CCD R&D @ Fermilab

J.Estrada

Detector R&D retreat

5/5/2011

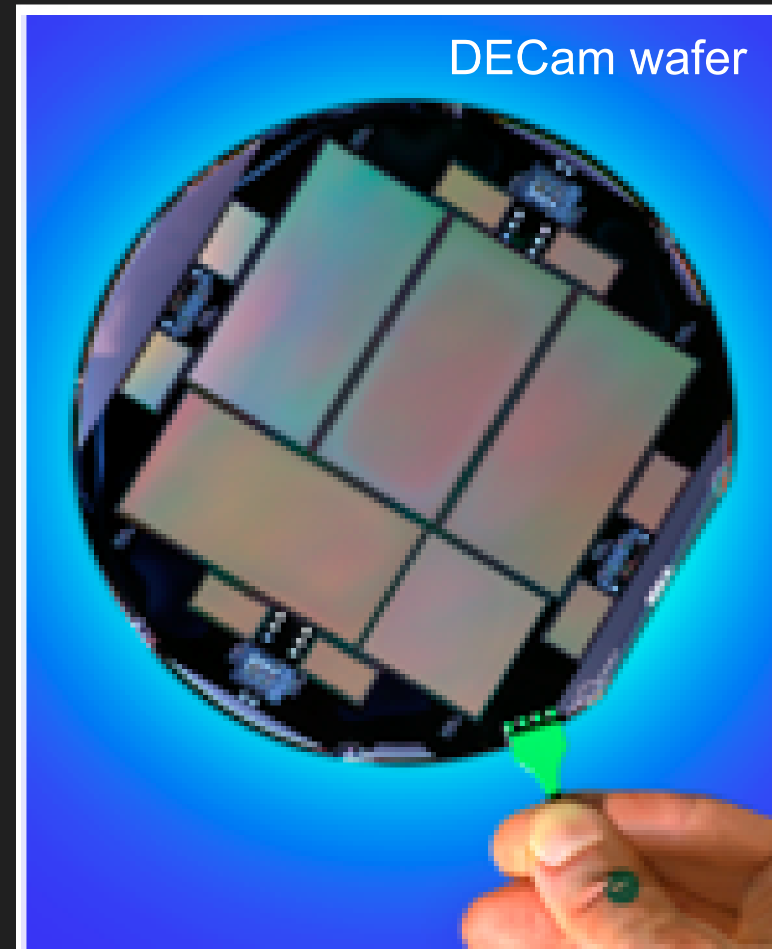
DECam focal plane detectors

Science goal requires DES to reach z~1

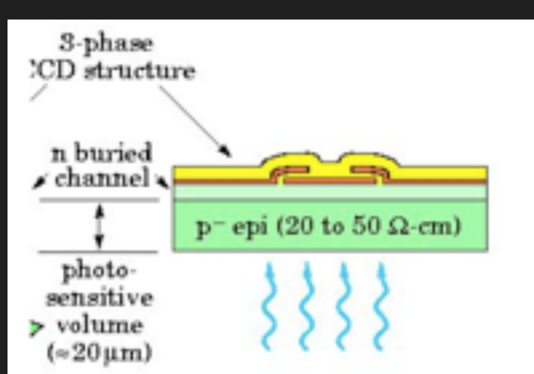
for DES we want to spend ~50% of time in z-filter (825-1100nm)
Astronomical CCDs are usually thinned to 30-40 microns (depletion):
Good 400nm response
Poor 900nm response

LBNL full depletion CCD are the choice for DECam:

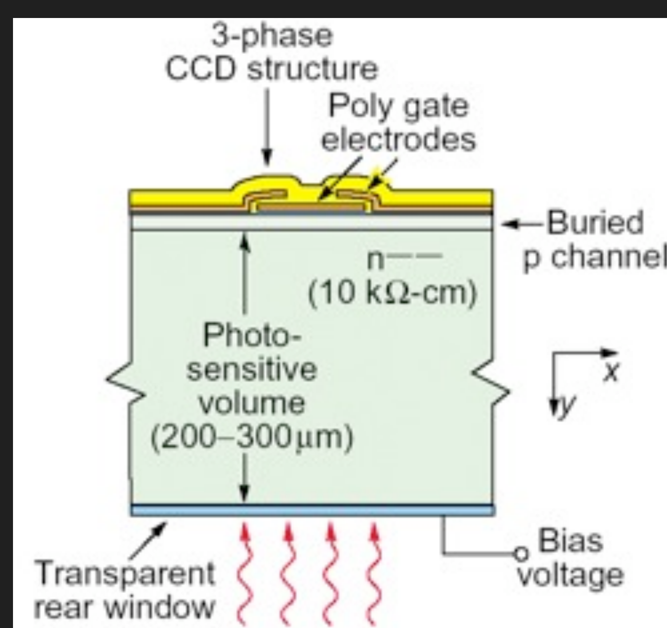
- **–250 microns thick**
- **–high resistivity silicon**
- **–QE> 50% at 1000 nm**



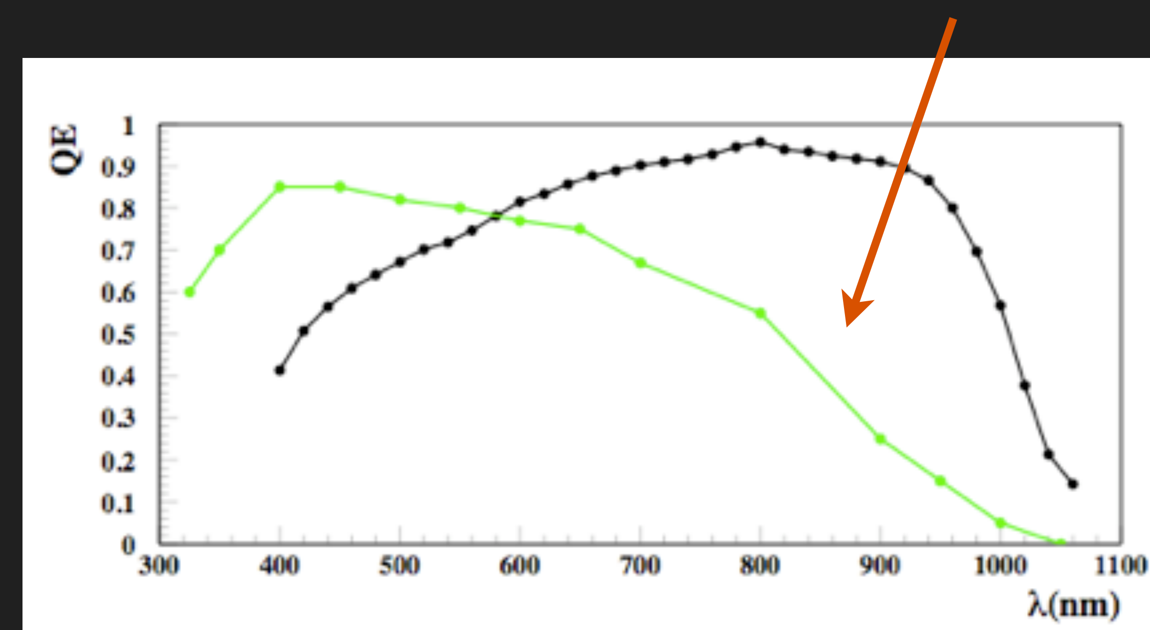
typical CCDs



new thick CCDs



higher efficiency for hi-z objects.



research lines

- ➡ sub-electron noise CCDs
- ➡ fast readout for multichannel CCDs
- ➡ neutron imaging
- ➡ low background applications

infrastructure + people

- ➡ equipment at FNAL
- ➡ international collaborators
- ➡ additional support

research lines

- ➡ sub-electron noise CCDs
- ➡ fast readout for multichannel CCDs
- ➡ neutron imaging
- ➡ low background applications

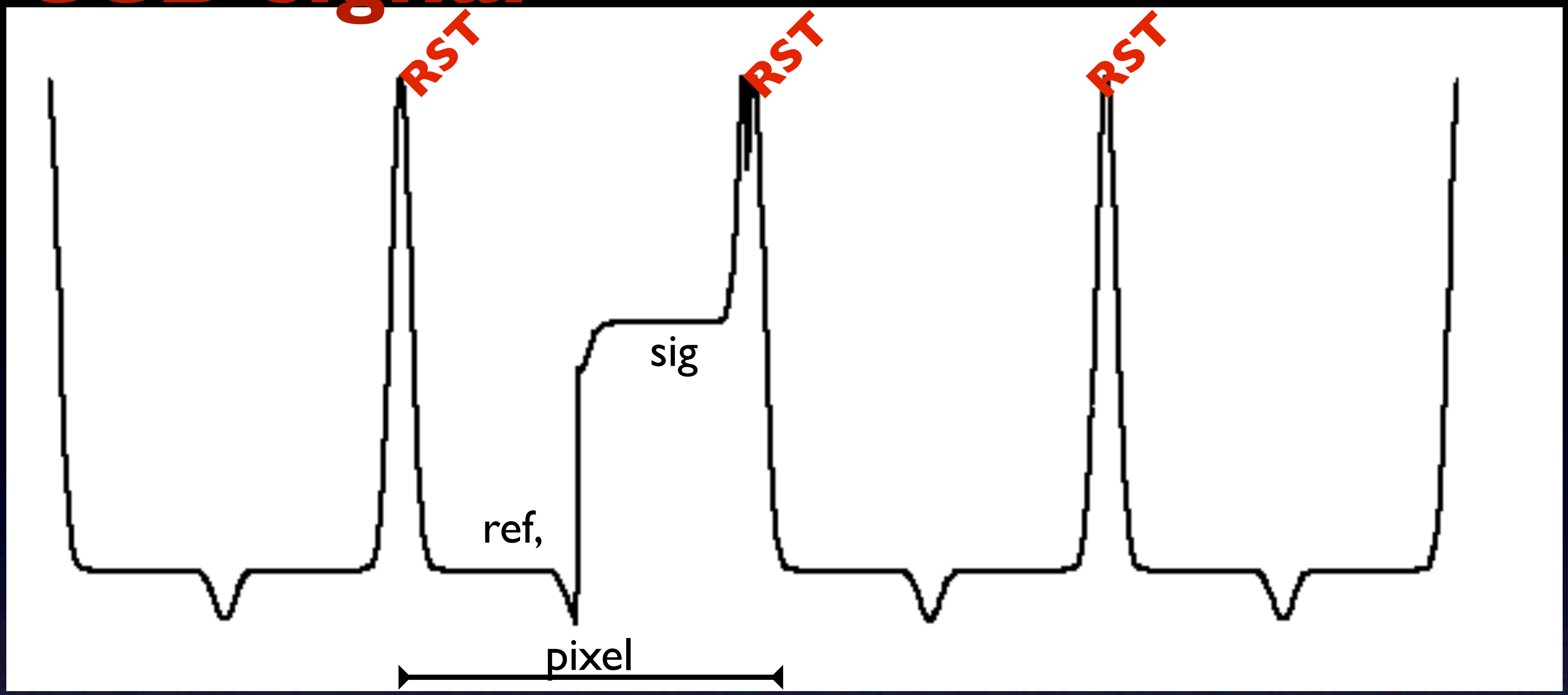
Sub-electron readout noise

- Scientific CCDs commonly achieve noise of 2e- RMS (=7.2eV),
- Currently look at two different approaches to push this limit:
  - digital filtering of the low frequency noise
  - skipper CCD

