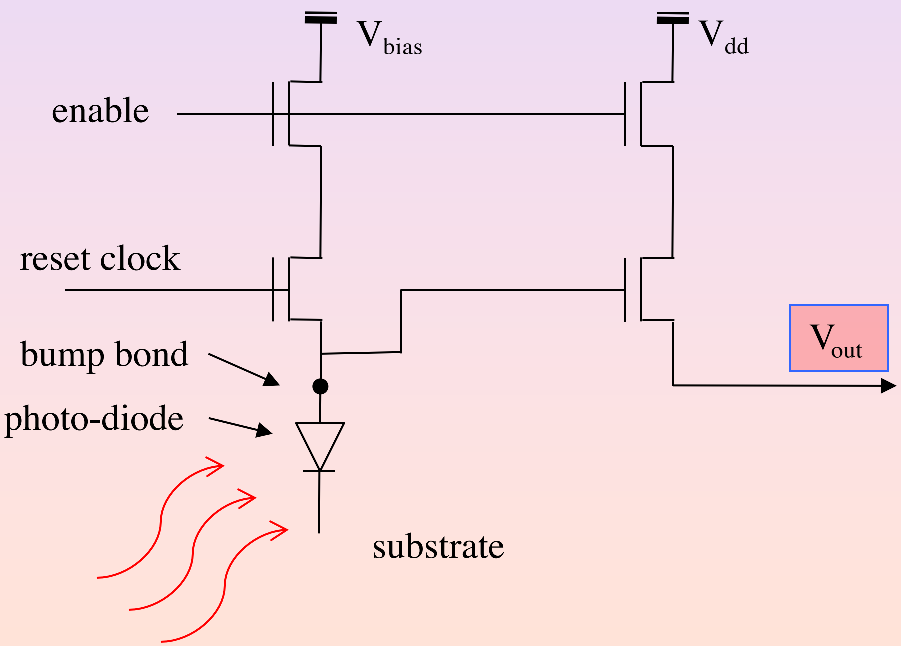
- Gain and read-noise of a detector can be determined empirically from a set of data taken
  - With constant source over a range of exposures
  - With constant integration with a range of source flux
- Noise definition:
  - g = gain = e^-/DN
  - R = detector noise (e^-)
  - p = photon noise (e^-) = $[\text{counts(DN)} \bullet g]^{1/2}$
  - $\text{Noise}^2 (e^-) = p^2 + R^2$
  - $(\text{Noise}/g)^2 \text{ (DN)} = (p/g)^2 + (R/g)^2$

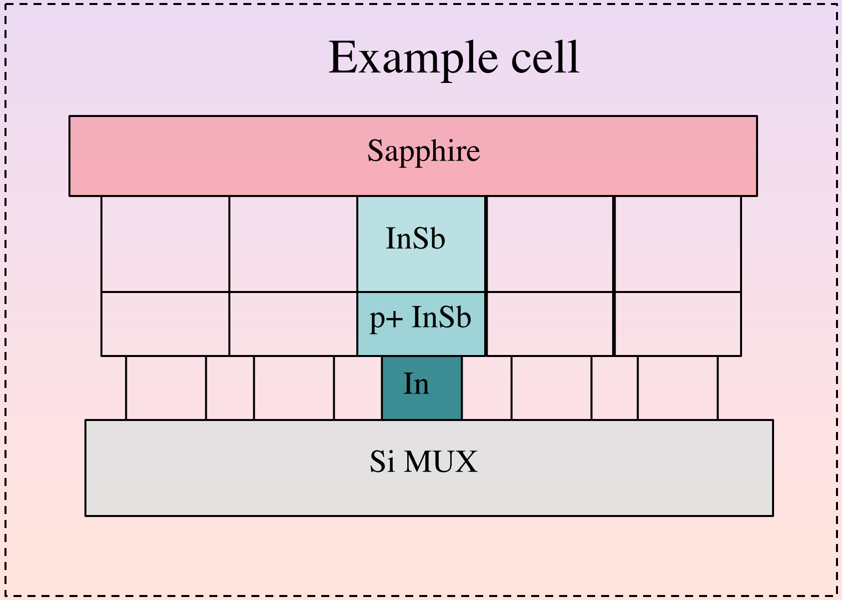
$$= \text{counts (DN)} \bullet g^{-1} + (R/g)^2$$

