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

Review: Signal

- Point source
  - We are measuring photon flux
  - $E_\gamma = f_\gamma A \; t$
- Resolved source
  - We are measuring surface brightness
  - $E_\gamma = I_\gamma A \, \Omega \; t$

$\boxed{S_\gamma}$

Signal-to-Noise (S/N)

total system efficiency

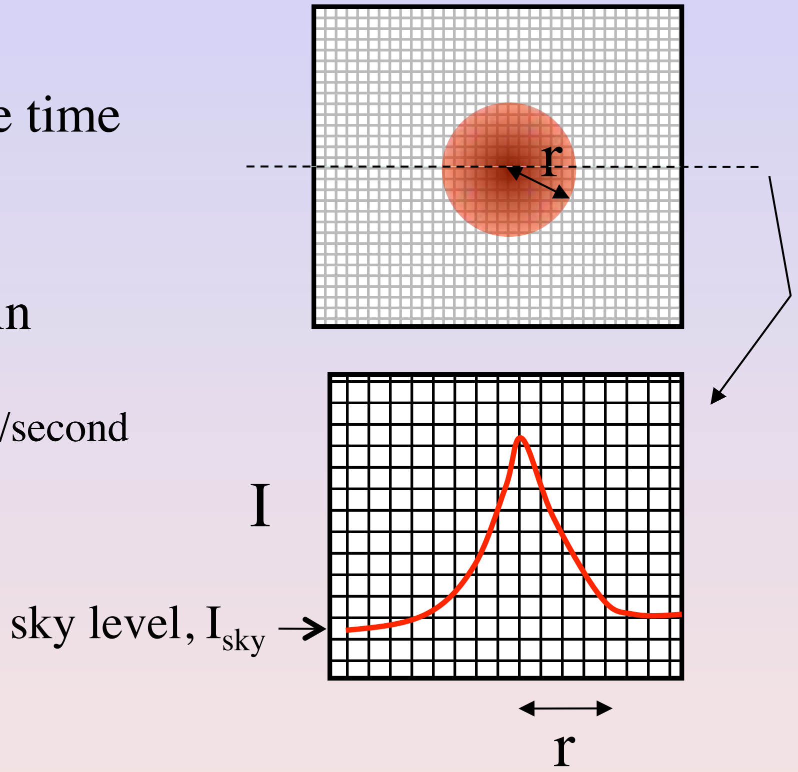
- Signal = $\underbrace{S_{obj}}\cdot \varepsilon \cdot t$

exposure time

detected e-/second: $S_{obj} = S_{DET} \cdot \text{gain}$

DN/second

- Consider the case where we count all the detected e- in a circular aperture with radius r.



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

Noise Sources

$\sqrt{S_{obj}\cdot\varepsilon\cdot t}$ ⇒ shot noise from source

$\sqrt{I_{sky}\cdot\varepsilon\cdot t\cdot\pi r^2}$ ⇒ shot noise from sky in aperture

$\sqrt{RN^2\cdot\pi r^2}$ ⇒ readout noise in aperture

$\sqrt{\left[RN^2+\overset{?}{\boxed{(0.5\times\text{gain})^2}}\right]}\cdot\sqrt{\pi r^2}$ ⇒ more general RN

$\sqrt{\text{Dark}\cdot t\cdot\pi r^2}$ ⇒ shot noise in dark current in aperture

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

$I_{sky}\cdot\varepsilon=\text{e}^-/\text{sec/pixel}$ from the sky, $S_{sky}=I_{sky}\cdot\pi r^2=I_{sky}\cdot n_{pix}$ ← NB

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

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

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

n_{pix} = # of pixels in the aperture = πr^2

$$\frac{\text{Signal}}{\text{Noise}} = \frac{S_{obj}\cdot\varepsilon\cdot t}{\left[\underbrace{S_{obj}\cdot\varepsilon\cdot t}_{\sqrt{(S_{obj}\cdot\varepsilon\cdot t)^2}} + \underbrace{I_{\text{sky}}\cdot\varepsilon\cdot t\cdot n_{\text{pix}}}_{\text{Noise from sky } e\text{- in aperture}} + \underbrace{\left(RN + \frac{\text{gain}}{2}\right)^2\cdot n_{pix}}_{\text{Readnoise in aperture}} + \overbrace{\text{Dark}\cdot t\cdot n_{\text{pix}}}^{\text{Noise from the dark current in aperture}}\right]^{\frac{1}{2}}}$$

All the noise terms added in quadrature

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

What is ignored in this S/N eqn?