- Possible Applications:
  - Low threshold experiment for Dark Matter
  - Low threshold experiment for Neutrinos
  - High resolution spectroscopy

Sub-electron readout noise : digital filter

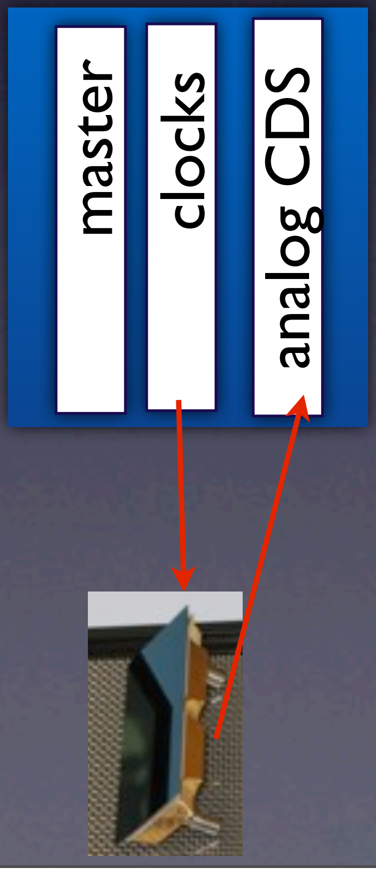
CCD signal



Correlated double sampling is done to eliminate RST noise. Integration of reference and signal eliminated the high frequency noise. This works well, but makes the readout sensitive to low frequency noise (1/f).

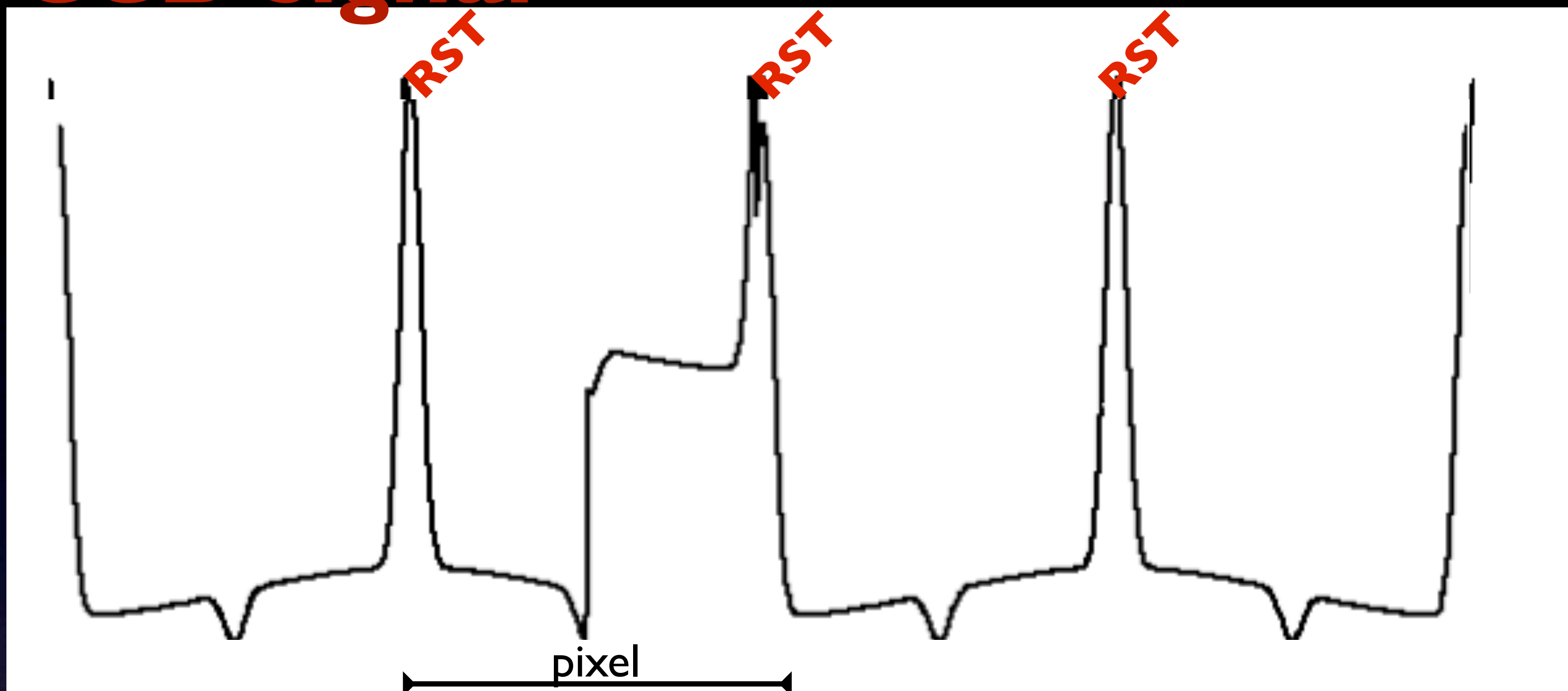
This is the ultimate limitation on CCD noise, otherwise making it slower would always reduce the noise.

CCD controller



Sub-electron readout noise : digital filter

CCD signal



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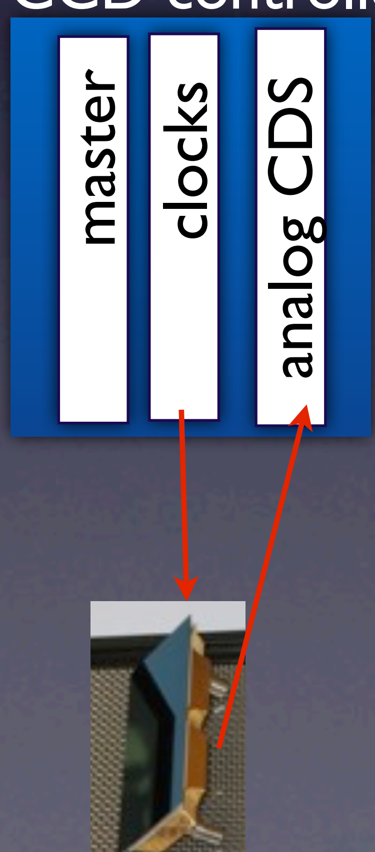
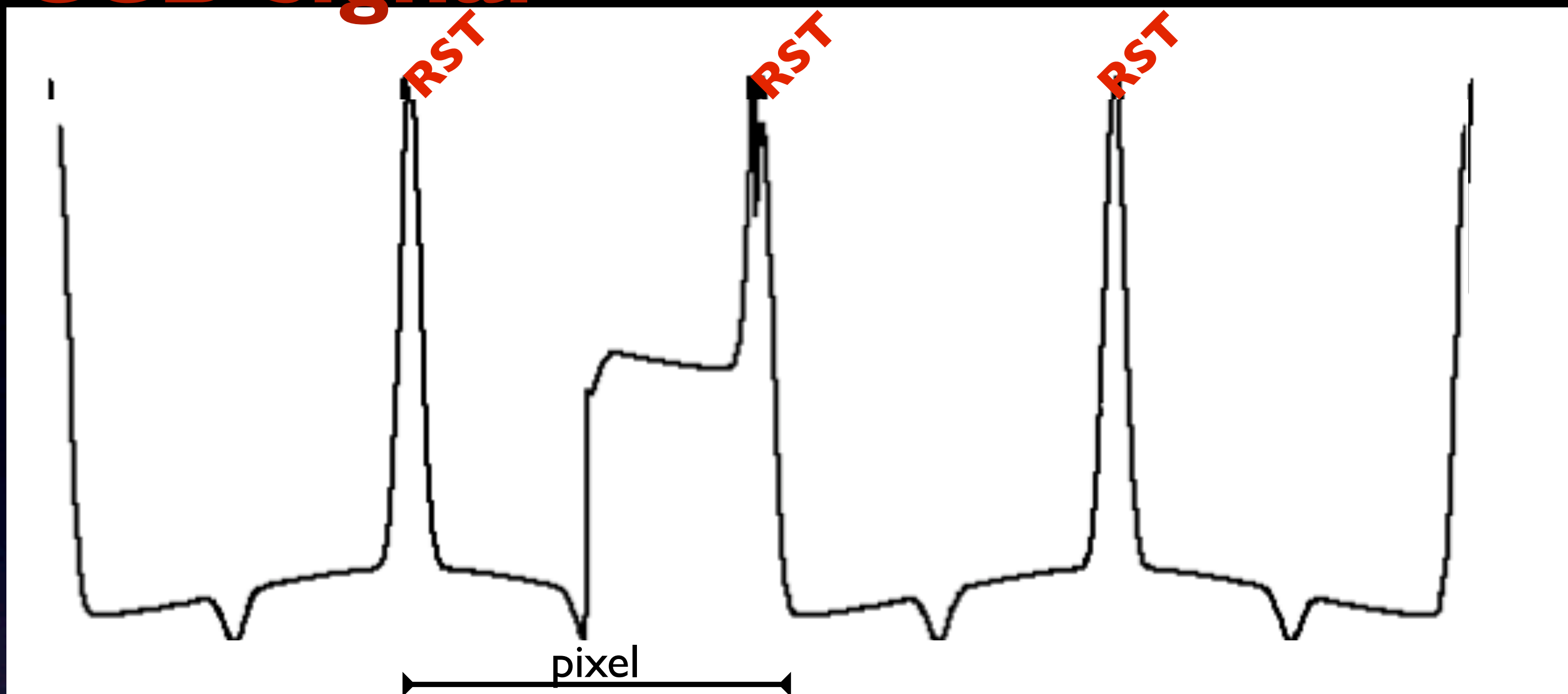


