Introduction to signal and noise in Astronomy CCD cameras

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Outline

1. Introduction to CCDs
2. Signal and noise in CCDs
3. Comparison of a few CCD cameras

Electronic detectors used in astronomy

- Single-element detectors:
  - Photodiodes
  - Photomultiplier tubes (PMT)
  - Avalanche photodiodes (APD)
- Imaging detectors
  - Vidicon
  - Charge-coupled device (CCD)
  - Intensified CCD (ICCD)
  - Electron multiplication CCD (EMCCD)
  - CMOS

Best signal-to-noise ratio for long exposures: CCDs!

What happens in a CCD

- Light incident on a pixel is absorbed in a photodiode region of a semiconductor, creating electron-hole pairs
- The electrons are captured in a storage region ("well")
- Readout follows a "bucket brigade" process
- Charge eventually reaches an amplifier, where it is measured

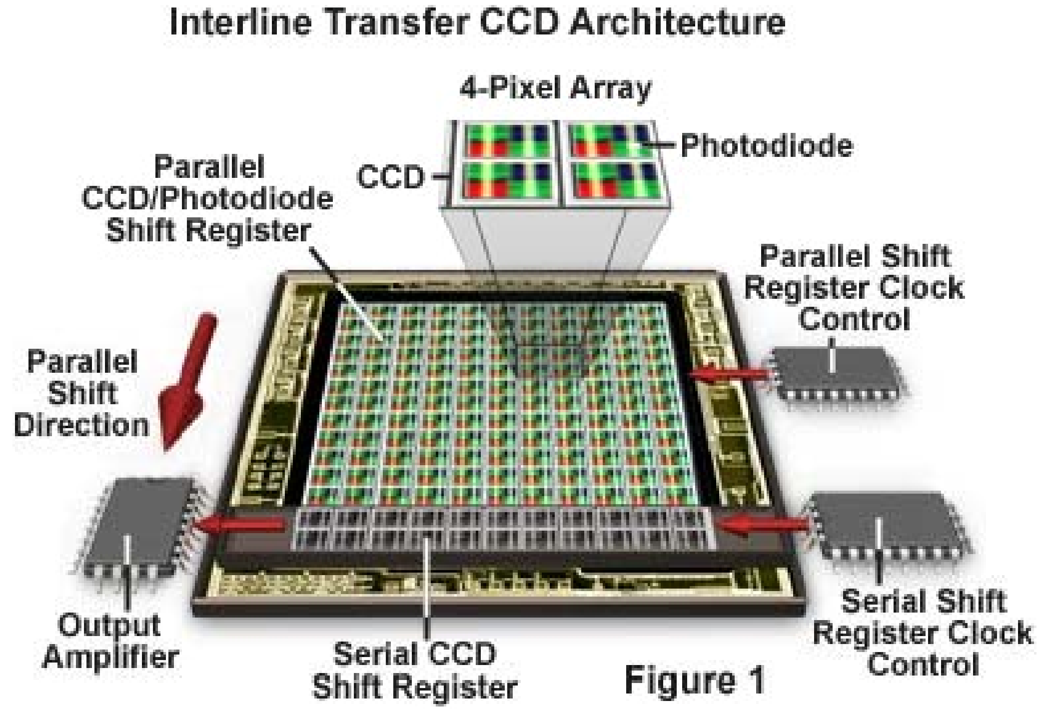


Figure 1

(Hamamatsu)

Types of CCDs

<u>Pixel type</u>

- Front-illuminated
- Back-illuminated
- Microlens
- Monochrome / Color

<u>Readout Architecture</u>

- Full frame
- Frame transfer
- Interline

Features expected in astronomy CCDs

Good:

- Efficient light response
- Low noise→ quantum-limited detection for > 100 photons
- Linear response
- Decent dynamic range (up to 16 bits)
- Access to raw data

Bad:

- Expensive
- Power hungry
- Heavy/bulky
- Blooming, smear (in some CCDs)
- Less "user friendly"

Signal and noise in CCDs

Introducing photons

- Light is "quantized" into energy units $h*c/\lambda$ = 3.6×10^{-19} Joules at 555nm
- Natural unit for discussing noise in electronic detectors
- Photon rates for some common light sources:
  - Green laser pointer: 10^{16} photons / sec
  - Sirius (through 6mm pupil): 10^{6} photons/sec
  - Mag 6 star (through 6mm pupil): 1000 photons/sec

<u>Approximate magnitude → photon rate conversion:</u>

Visible photons/sec/m^2 ≈ $10^{(10.0-0.4*Mv)}$

Quantum efficiency

For CCDs, QE = #electrons / #incident photons

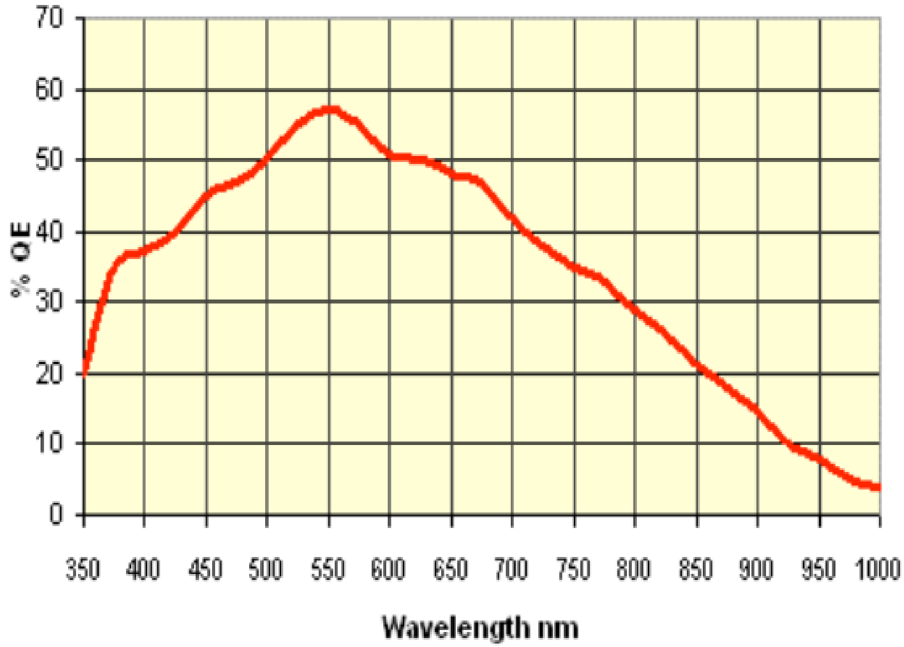
QE values can range from 20% to 95% depending on CCD, wavelength

For astronomy CCDs, QE curves should be given by the manufacturer !

