Low Noise CCD Readout

- CCDs – how they work
- CCD Lab at FNAL
- Contributions to charge collection
- Noise and Dark Current
- Low noise – state of the art is 2 to 3 e^-
- An idea to improve that to < 0.5 e^-
- Science Prospects
- Developing University Collaboration

Center for Particle Astrophysics

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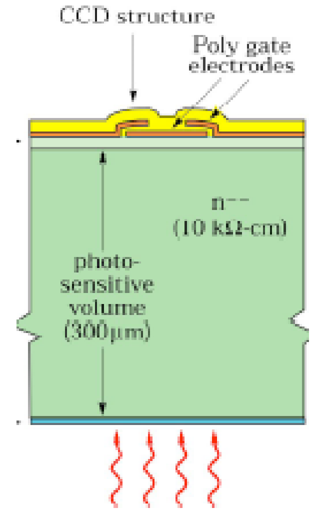
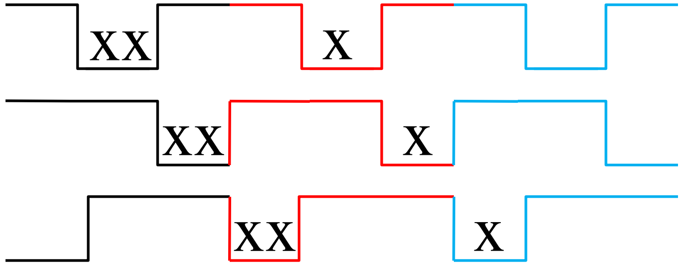
Gustavo Cancelo

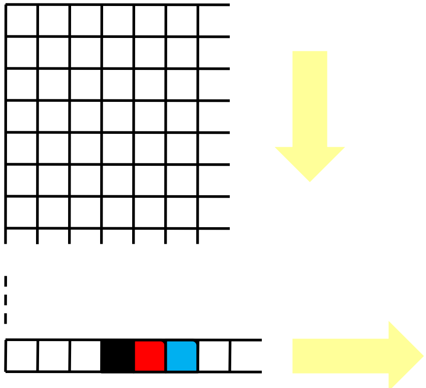
CCDs

- CCDs are 2D capacitor arrays with 10 to 15 micron pixels. Each pixel has 3 clock phases.
- CCDs Collect & Store Charge
  - Photons with energy < 1.14 eV (l<10868A) can knock an electron out of the Si valence band.
  - A substrate voltage sweeps charge to polygate electrodes (pixels).



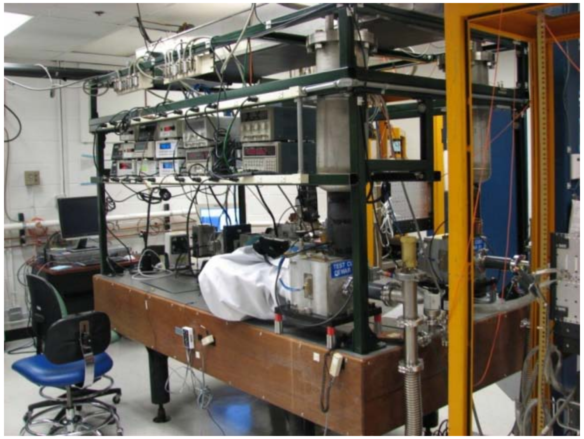
– CCDs Readout
  - Three Clock Phase Charge Movement
  - Next row clocks down to “serial register”
  - The “serial register” clocks towards the edge so that each pixel can be readout one at a time.

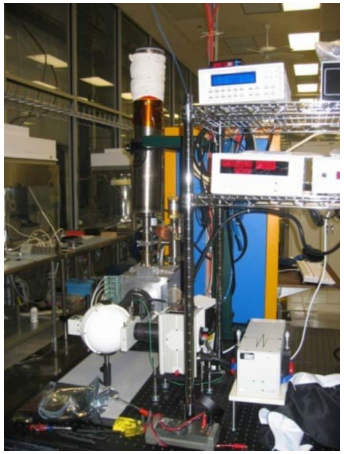




CCD Lab @ FNAL

- We have been studying thick, p-type, fully-depleted CCDs produced at LBNL for DECam and SNAP. We have some experience with conventional CCDs.
- We perform all CCD characterization tests using our equipment at SiDet.
- There is a variety of optical equipment tailored to the special requirements.
- Table on the right is DECam CCD specifications, provided as an example.