A relation existing between mean counts and standard deviation (in DN) that yields the gain (e-/DN) and read-noise (e- rms)

Near-Infrared Detectors

- Hybride photo-diode or photo-voltaic arrays
  - InSb or HgCdTe semi-conductors, grown on polished sapphire substrate: this is what converts photons to electrons
  - Bump-bonded with In (a conductor) to Si read-out structure (MOSFET or CMOS multiplexer)





Three primary NIR detectors

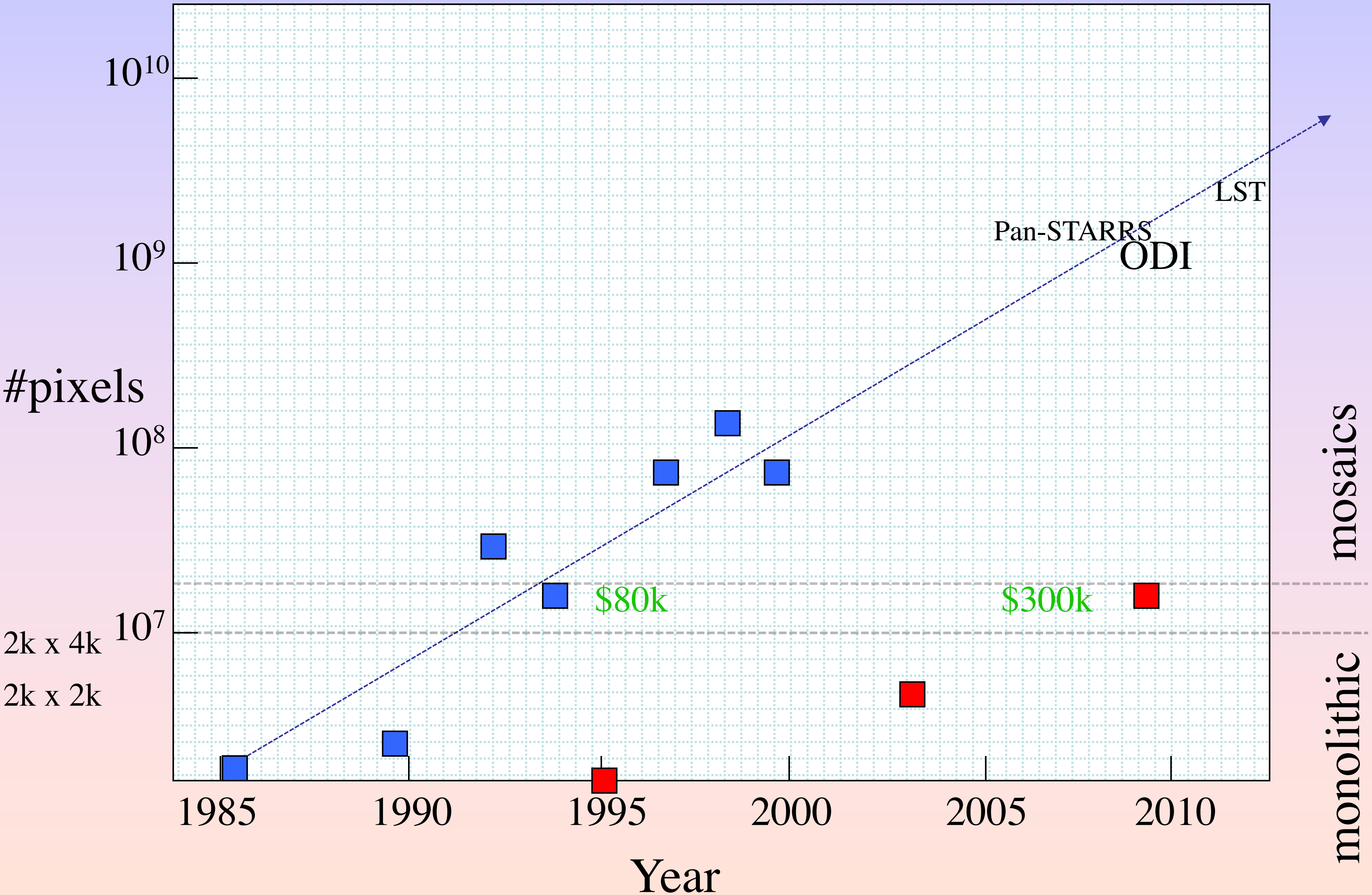
- HgCdTe: 0.5-5 micron sensitivity, QE up to 80%.
  - Blue sensitivity requires substrate thinning. Red cut-off determined by Hg:Cd mix (out to 17 micron, but saphire only transmits to 6.5 micron). NIR spectrograph for SALT uses mix that cuts off at 1.7 microns.
- InSb: typically 0.9-5 micron, again depends on doping.
- InGaAs: 0.8-1.7 micron, possible extension to 2.2 micron. Much lower cost.
- (Also PtSi, but different physical principle and low QE – 2-3%)
  - Both semiconductors overlap with CCD wavelength sensitivity.
  - HgCdTe vendor has pushed short wavelength sensitivity.
  - InSb vendor pushed long wavelength sensitivity – into the thermal IR. Implications for instrument design: blocking, cooling, backgrounds, performance, etc.
  - Historically InSb's had 30% higher QE (80 vs 60), but this appears no longer to be true.