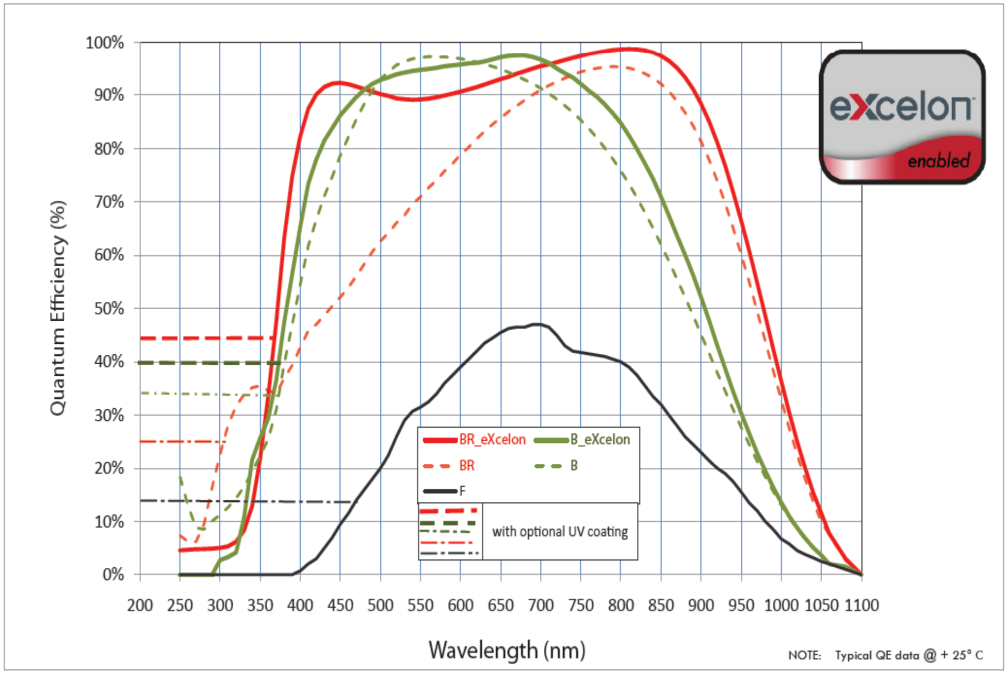
Examples:

(SBIG)

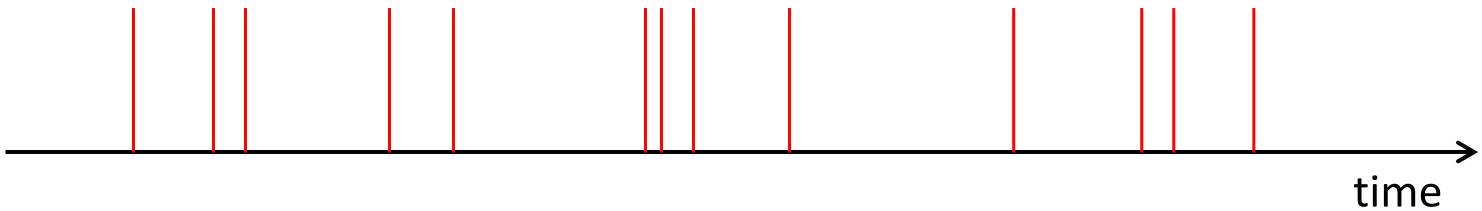
Quantum Efficiency
ST-8300



(Princeton Instruments)



Photon shot noise



- In most situations, photons arrive independently (Poisson process)
- Uncertainty (standard deviation) in photon number = square root of mean
- Example: if you detect 10,000 photons, noise = 100 photons = 1% (actually achieving 1% pixel-to-pixel variation will probably require flat field correction)
- Shot noise is intrinsic to the light field, and unavoidable
- Goal for any detector: to have shot noise be the dominant noise source