- Explicit inclusion of collecting aperture
- Break-out of terms that go into total system efficiency (starting from the top of the atmosphere)
- Bias level/structure correction and errors
- Flat-fielding correction and errors
- Charge Transfer Efficiency (CTE) 0.99999/pixel transfer
- Non-linearity when approaching full well
- Scale changes in focal plane
- 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.

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

Note: seeing or source-size comes in with n_{pix} term

<u>1a. Bright Sources:</u> $(S_{obj}\, \varepsilon\, t)^{1/2}$ 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*)

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

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

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

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

$$\mathrm{S/N} \propto \frac{S_{obj}\,\varepsilon\, t}{\sqrt{n_{pix} RN^2}} \propto t$$

Note: seeing comes in with n_{pix} term

What does this imply about exposure time?

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*, DQE$_{sys}$, of which CCD QE is only one part.

How are these quantities formulated?

S/N regimes (recap)

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

<u>1. Photon Limited:</u>

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

<u>2. Read-noise Limited:</u>

What does this imply about exposure time?

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

Photon propagation

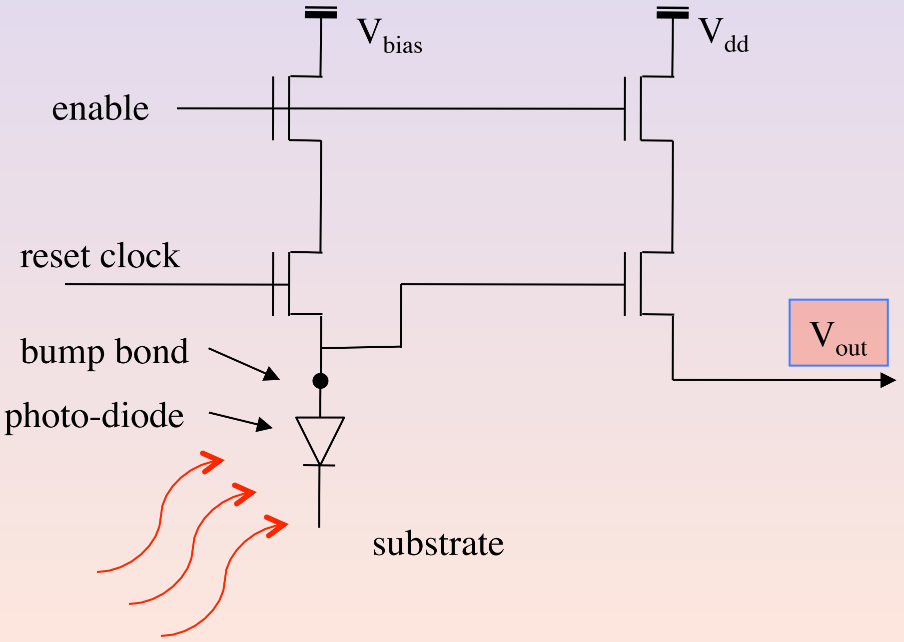
- Gain and read-noise of a detector can be determined empirically from a set of data taken
  - With constant source over a range of exposures
  - With constant integration with a range of source flux
- Noise definition:
  - g = gain = e^-/DN
  - R = detector noise (e^-)
  - p = photon noise (e^-) = $[\text{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