Sub-electron readout noise : digital filter

CCD signal



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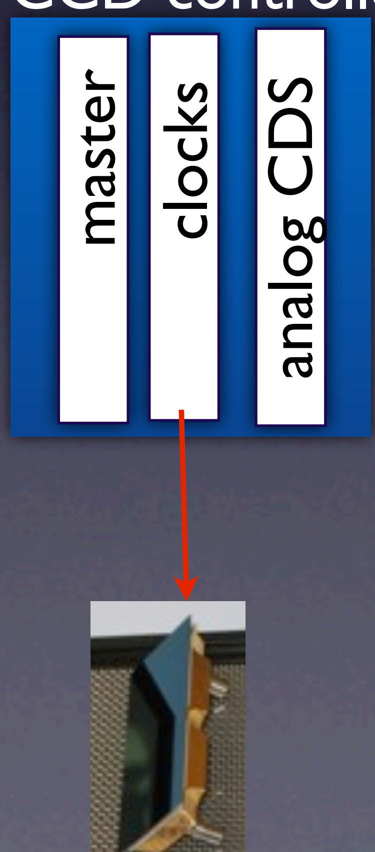
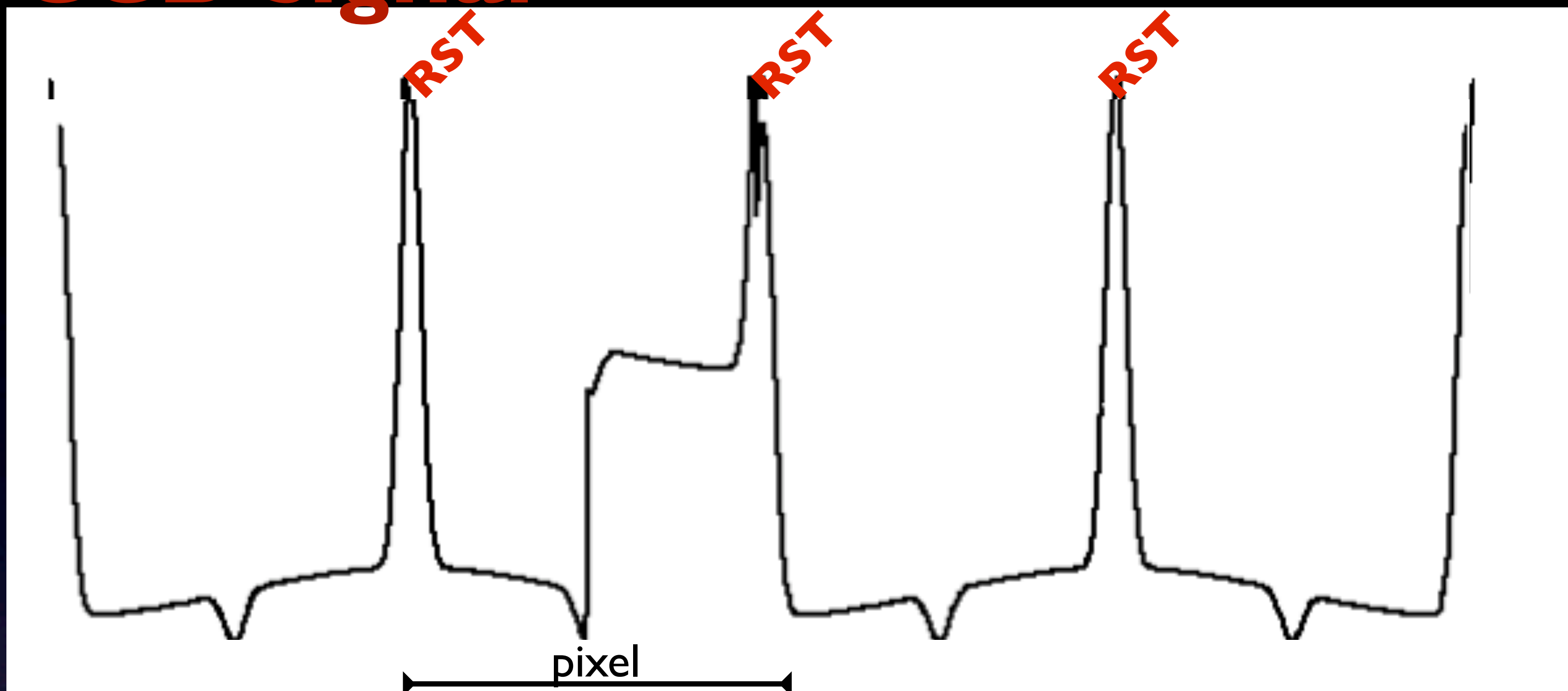