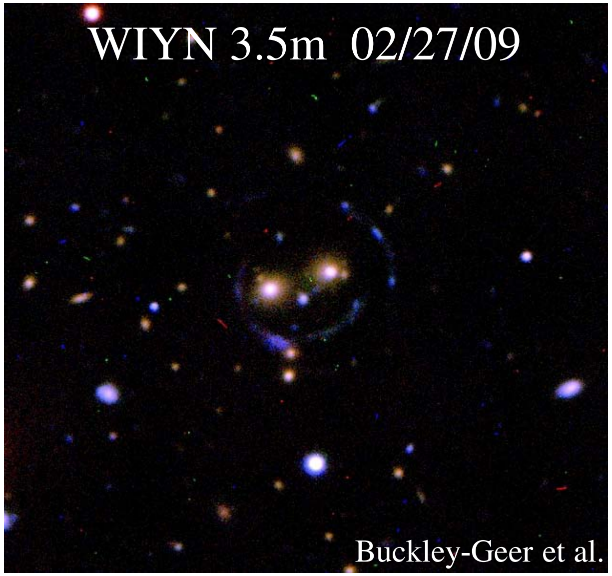




	DECam CCD Requirements
Pixel array	2048 4096 pixels
Pixel size	15 μm x 15 μm
# Outputs	2
QE(g,r,i,z)	60%, 75%, 60%, 65%
QE Instability	<0.3% in 12-18 hrs
QE Uniformity in focal plane	<5% in 12-18 hrs
Full well capacity	>130,000 e^-
Dark current	<~25 e^-/hr/pixel
Persistence	Erase mechanism
Read noise	< 15 e^- @ 250kpix/s
Charge Transfer Inefficiency	$<10^{-5}$
Charge diffusion	1D σ < 7.5 μm
Cosmetic Requirements	<# Bad pixels> <0.5%
Linearity	1%
Package Flatness	Effectively +–10 μm

Contributors to Counts

- Number of counts in a pixel depends on imaging time, photon flux, dark current, and readout noise.



$$\text{Signal} \propto \text{time} * 10^{Magnitude/2.5}$$

$$\text{Dark Counts} \propto \text{time} * T^{1.5} e^{-E_{bandgap}/(2kT)}$$

Readout noise is more complex, depending both on the CCD and the readout system. We use correlated double sampling readout and are most concerned about two contributions:

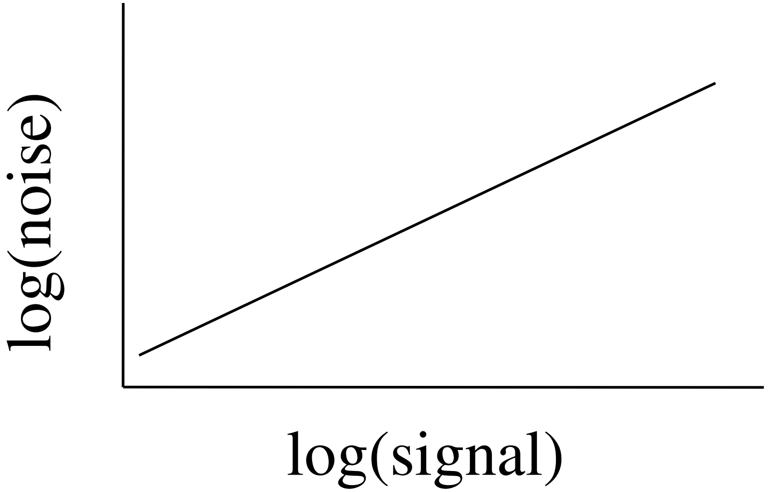
Source follower noise

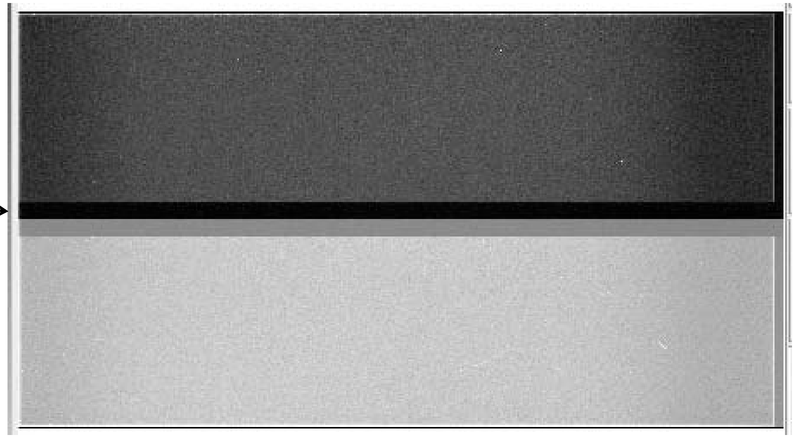
System noise

More discussion of readout noise is coming up later.