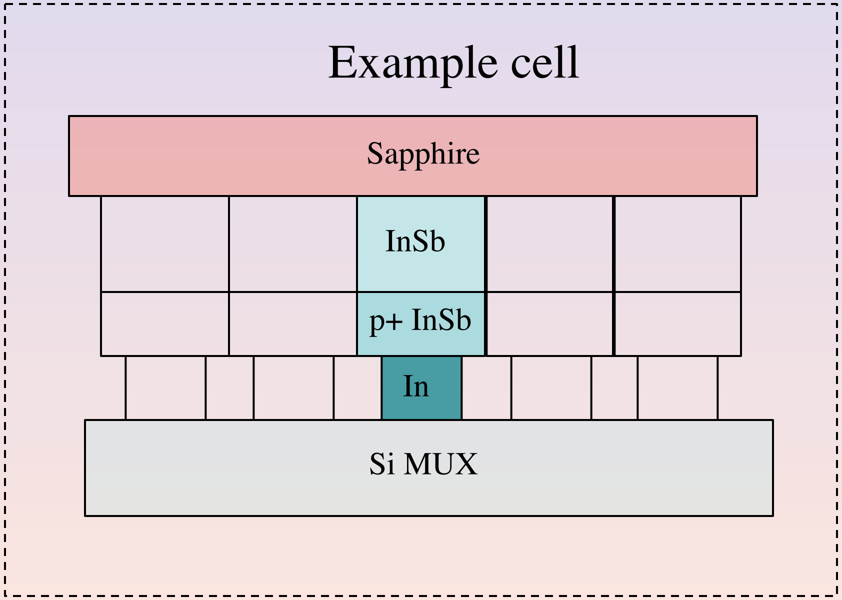
    $= \text{counts (DN)} \bullet g^{-1} + (R/g)^2$

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)




Example cell

Two primary NIR detectors

- HgCdTe: 0.5-2.5 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).

- InSb: typically 0.9-5 micron, again depends on doping.

- (Also PtSi, but different physical principle and low QE – 2-3%)

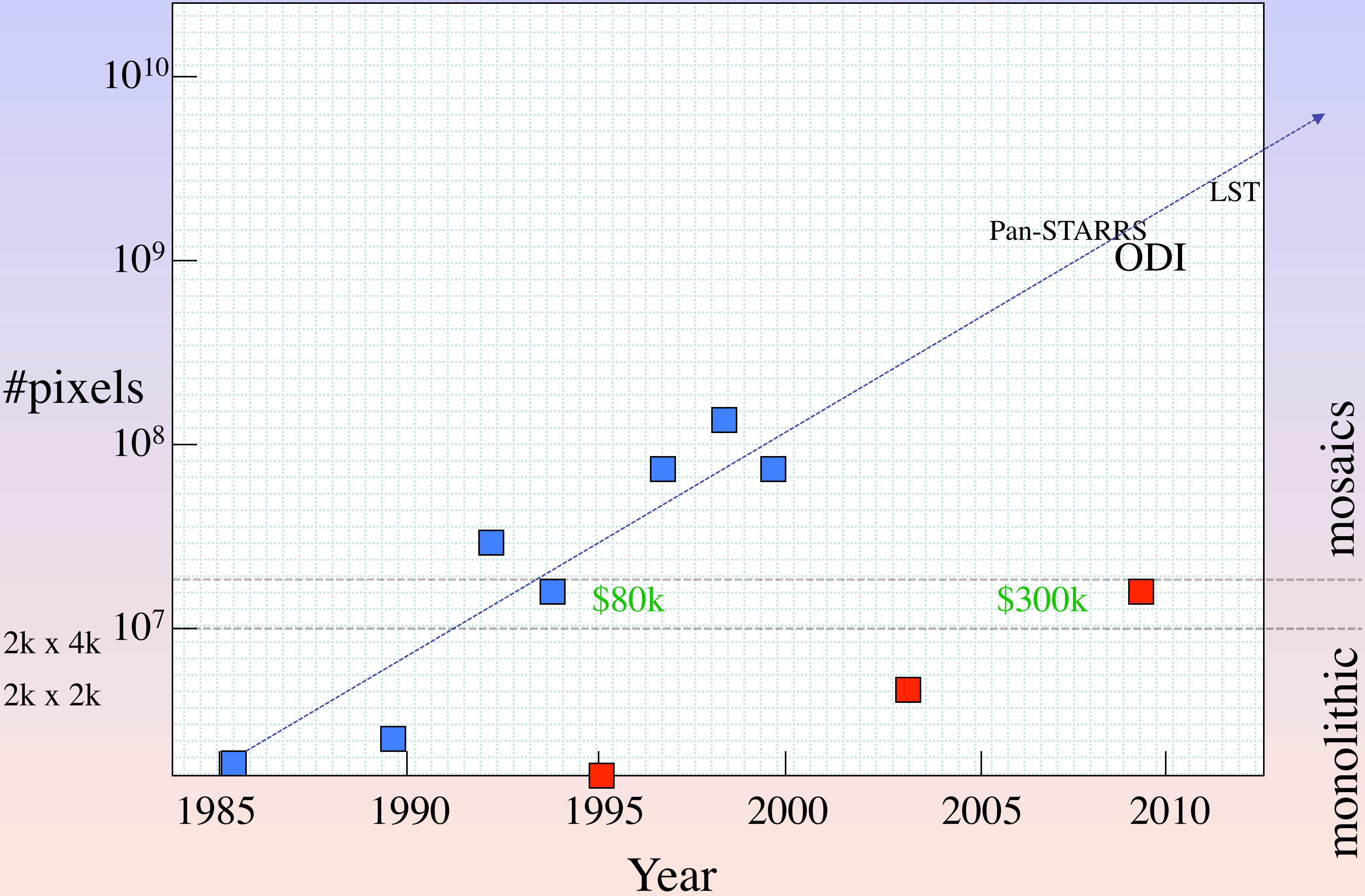
  - Both semiconductors overlap with CCD wavelength sensitivity.
  - HgCdTe vendor has pushed short wavelength sensitivity.
  - InSb vendor has pushed long wavelength sensitivity – into the thermal IR. Has implications for instrument design, blocking, cooling, backgrounds, performance, etc.
  - Historically InSb's have had 30% higher QE (80 vs 60), but this appears to 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 9-24 micron/pix)
- **Dynamic range:**
  - 3×10^5 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 $$$