Sub-electron readout noise : digital filter

CCD signal



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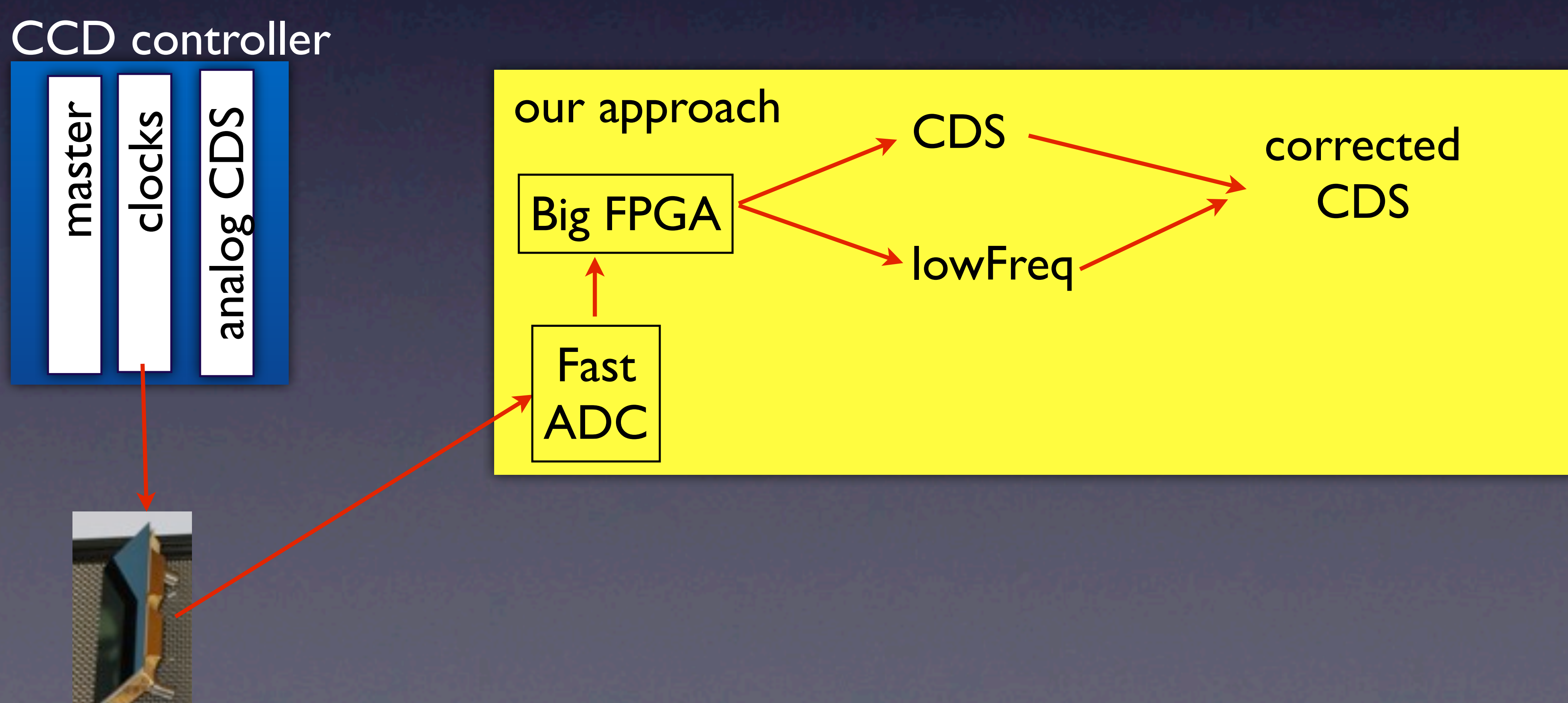
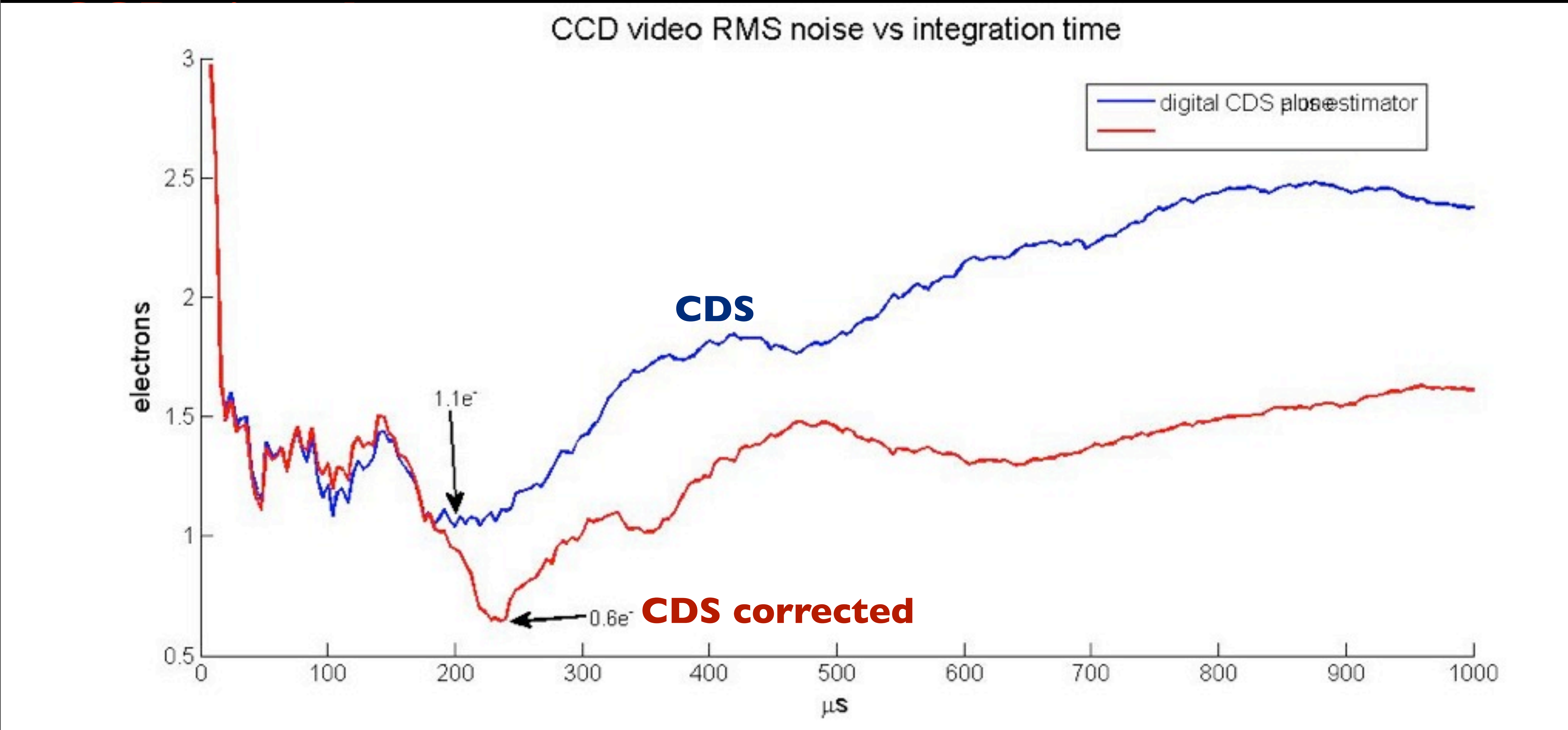
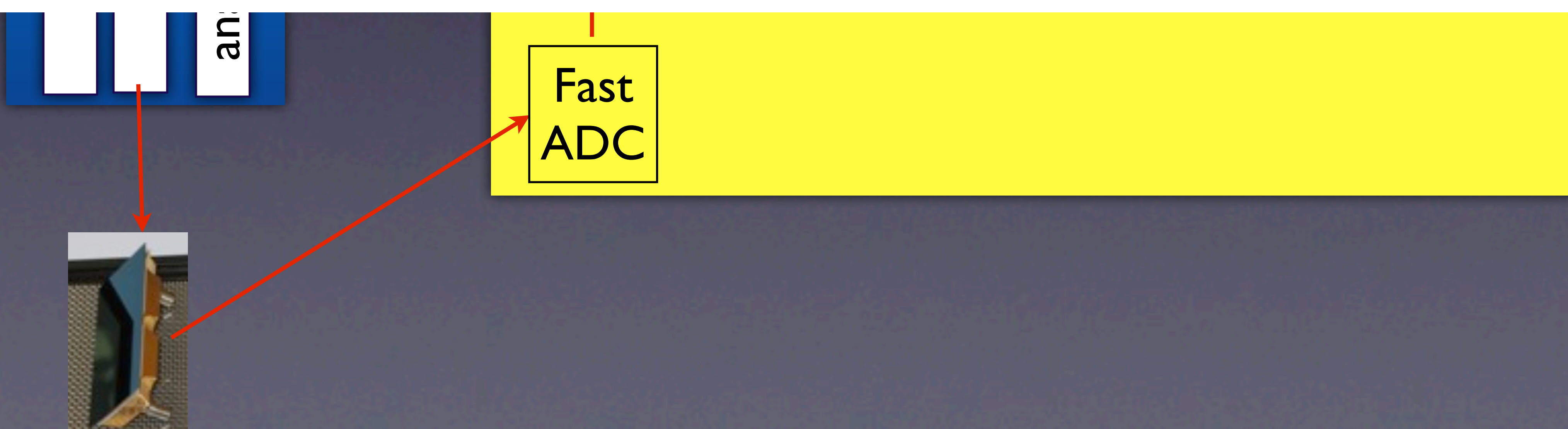
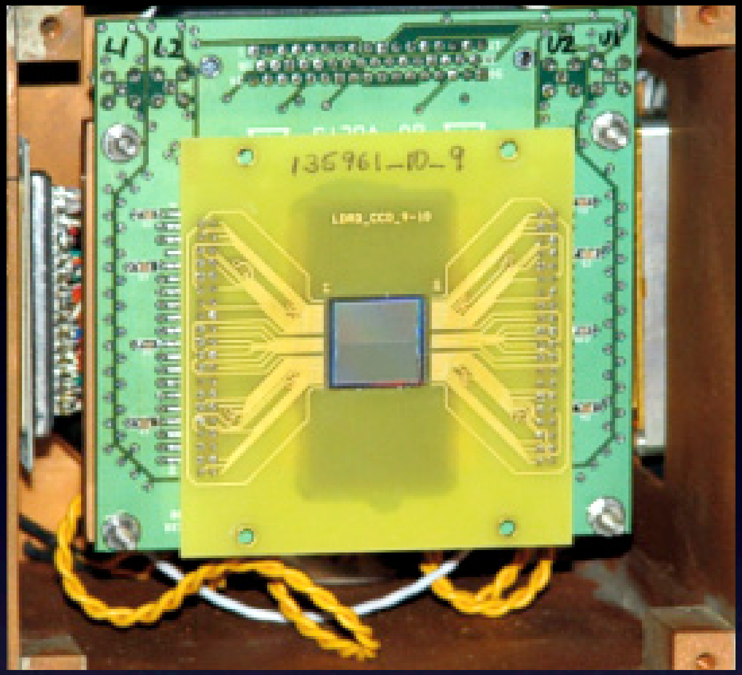


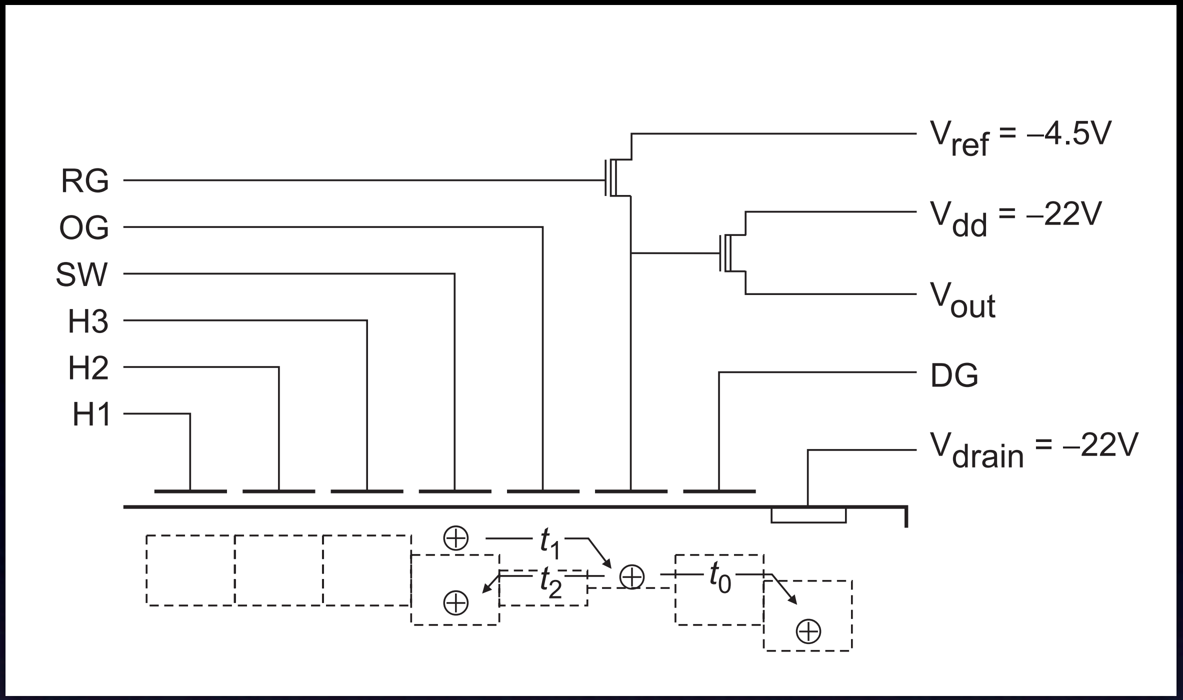
Sub-electron readout noise : digital filter