Noise & Dark Current

- Measure the readout noise using a series of test images called a “photon transfer curve”.
  - Slope is ½*gain due to shot noise (root-N of γ’s).
  - Readout noise is the y-intercept (no signal).
- The readout noise is also determinable from the “overscan pixels”.
- Dark current is easily determined from “shutter-closed” images.





State-of-the-Art

- Typically, astronomical CCDs have 5 to 20 electrons of readout noise. Faster => more noise.
  - The Hubble (WFPC2) has 5 e^- read noise. http://www.stsci.edu/instruments/wfpc2/Wfpc2_hand4/ch1_introduction2.html
  - Gemini GMOS-N 3.4 to 4.8 e^- http://www.gemini.edu/sciops/instruments/gmos/imaging/detector-array?q=node/10425
  - Mosaic-2 Imager on Magellan < 3 e^- in slow readout mode. http://www.lco.cl/telescopes-information/magellan/instruments/magellan-news/imacs-mosaic_2-reduced-read-noise
  - With the NOAO Monsoon System and the Leach Controller (Astronomical Research Corp.) we achieve 2 electrons readout noise operating DECam or SNAP CCDs at a slow readout speed.

Opportunity for low noise readout

- Instrumentation recently developed for beam diagnostics will allow us filter the noise. It takes advantages in 2 technological improvements
  - Mhz speed analog-digital conversion
  - Big FPGA
  - We would build a system to do it.
- Initial tests suggest we can achieve < 0.5 electrons readout noise. Perhaps even better than that. See Gustavo’s talk.

Science Opportunities 1

- Improvement in Signal-to-Noise (S/N) in astrophysics is
  - sometimes accomplished by increasing the area of the primary mirror (numerator), which is expensive.
  - we can decrease the Noise (denominator).
- The obvious applications are low signal dark energy studies
  - High resolution spectroscopy, particularly of objects with a large redshift,
  - Faint-object spectroscopy,
  - Imaging with narrow-band filters.

Developing University Collaboration

- D. Depoy (Texas A&M) has sent a letter
  - See next slide.
- Brenna Flaugher (FNAL) is developing goodwill (and possible collaboration) with the greater astrophysics community through the judicious loaning of small (and otherwise not very useful) CCDs in picture frame package.
  - Mike Pierce @ U. Wyoming
  - Various others in the works.

Developments in University Collaboration

From: Darren DePoy
To: brenna@fnal.gov; estrada@fnal.gov; diehl@fnal.gov
Subject: Potential very low noise CCD use
Date: Saturday, March 21, 2009 3:22:58 PM

Dear Tom, Juan, and Brenna --

You recently described work being done on creating CCD systems with extremely low read noise. This is a very exciting development, particularly if the noise can be reduced to below one electron. This level of noise would allow an increase in signal-to-noise equivalent to a correspondingly larger telescope primary diameter for certain types of observations. For example, decreasing the noise from typical values of 3-5 electrons to <1 electron would allow a 4m-class telescope to perform as well as or better than a 10m-class telescope.

Such an improvement in a DECam-like CCD, coupled to the exceptional quantum efficiency in the far-red of those devices, would permit observations of a wide range of targets of interest to dark energy studies. For example, installed in a high resolution spectrometer such a system could be used to observe faint Ly-alpha absorption lines along the line of sight to very distant galaxies or quasars, which can be used to measure the mass power spectrum in the Universe. Such a CCD system could also be used to obtain spectra of almost any other interesting target: type Ia supernovae at high redshift, lensed arcs of strong gravitational lenses, and standard distance ladder calibrators.

A field test of such a low-noise CCD system would be very valuable, particularly if the device is a 2Kx4K device in a picture frame package. I have a spectrometer that can accommodate this sort of CCD and I can arrange for telescope time for test observations.