Near-Infrared Detectors

- **Format:**
  - 64x64 in 1988
  - 256x526 by 1990 (HST/NICMOS)
  - 1048x1048 in 1995
  - 2048x2048 early 2000's
  - vendors taking orders for 4096x4096
- **Pixel size:**
  - originally 76 micron/pix; now typically 18-27 micron/pix (CCDs have 3-24 micron/pix)
- **Dynamic range:**
  - $3x10^5$ to 10^6 e- full well – comparable to CCDs.
- **QE:** comparable to CCDs
- **Dark current:** typically much higher than for CCDs
- **Read-noise:**
  - 400 e- circa 64x64
  - 40 e- by mid-90's 1024x1024 arrays
  - 15-20 e- with correlated multiple sampling

Requires more cooling
Why?

CCD and NIR array size and $$$



A500/L-5

Differences with optical CCDs

- Aside from *cost, size* (no longer really an issue), *read-noise* and *dark current*….

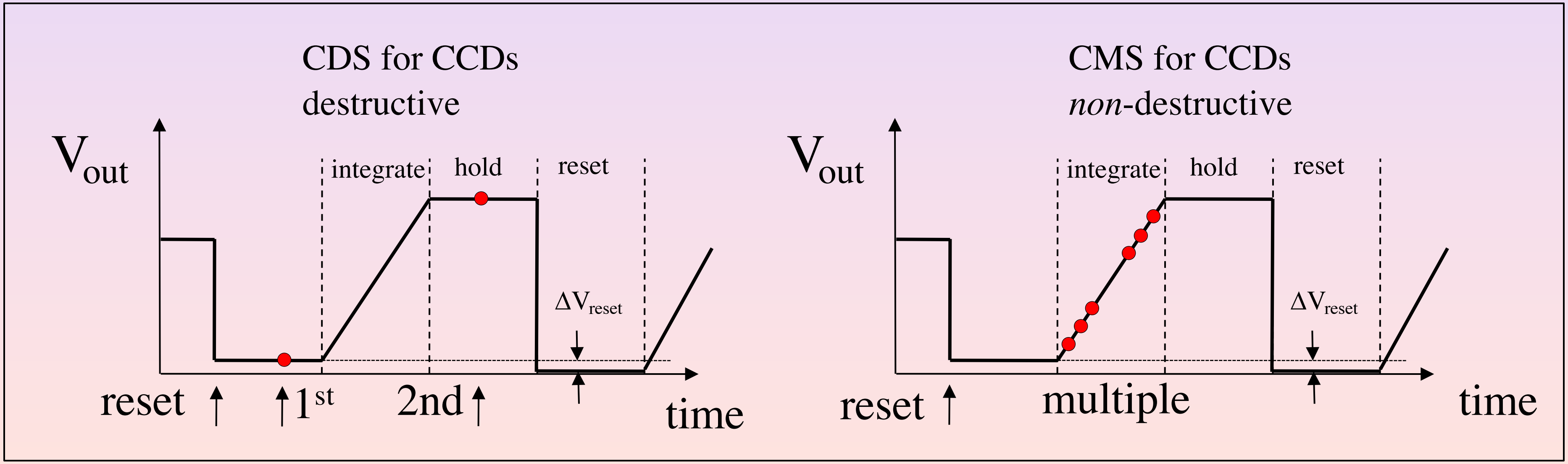
- Detectors are not charge buckets or corrals, but diodes: charge is collected, but fixed (until reset).
  - No shifting of charge along rows or columns
- Charge on each pixel is addressed via the Si multiplexer and sampled directly.
  - (Multiple) sub-arrays can be directly (and efficiently) addressed for read-out, even at different rates.
- Sampling of this charge (as a voltage) is *non*-destructive.

- Detectors are fundamentally non-linear

What does this imply for sampling, performance, and observing modes?

IR Array read-out modes

- As with CCDs, voltage produced by photoelectrons is sampled with an integrating circuit and digitized.
- Again, there is kTc noise associated with charge-injection when resetting the sample and integration circuitry voltages.
- Non-destructive reads allow for more than correlated double-sampling (CDS).
- Now correlated multiple sampling (CMS or *Fowler* sampling)



- Note where the voltage is sampled in CMS. *Why is this possible? Why is it advantageous? How many samples are ideal? What is the ideal temporal spacing?*