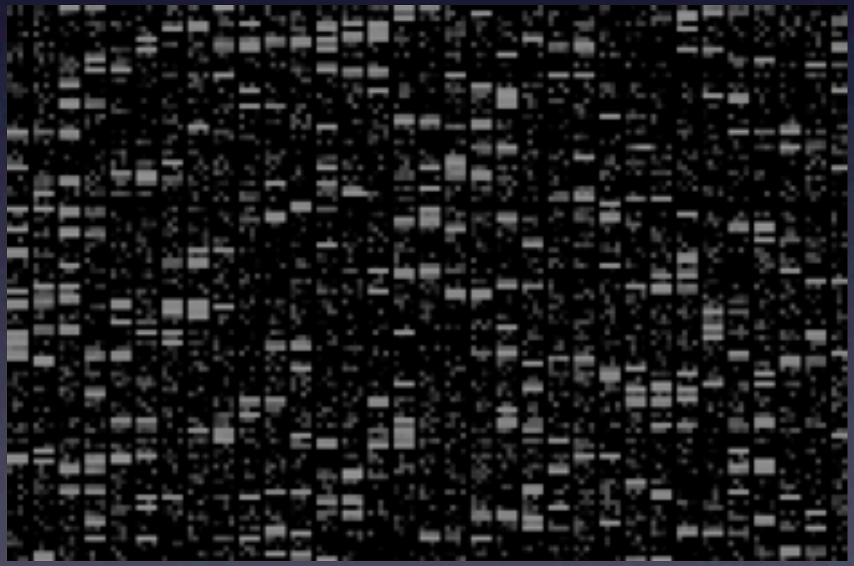




Sub-electron readout noise : skipper







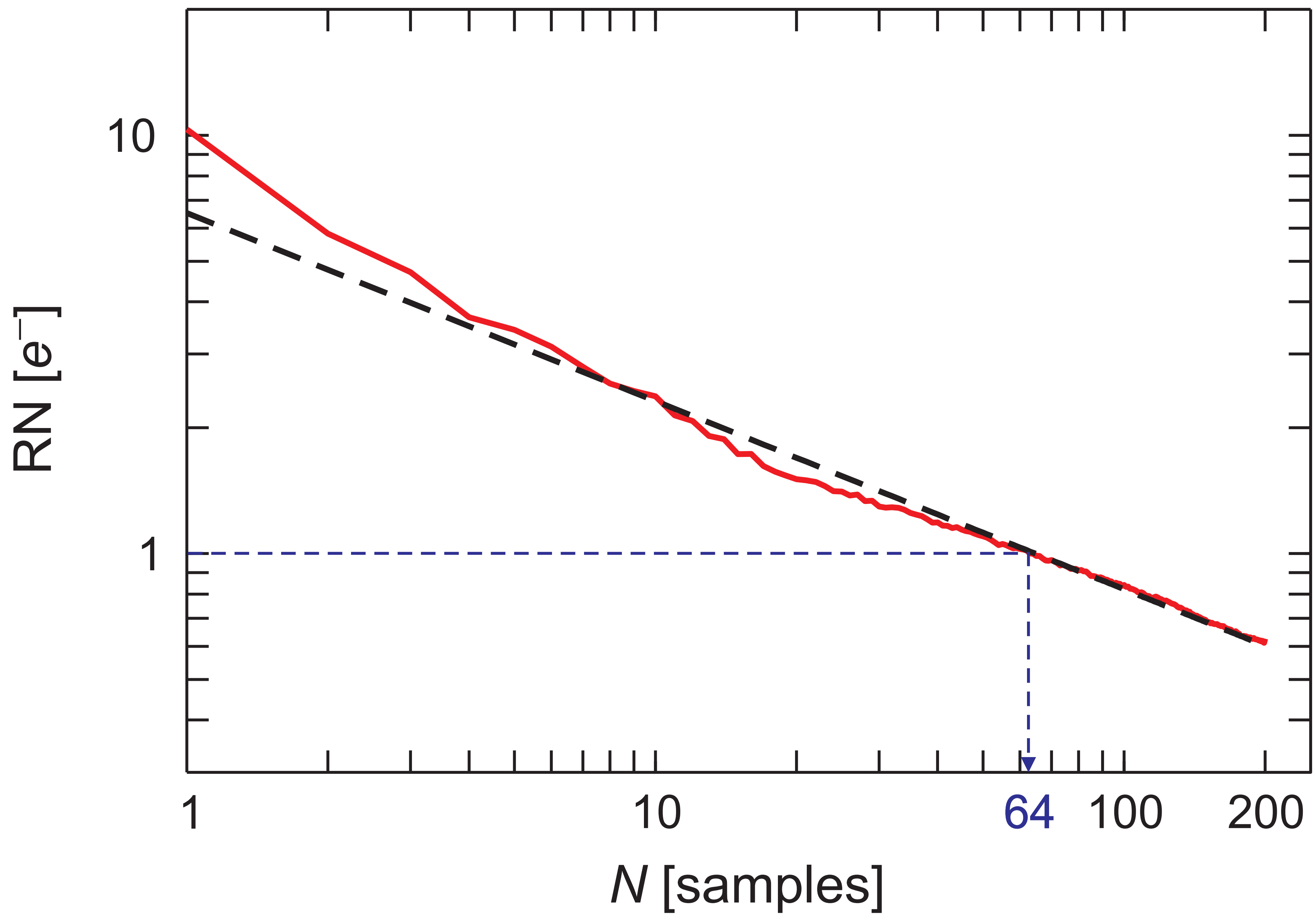
new readout system that allows us to move the charge in and out of the sense node (floating gate). Getting multiple (~800) independent readouts of the same pixel.

It was tricky to tune (good to have a smart student with lots of time to look at this).

Sub-electron readout noise : skipper

It works!

Last week we got to 0.2e- RMS with 800 samples



Sub-electron readout noise : Future

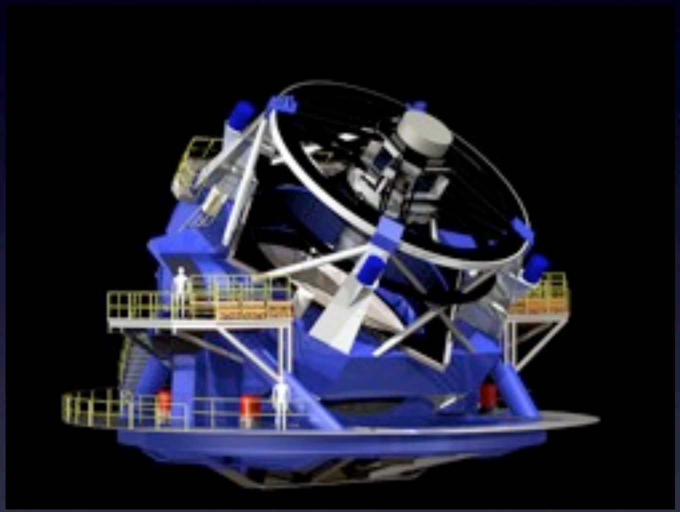
- Two possibilities for getting less than 1e- of noise in the CCD, publish and implement them in experiments.
  - digital filtering : we need to make this more practical for reading out large CCDs. We have to integrate this in the CCD controller. Then we could use this for a spectrograph or a low background experiment.
  - skipper : the detector is working, but we need to build preamp boards, flex circuits and packaging to get it ready for a low background experiment.

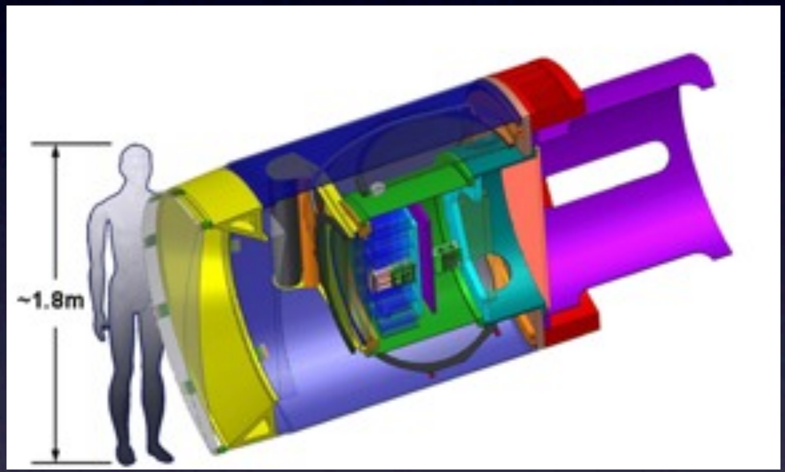
research lines

- ➡ sub-electron noise CCDs
- ➡ fast readout for multichannel CCDs
- ➡ neutron imaging
- ➡ low background applications

fast readout for multichannel CCDs

- FNAL has participated in a couple of very important astronomical survey: SDSS and now DES. The next step here is imagers with more detectors and faster readout. The best example of this is LSST.

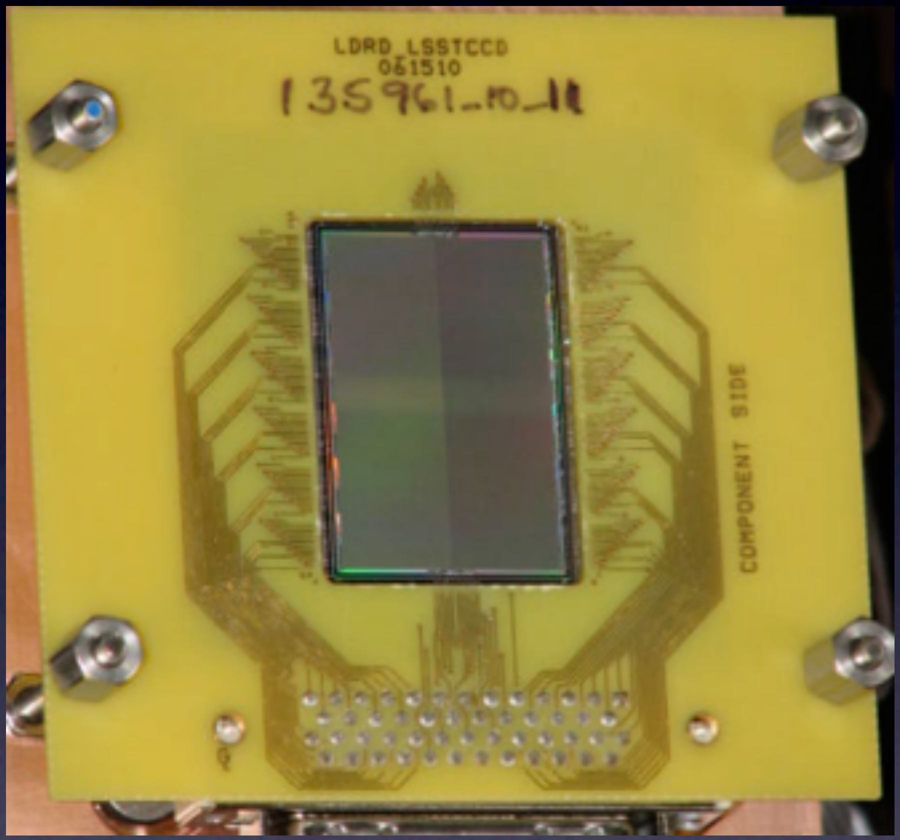




- For the detectors the main challenge is fast readout (500 kpix/sec) and still keep a low readout noise.