Differences with optical CCDs

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

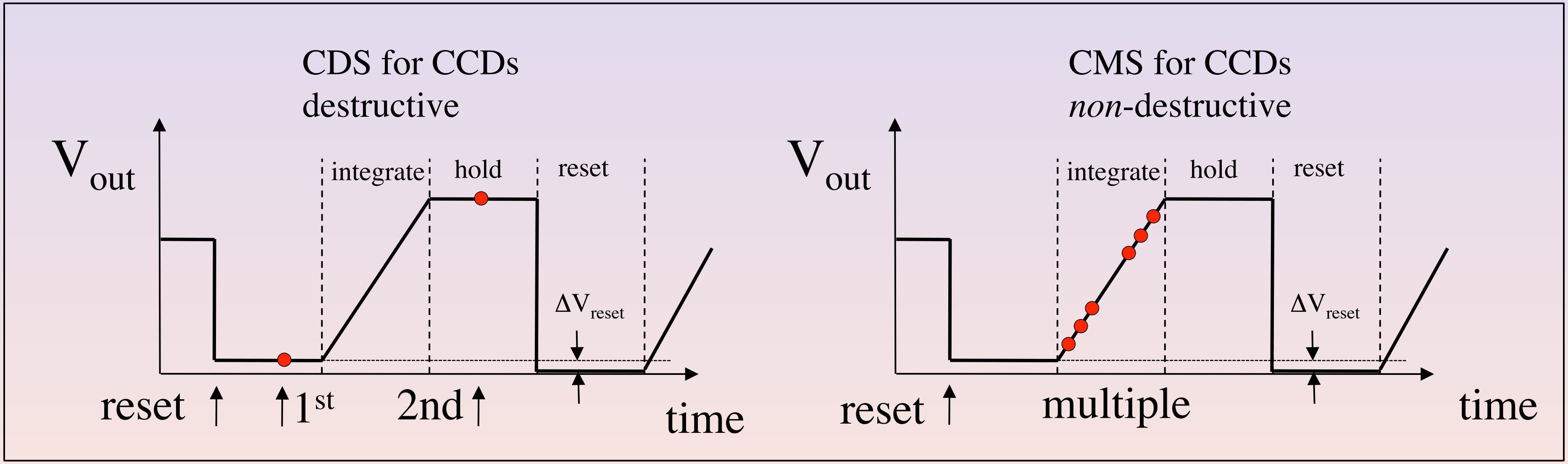
- Detectors are not charge buckets or corrals, but diodes: charge is collected, but fixed (until reset).
  - No shifting of charge along rows or columns
- Charge on each pixel is addressed via the Si multiplexer and sampled directly.
  - (Multiple) sub-arrays can be directly (and efficiently) addressed 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