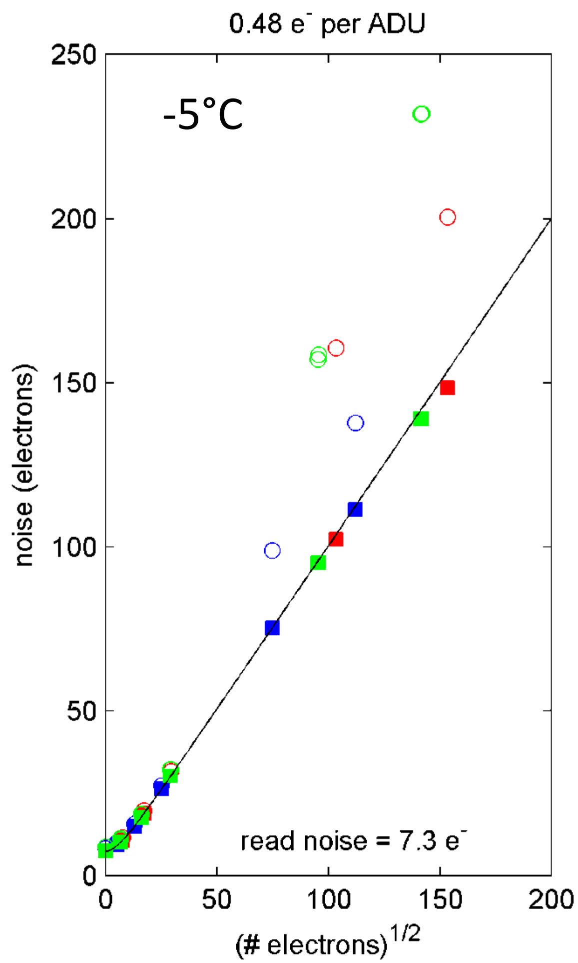
Shot noise demonstration

Using ST-4000XC camera

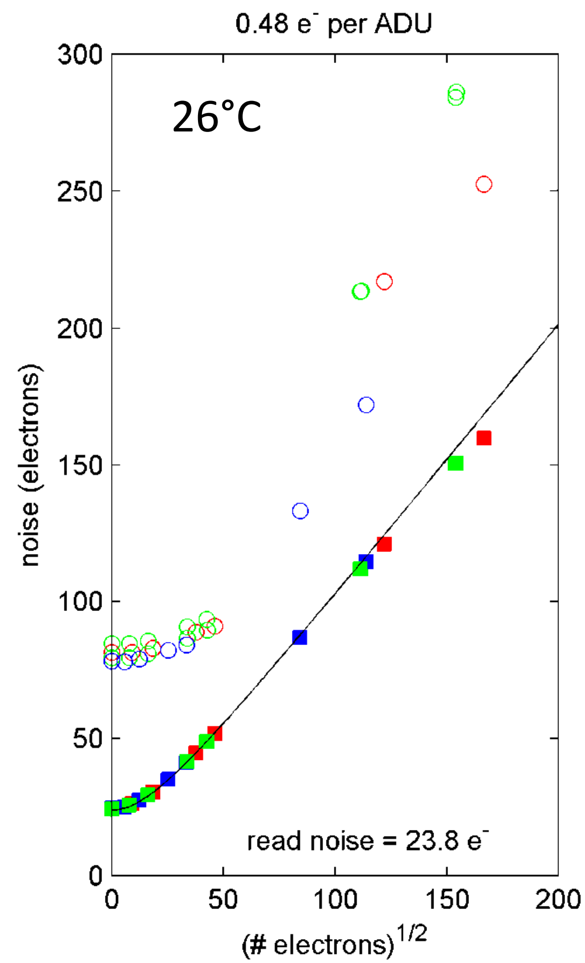
<u>Solid squares:</u>
temporal variation only

<u>Empty circles:</u>
includes temporal plus spatial variation

COOLED



ROOM TEMP.