fast readout for multichannel CCDs : results

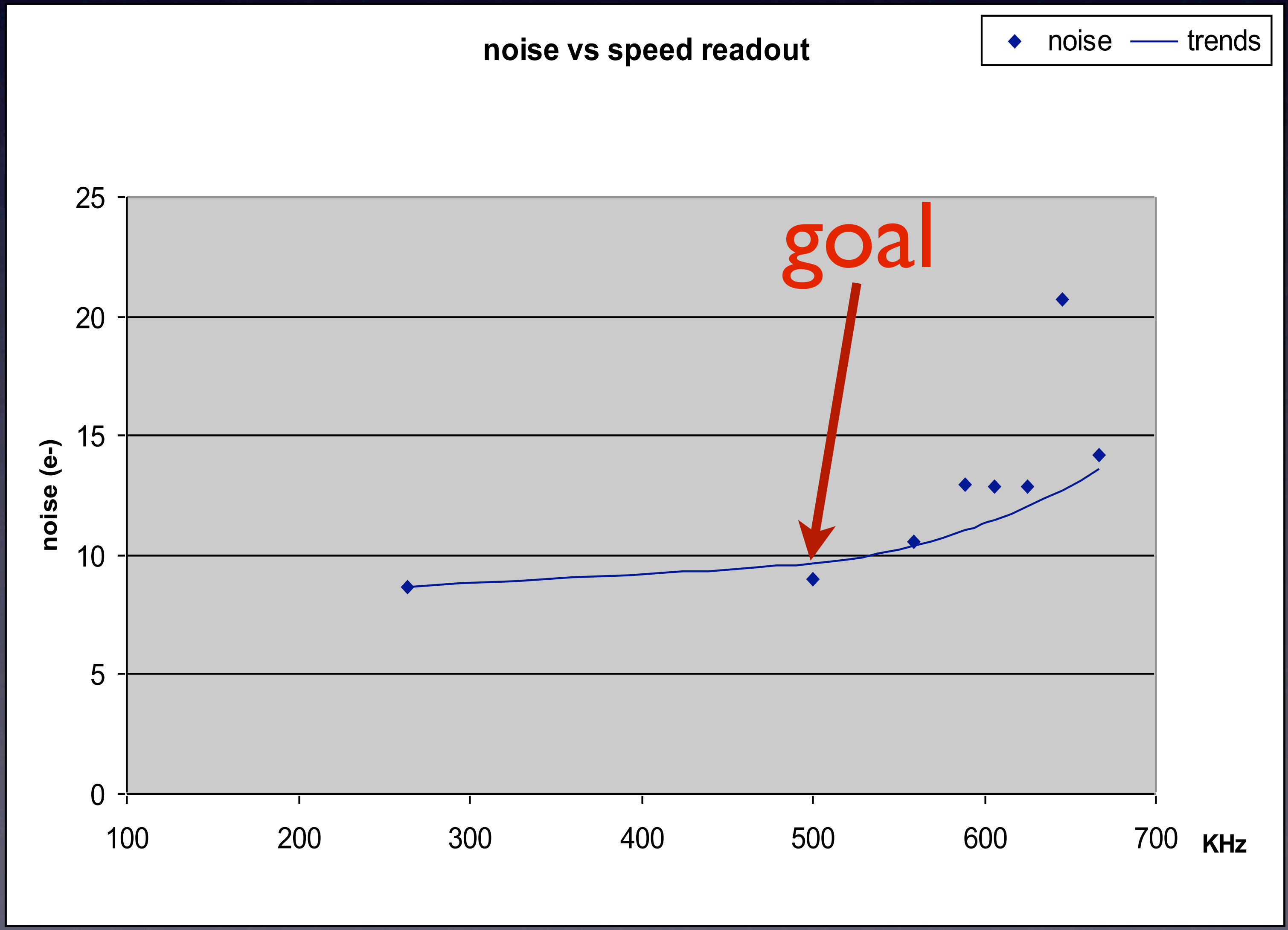
another new detector from LBNL. 12 amplifiers per side each side 0.5 Mpix per amp



We were able to achieve the goal. Performance is better than what other LSST detector candidates have achieved at 500 kpix/sec.

•Modified DECam prototype hardware to accommodate this detector.

•Invited an student from Madrid to work on optimizing the readout for this CCD. We set as a goal the LSST requirements for the detector.



fast readout for multichannel CCDs : future

- ...thought that showing that this detector met the most challenging LSST spec was enough to convince the camera team to use the LBNL CCDs and the FNAL package for their instrument. I did not work that way.
- This is an interesting detector for other astronomical projects. Any camera with fast readout time would benefit from this CCD.
- The detector is also interesting as a particle tracker (test beam pushed by David Christian). Large format CCD with fast readout with electronic gate.
- what we want to do next:
    - get a detector with good optical quality and complete a detail characterization of the device.
    - study the performance of LSST CCD with this readout system

research lines

- ➡ sub-electron noise CCDs
- ➡ fast readout for multichannel CCDs
- ➡ **neutron imaging**
- ➡ low background applications

neutron imaging : why bother with this?

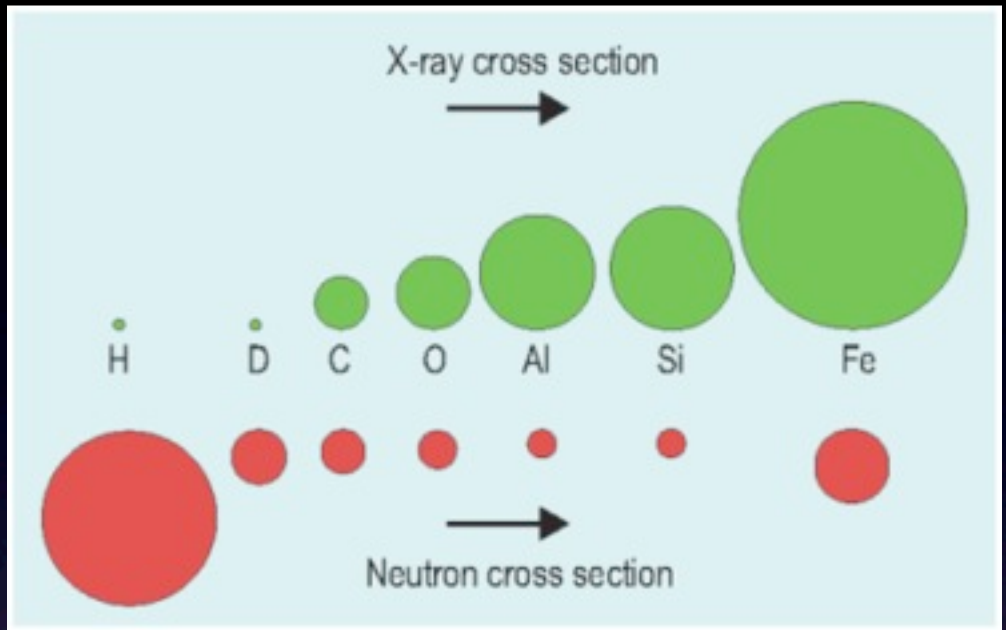
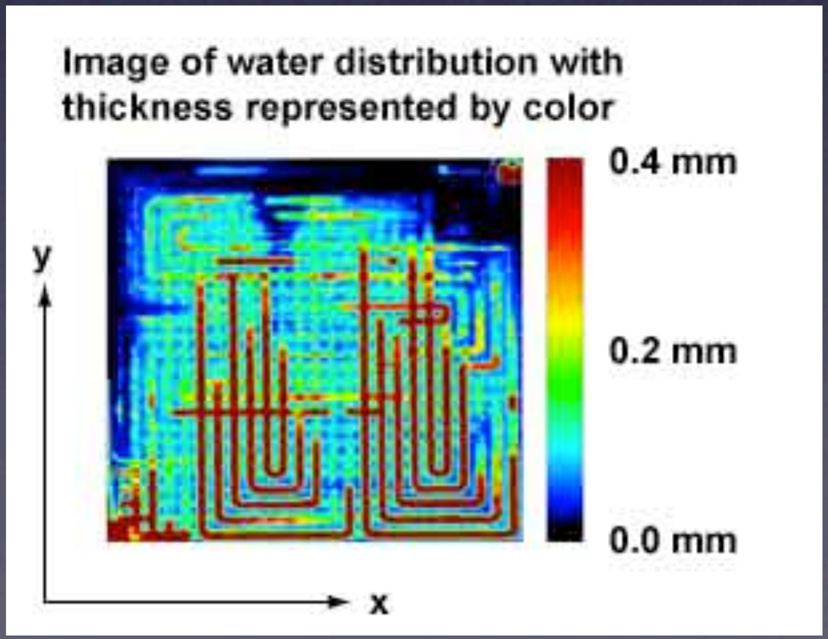
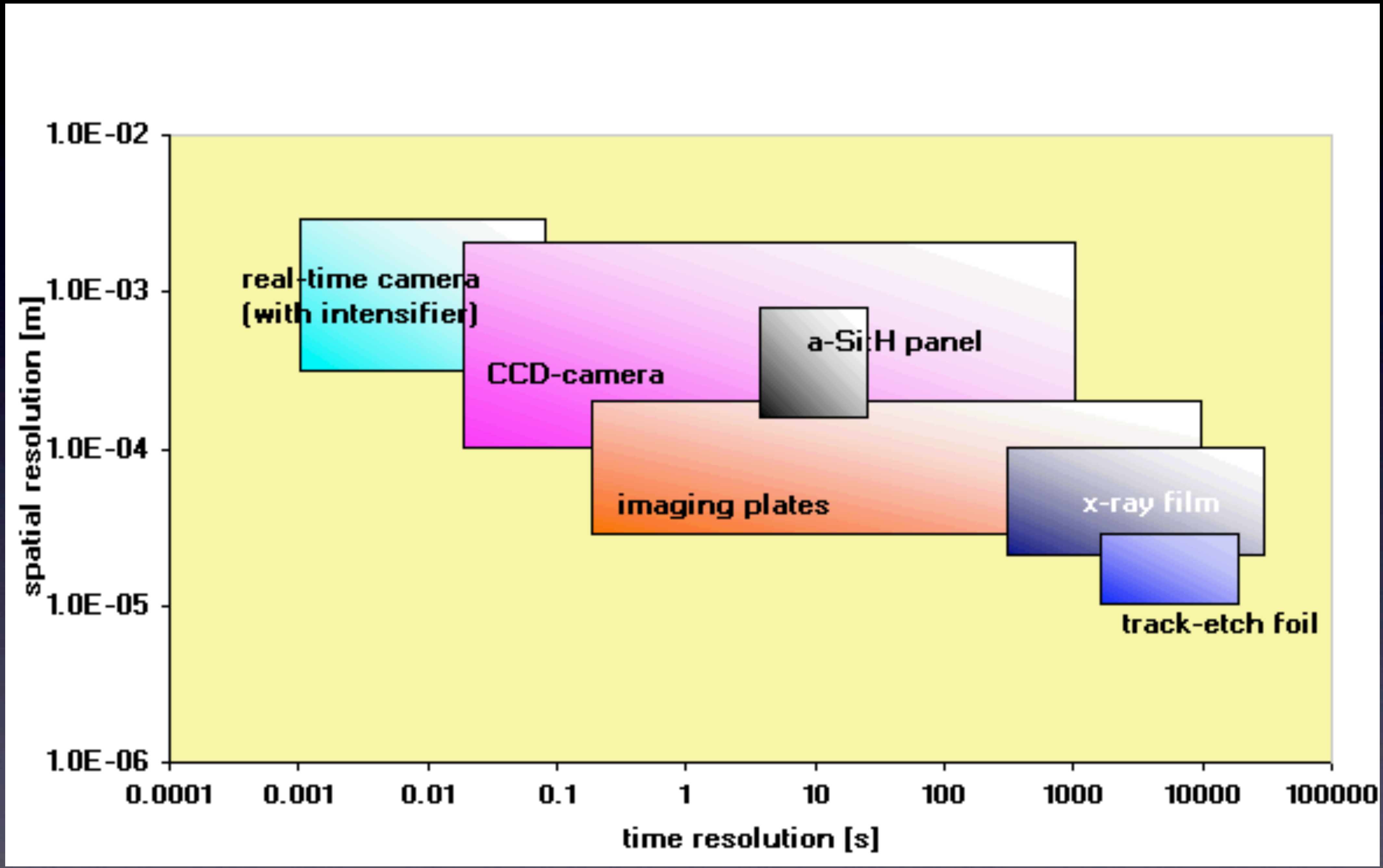


Fig. 2. Neutron and x-ray scattering cross-sections compared. Note that neutrons penetrate through Al much better than x rays do, yet are strongly scattered by hydrogen.