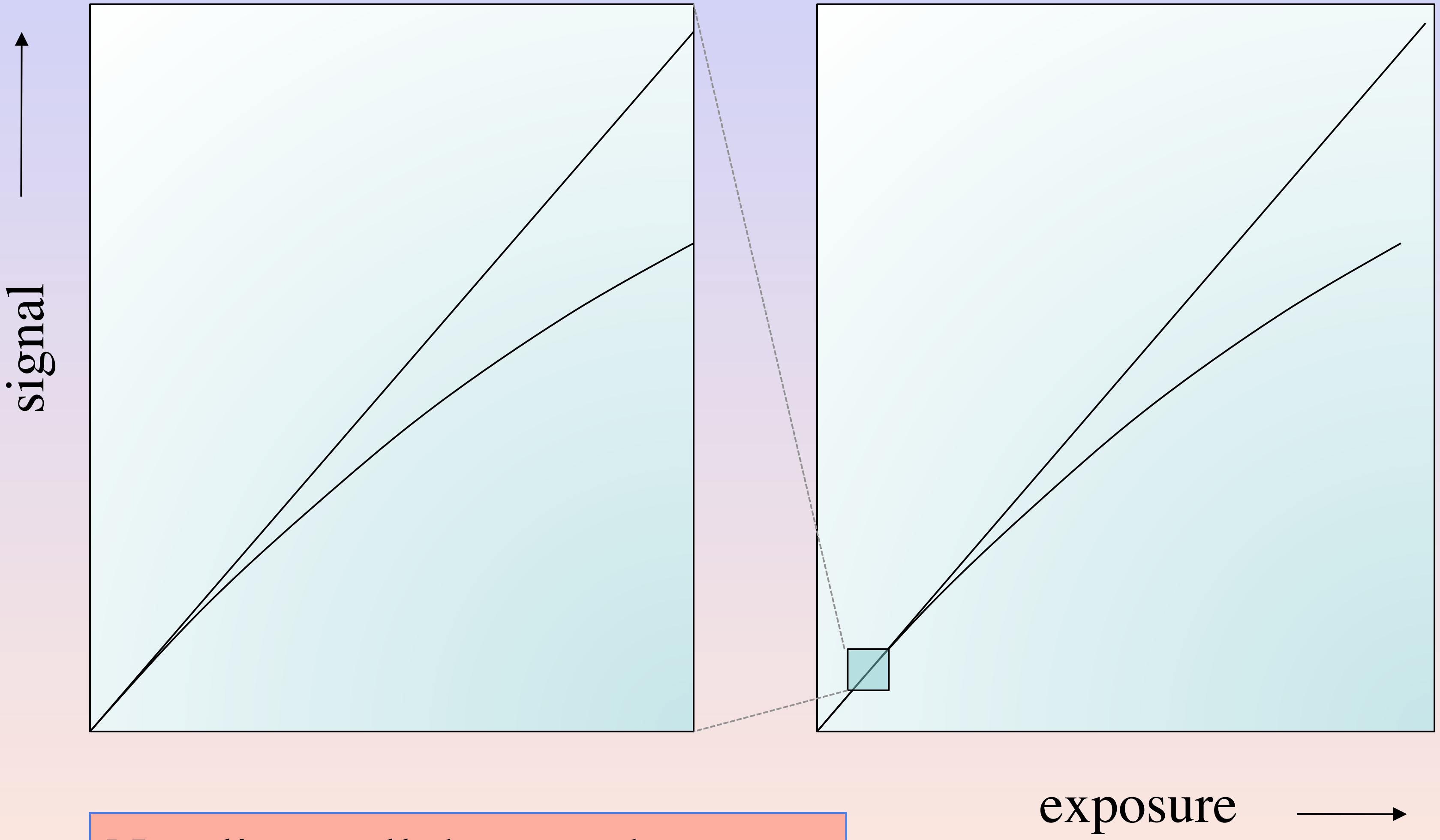
- Photo-diodes operate by having a capacitance at their pn (detector) junction.
- This capacitance depends on the (reverse) voltage across the junction.
- This voltage depends on the total number of electrons in the conduction band of the photo-diode (either thermal or photoelectrons)

⇨ 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
  - <u>WIYN</u>
    - ➢ WHIRC
    - ➢ Bench Spectrograph
    - ➢ MiniMo
    - ➢ OPTIC
    - ➢ ODI
  - <u>SALT</u>
    - ➢ SALTCAM
    - ➢ RSS

Assignment:
❖Work in pairs
❖Tabulate information
❖Assess availability, ease of access
❖Bring to class to present