Readout noise

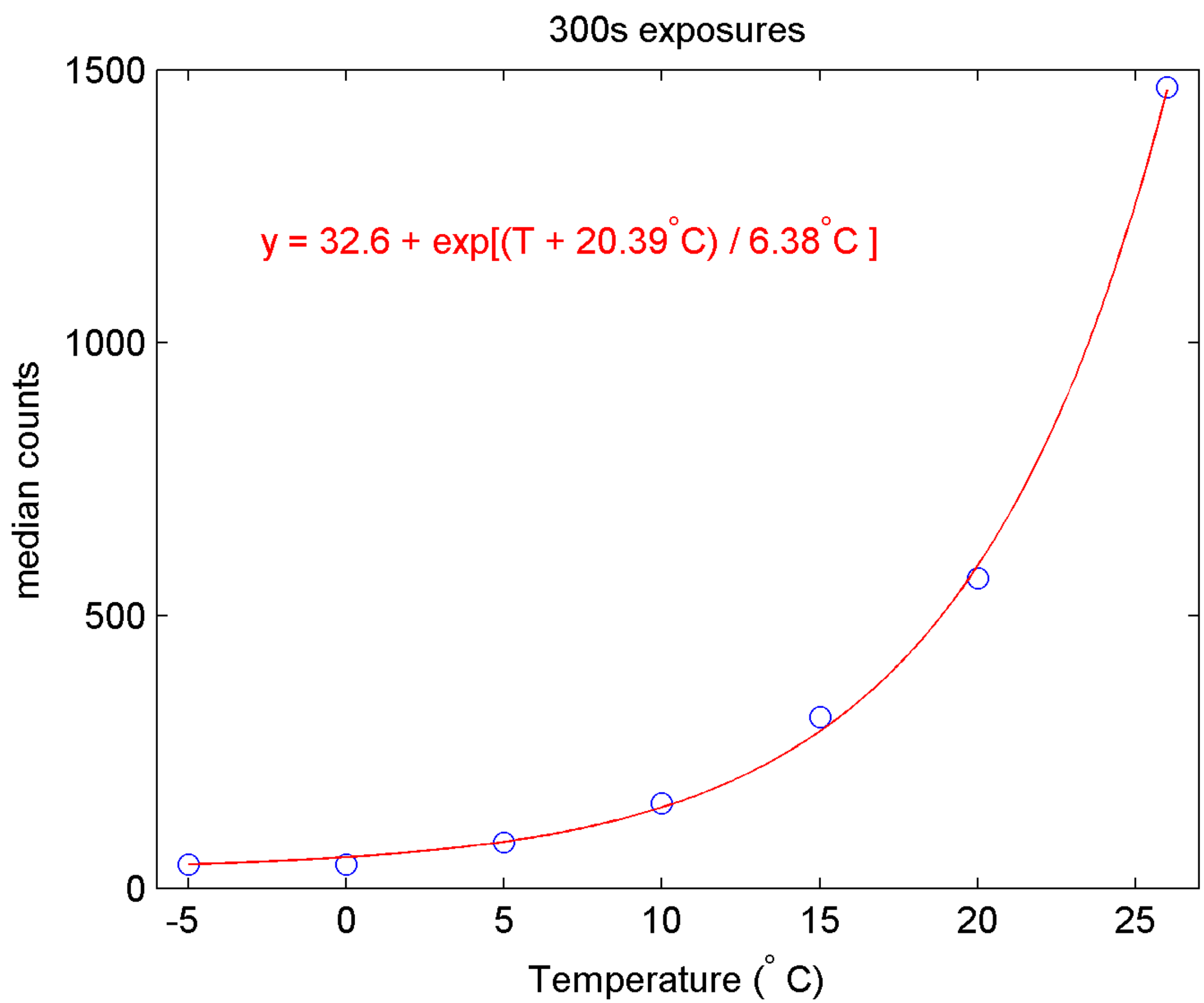
- Noise associated with amplifier used to detect electronic charge from pixels
- Should be <10 electrons for a good astronomical CCD
- Typically, readout noise increases with readout speed
- For N exposures, total readout noise increases by $\sqrt{N}$
- <u>Should be specified by manufacturer</u>

Dark current

- Electrons slowly accumulate in pixels even in absence of light
- Strongly dependent on semiconductor defect density, and temperature
- Mean dark contribution (and resulting fixed pattern noise) eliminated by subtracting dark frames
- Associated shot noise contribution remains after subtraction (with additional penalty if only a single dark frame is used)
- <u>Varies greatly between cameras</u>
  - Research grade CCDs with 3-stage coolers: negligible dark current
  - Mid-range CCDs with 1-stage cooler: dark current is small enough using dark frames
  - Uncooled CCDs: dark noise makes a significant contribution