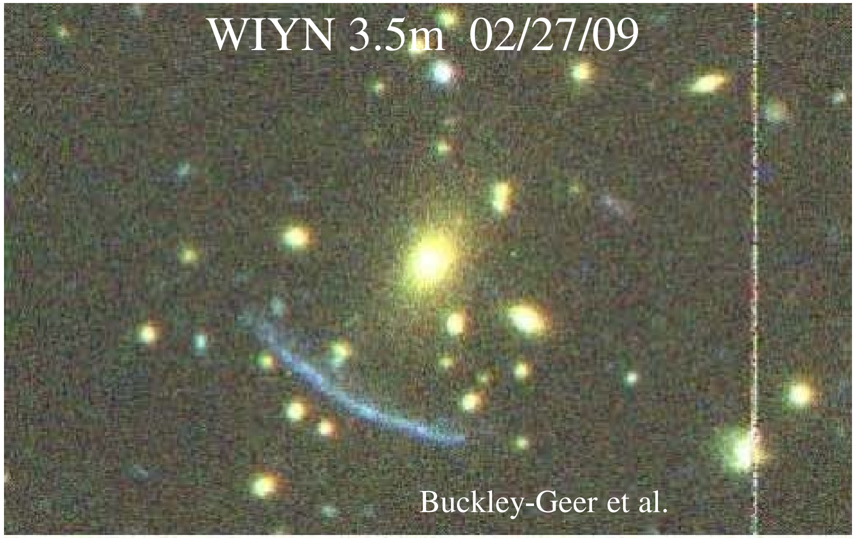
Please let me know if you are interested in pursuing this idea.