Detector non-linearity

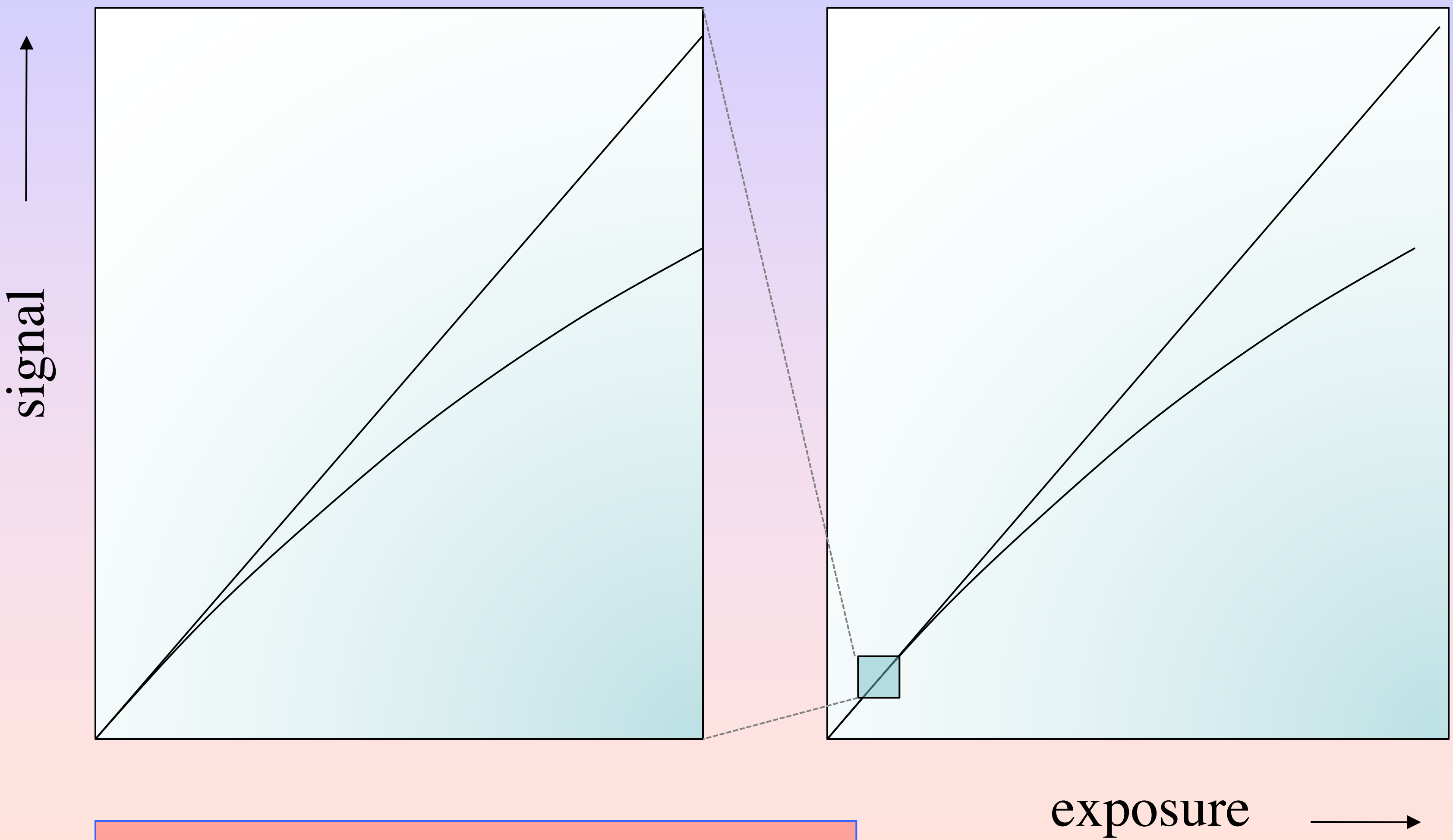
- Photo-diodes operate by having a capacitance at their pn (detector) junction.
- This capacitance depends on the (reverse) voltage across the junction.
- This voltage depends on the total number of electrons in the conduction band of the photo-diode (either thermal or photoelectrons)

⇨ NON LINEAR

- ➢ Non-linearity must be calibrated
- ➢ Adds dimension to data gathering, reduction and calibration

Question: If NIR detectors require non-linearity corrections, how come we worry about CCD non-linearity?

Detector non-linearity



Non-linear all the way down…

Mid- and Far-Infrared Detectors

- It's all about tuning the band-gap for the right photon energy level, and then suffering the consequences of the material-sciences headaches

- (Blocked) Impurity band conductors (IBC, or BIB):
  - doped Si using Ga, As, or Sb:
  - 5-28 micron wavelength sensitivity up to 1024x1024 array size

- Extrinsic Ge semiconductors, Ga doped
  - Large photon diffusion requires large pixels (500-700 microns)
  - Examples:
    - Spitzer/MIPS (32x32 array) 70 micron sensitivity
    - Herschel/PACS - same
    - AKARI satellite: 160 micron sensitivity

Find values for WIYN & SALT instr.

- Detector gain, read-noise, system efficiency
  - WIYN
    - WHIRC
    - Bench Spectrograph
    - ODI
    - NEID
  - SALT
    - SALTCAM
    - RSS
    - HRS

Assignment:
- Work as a team
- Tabulate information
- Assess availability, ease of access
- Bring to class to present