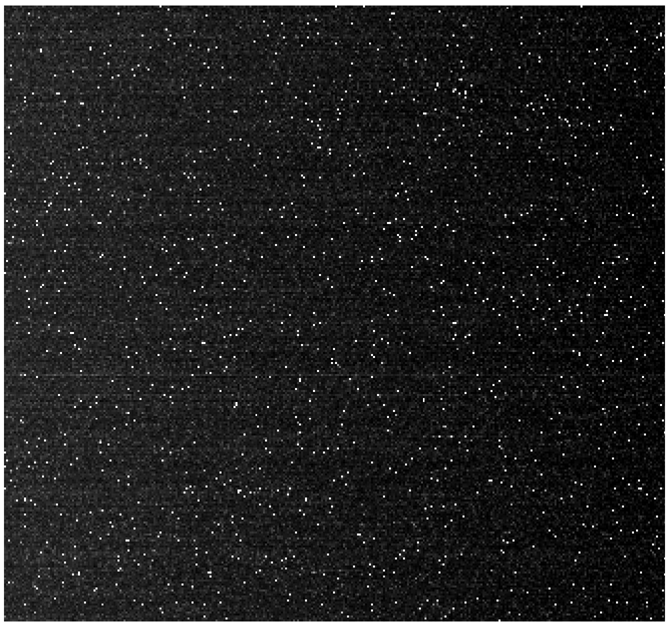
Dark current example

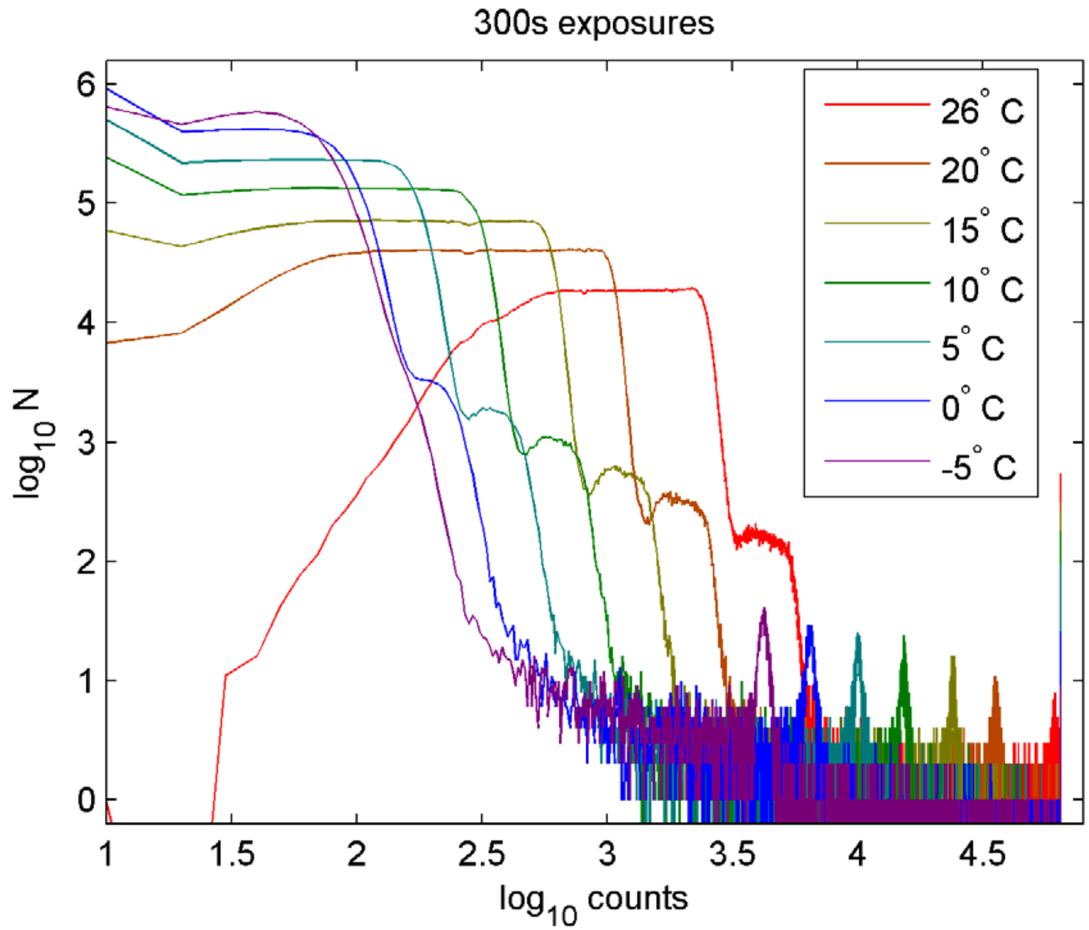
Using ST-4000XC camera



Dark current example (2)

26° C (room temp)





Signal/Noise summary

$$\text{Signal} = \eta\, r_{\text{star}} T$$

$$\text{Noise} = \sqrt{(\eta\, r_{\text{star}} + \eta\, r_{\text{sky}} + d)T + n_{\text{exp}}\sigma^2}$$