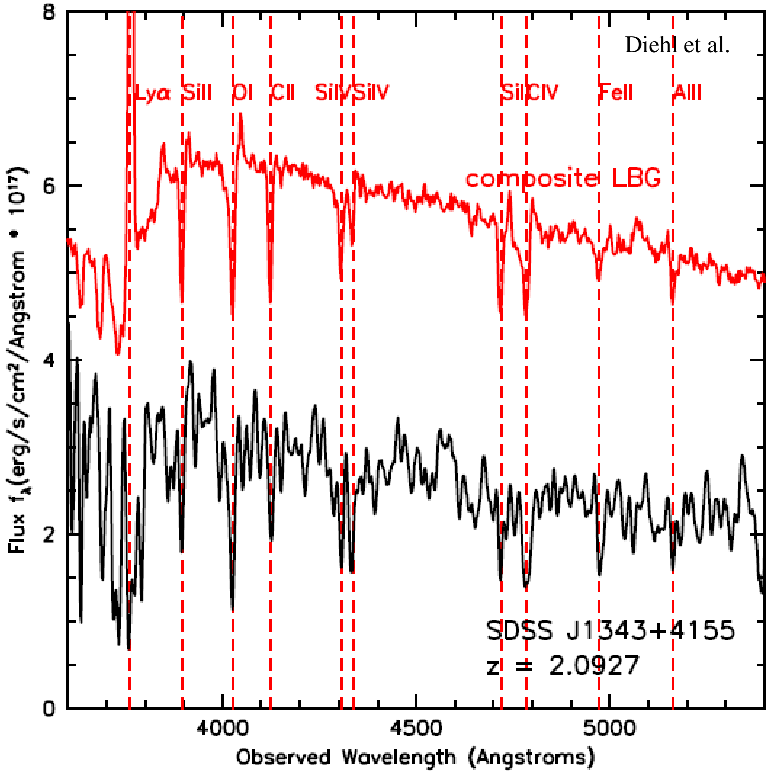
Best regards,

Darren DePoy
Rachal/Mitchell/Heep Professor of Physics
Texas A&M University

Example: Ly α absorption line

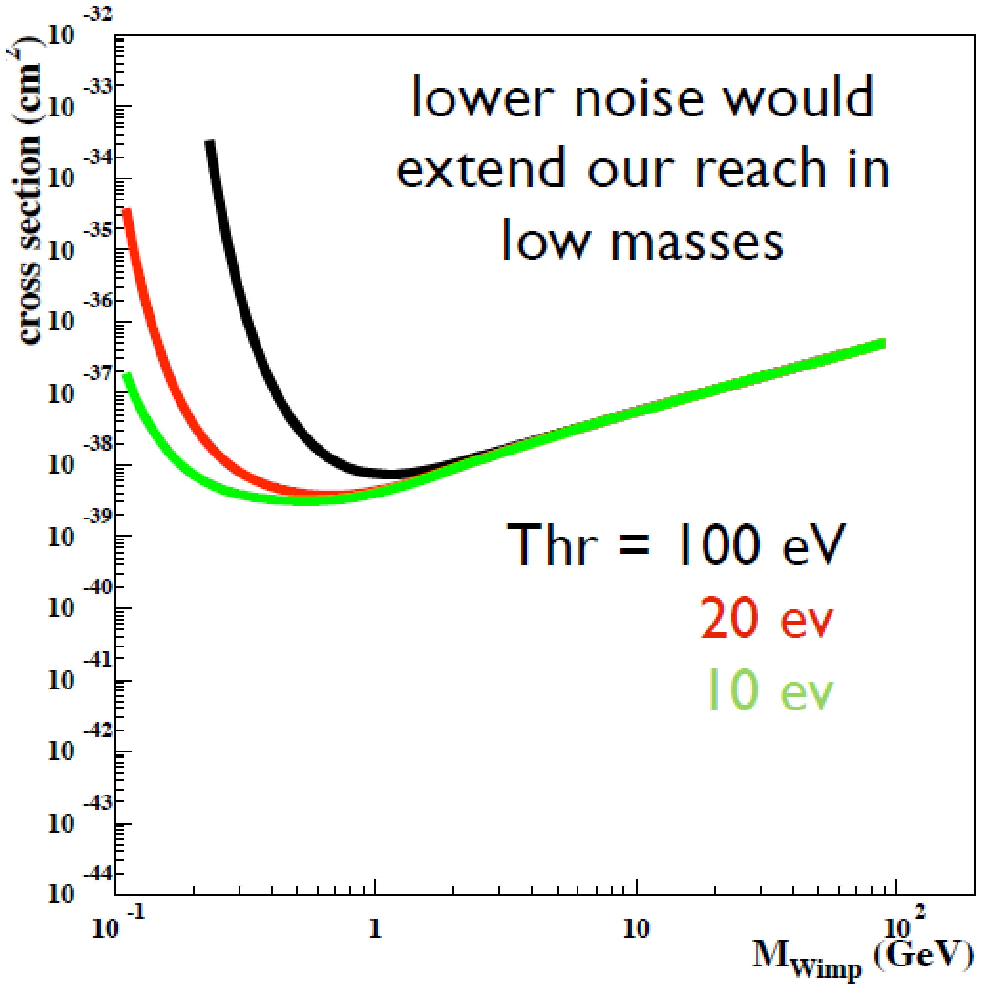
- A strongly-lensed galaxy at z = 2.0927 showing a Ly α absorption line.
- In this case the line is at the same redshift as the galaxy, indicating the H gas is associated with it.





Science Opportunities 2

- The CCDs can be used for a dark matter search.
- J. Estrada is doing just that.
- To right: dark matter mass limits, extrapolated from present measurements in MINOS hole.
- Strong dependence on readout noise, less implies lower threshold



Summary

- Brief description of how CCDs work & some CCD Tests
- Contributers to counts in nice CCDs include photons, dark-current, and readout noise
- The state-of-the-art in low noise CCD readout is 2 to 3 electrons and FNAL has achieved that.
- We have an idea to achieve lower readout noise and plan to try. The next talk will show initial results.
- Effect of lowering readout noise is similar to increasing area of the primary mirror (and therefore valuable).
- There are applications for studying Dark Energy and Dark Matter that would this improvement would strengthen.
- We are beginning to work with university colleagues to develop plans for collaboration.
- Note: this was favorably reviewed March 24, 2009 by FCPA. See DES-DOCDB 2858.

Backup & Extra Slides

Notes

- This idea was favorably reviewed March 24, 2009 by an FCPA ad-hoc committee. Presentations from HTD, Estrada, and Cancelo. A report was written. All of that is available at DES-DOCDB 2858 and probably on some FCPA link.
- A budget was sent to Dan B., Greg Bock, Mike Lindgren, Vicki White, and probably Bob. T. The bulk of cost (not high) is effort ~ 1 to 1.5 FTE.
- My sense is that we are going to continue to get support in the Divisions for the development of the low noise readout.
- Collaborative opportunities include ideas such as Depoy's, collaboration with Brenna's "friends", collaboration with the instrument builder(s) at UoC (also "friends"), collaboration on big spectroscopic dark energy instruments that we've heard rumor of, etc …

Dan’s Questions

1) Will the proposed science goal be seen as compelling on the national scene (i.e. to PASAG) and within the DOE mission?

   This isn’t new for the DOE, which has a track record measuring dark matter and dark Energy in experiments on telescopes and in deep holes.

2) What is the main science goal and what is the expected timescale for achieving it?

   Very Low Noise Spectroscopy (somebody invent an acronym) will present opportunities for dark energy and dark matter measurements. From 2 to 12 months to prove the technology. Then we’ll begin to talk about experiments.

3) What are the risks that the main science goal will not be achieved?

   Failure to make the technology work.

4) How does the planned program address these risks?

   Directly.

5) Why is Fermilab the best place to take this initiative?

   We are taking advantage of instrumentation developed for beam diagnostics at Fermilab. Gustavo and his department did that; now he’s applying it to this problem, too.

6) What are the chances that others will reach the main science goal before we do?

   Small. Darren Depoy knows all of the instrument builders (in the US at least).