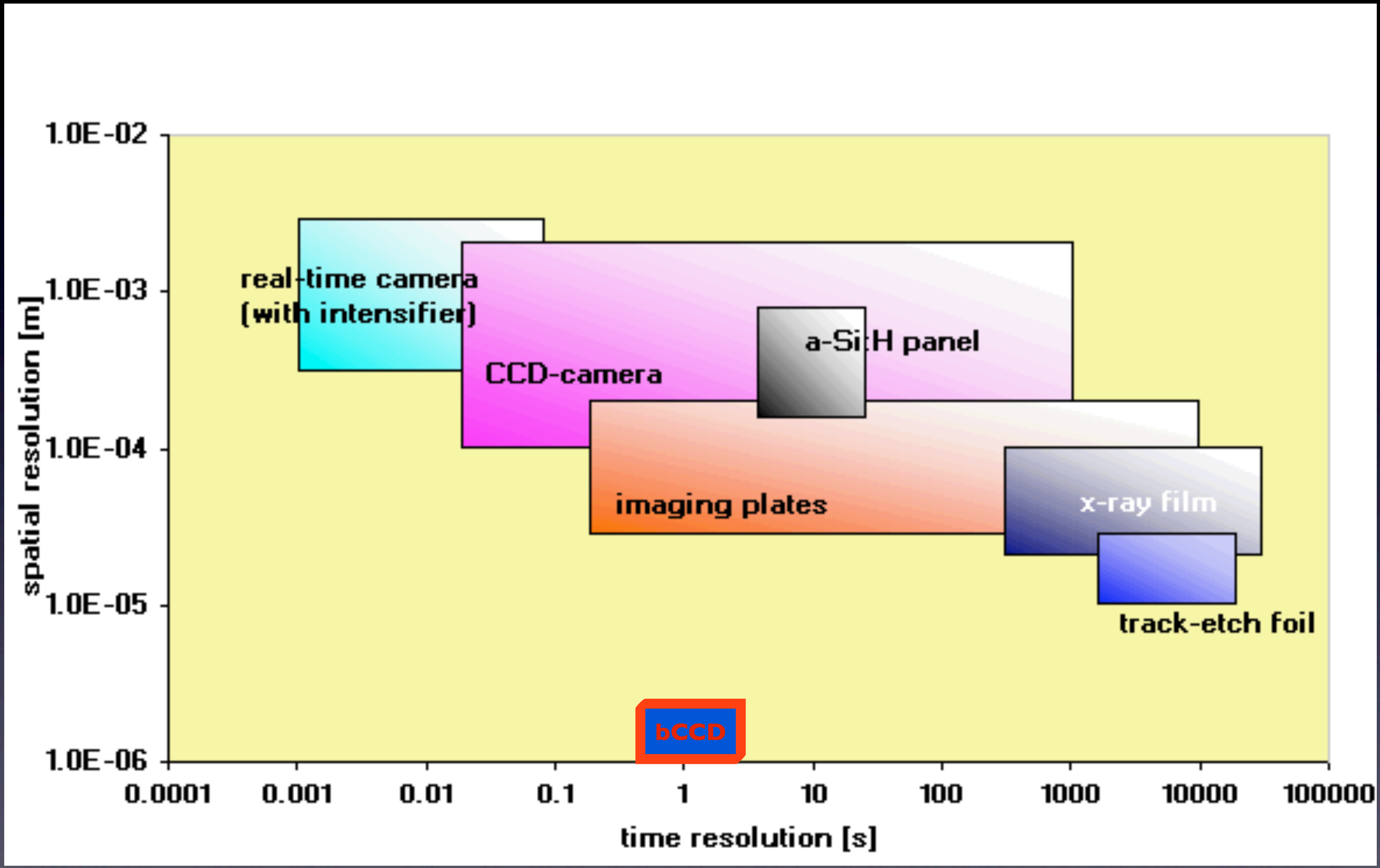


key tool for Basic Energy Science!

neutron imaging : state of the art



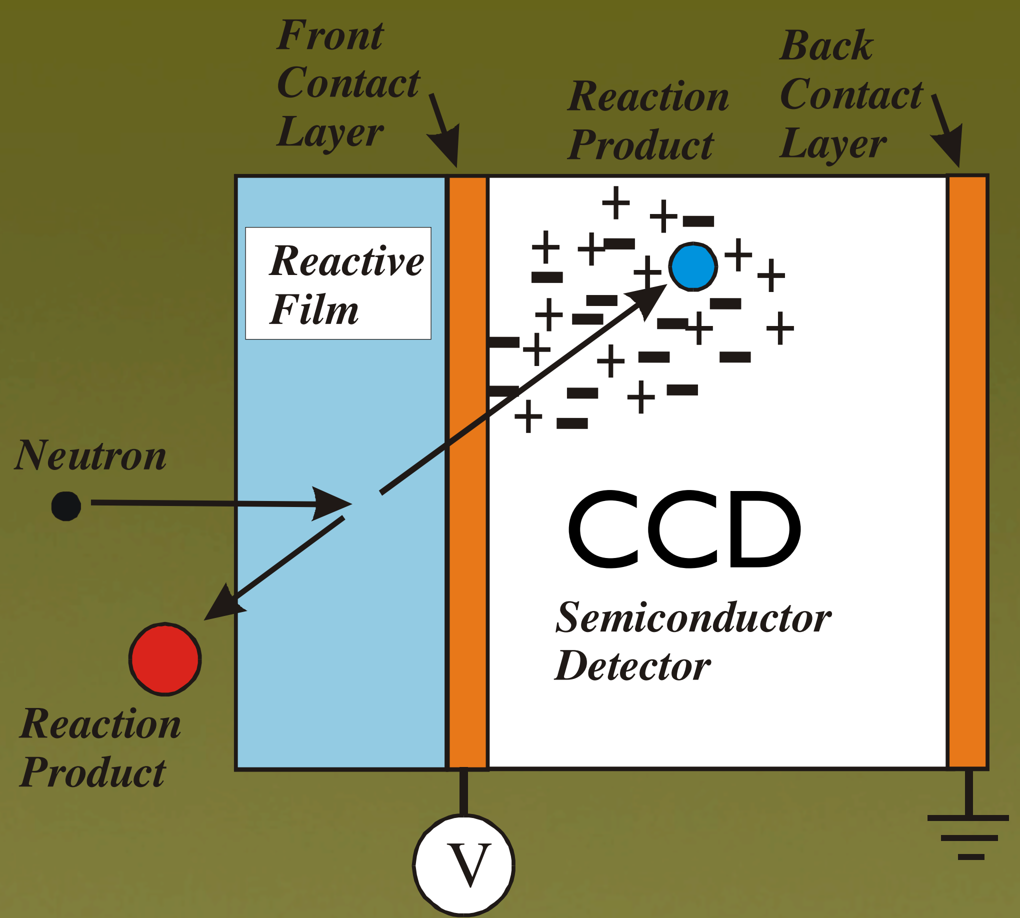
neutron imaging : state of the art



the CCDs would allow us to achieve micron level resolution and at the same time 1 frame per second....

neutron imaging : results and near future

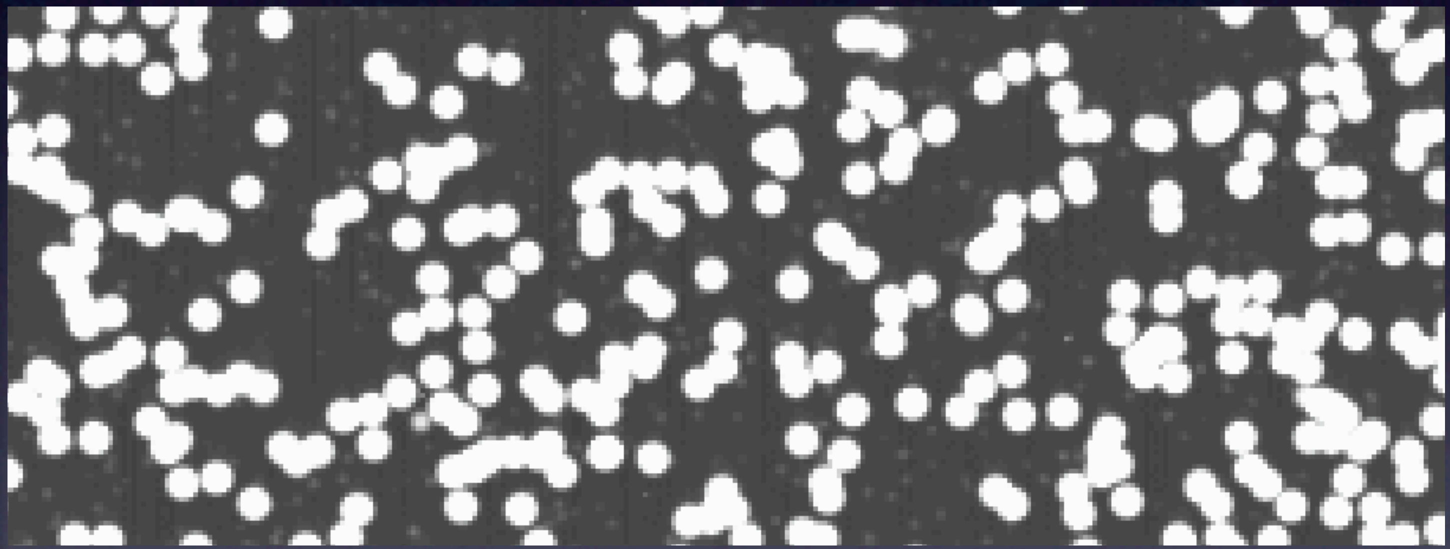
our scheme...