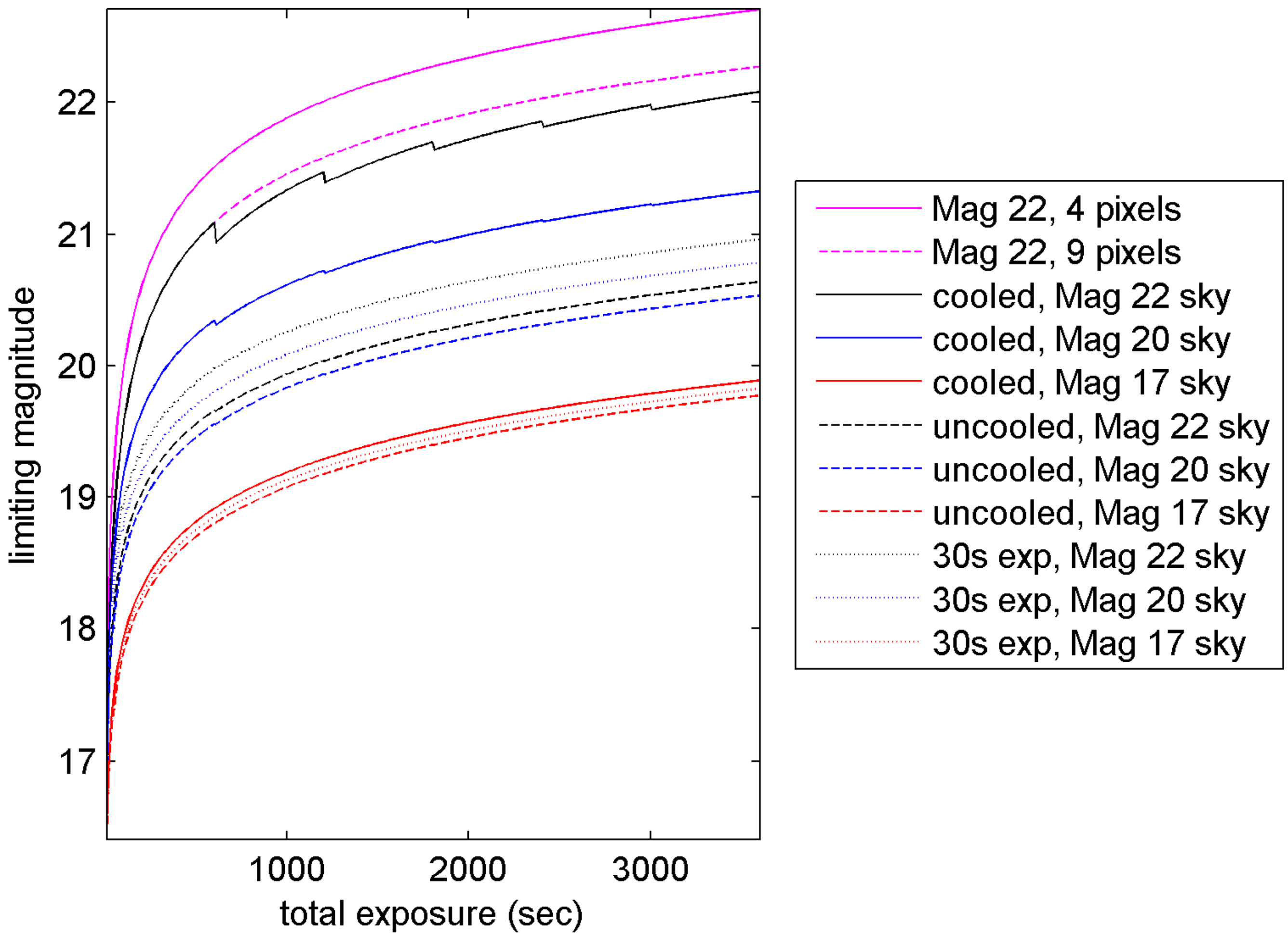
η = combined quantum efficiency (telescope and camera)
r_{star} = incoming photon rate from star
r_{sky} = incoming photon rate from sky glow
d = dark count rate
T = exposure time
n_{exp} = number of exposures
σ = readout noise amplitude per exposure

Requirement to detect a star: Signal/Noise ~ 3 (?)

Limiting star magnitudes

Estimated for 8", f/6 Newtonian with ST-4000XC single-shot color camera

Varying:
- **Sky brightness**
- **Seeing**
- **Cooled/uncooled**
- **Exposure time**



Useful link: http://www.nature1st.net/bogan/astro/optics/ccdlimit.html

Comparing a few cameras

Orion Starshoot Deep Space Color Imaging Camera

<u>Good</u>

- Relatively inexpensive
- Lightweight
- Powered by USB alone (without cooling)

<u>Bad</u>

- Small CCD (752x582)
- Open-loop TE cooler
- Critical specifications not given
- Excessive readout noise, sometimes with patterns
- Colors can separate for short exposures

SBIG ST-4000XC

Good
- Relatively large CCD (2048x2048)
- Low noise
- Second CCD for self guiding
- Closed-loop cooler
- Includes mechanical shutter

Bad
- Big and heavy – need to rebalance mount
- Clunky power adapters, cable management
- Expensive
- Modest QE

SBIG ST-8300

Good

- Relatively large CCD (3326x2504)
- Low noise
- Closed-loop cooler
- Includes mechanical shutter

Bad

- Modest QE

Specification comparison

	Orion DSCI	SBIG ST-8300	SBIG ST-4000-XC	PI Pixis 2048B
CCD chip	Sony ICX259AK	Kodak KAF-8300	Kodak KAI-4022C	E2v CCD42-40
Max. quantum efficiency	?	57%	46%, 42%, 34%	97%
Readout noise (e)	?	9.3	7.9	3.5
Dark current (e/pixel/sec)	?	0.02	~0.02*	0.005
Cooling	1 stage*	1 stage	1 stage	3 stage
Mech. shutter?	no	yes	yes	no
Color filters	CMYG	mono	RGGB	mono
Pixel size	6.5 x 6.25 μm	5.4 μm	7.4 μm	13.5 x 13.5 μm
Self-guiding?	no	no	yes	no
# Pixels	752x582	3326 x 2504	2048 x 2048	2048 x 2048
Price	$250	$2000	$3000	~$30000
pixels/$	1750	4160	1400	140

Summary

- Astronomy CCDs come in a wide range of price and performance levels
- Good astronomy CCDs have high quantum efficiency and low dark current, and cost a lot
- The relative advantage depends heavily on the observing site (sky glow) and telescope focal ratio