$$^{10}\mathrm{B} + \mathrm{n} \rightarrow \begin{cases} 6\% : & ^{7}\mathrm{Li}(1.015\,\mathrm{MeV}) + \alpha\ (1.777\,\mathrm{MeV}), \\ & Q = 2.792\ \mathrm{MeV(to\ ground\ state)} \\ 94\% : & ^{7}\mathrm{Li}^{*}(840\,\mathrm{keV}) + \alpha\ (1.470\,\mathrm{MeV}), \\ & Q = 2.310\ \mathrm{MeV\,(1st\ excited\ state)} \end{cases}$$

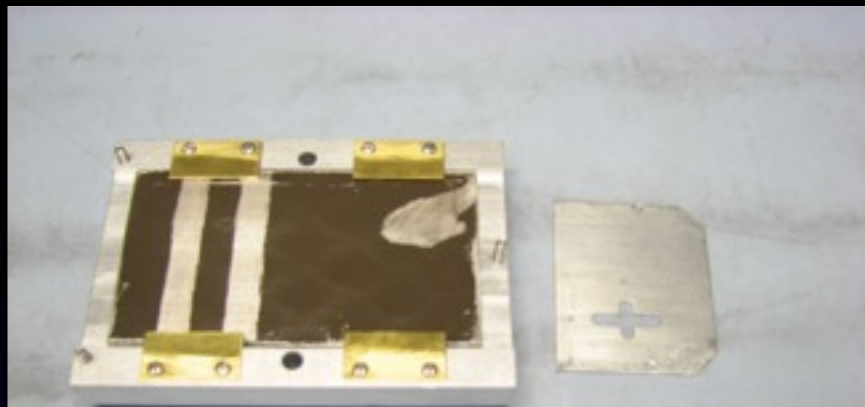
- Borated film close to the CCD surface will produce an alpha particle when it sees a thermal neutron.

- Due to the high-resolution pixels of the CCD, we can locate the alphas with a precision of the order of 1 micron.

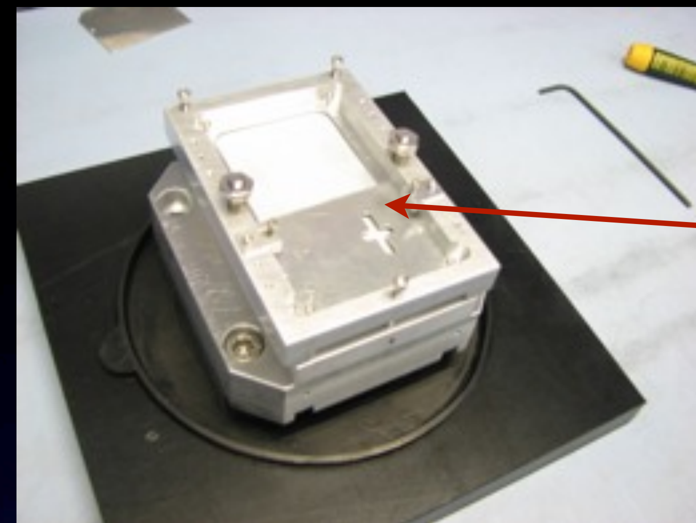


due to plasma effect alphas are very easy to distinguish in a CCD image. Here compared with X-rays.

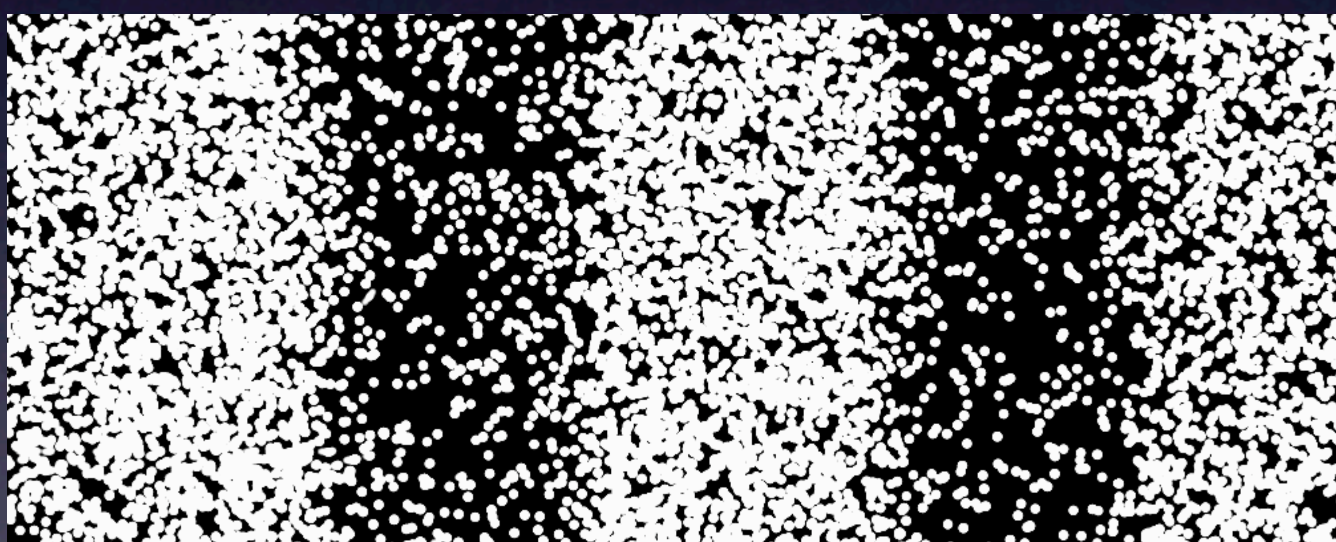
neutron imaging : proof of principle



borated film in from of CCD and Cf-252 source with poly to get thermal neutrons

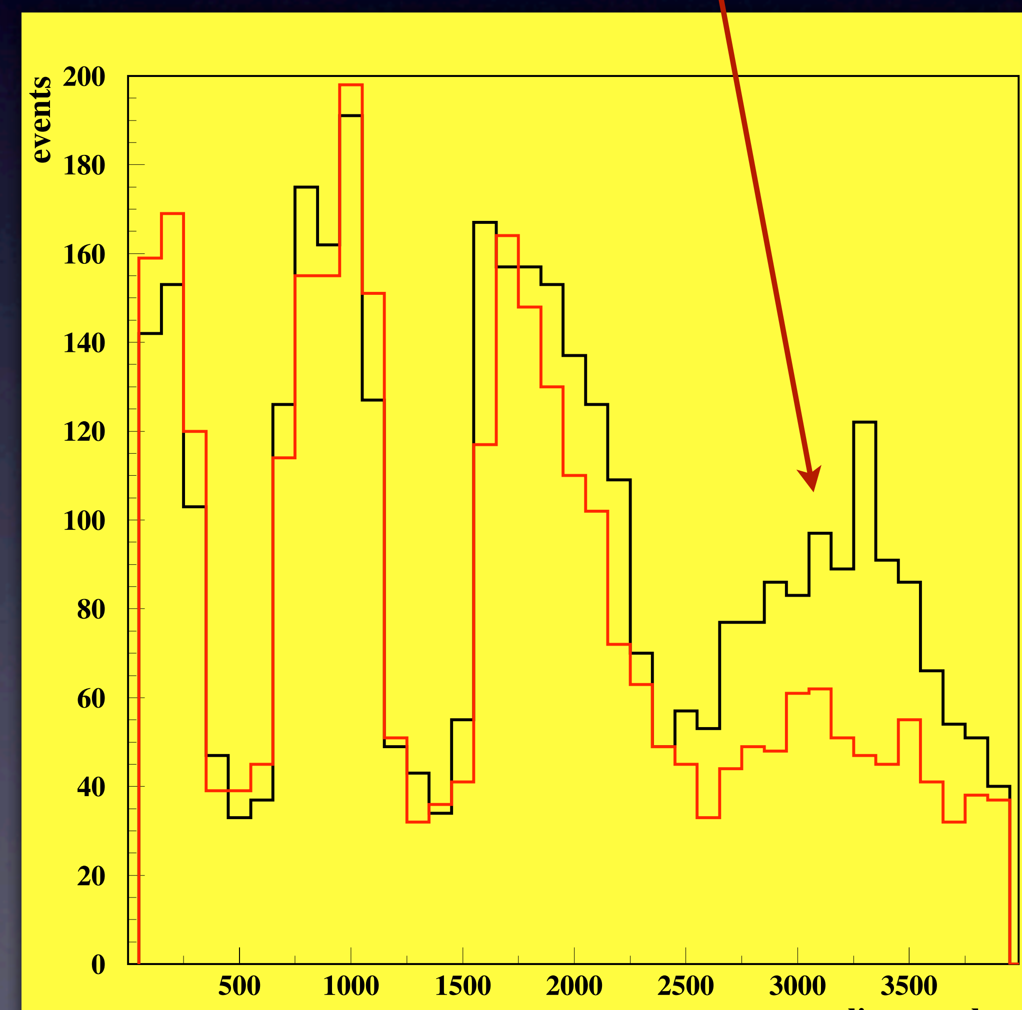


Cd neutron shadow



Stripes on borated plate

imaging worked with about 1mm resolution due to large distance between Boron and Silicon



neutron imaging : longer term plans

next: yesterday got from ANL a new ceramic plate that will put the borated surface ~5um from the CCD. We will try again with the Cf-252 source and should get much better resolution.

need beam: the Cf-252 source is not the best beam. We need a real beam of collimated low energy neutrons. Our collaborators in Argentina have an experimental reactor with an imaging beam available for us starting in September 2011. Vic Scarpine is trying to set up a thermal neutron beam in the neutron therapy facility.

borated CCD: we plan to investigate the possibility of depositing the boron directly on the CCD (and still have a working CCD at the end).

research lines

- ➡ sub-electron noise CCDs
- ➡ fast readout for multichannel CCDs
- ➡ neutron imaging
- ➡ low background applications

low background applications

using DECam CCDs and electronics

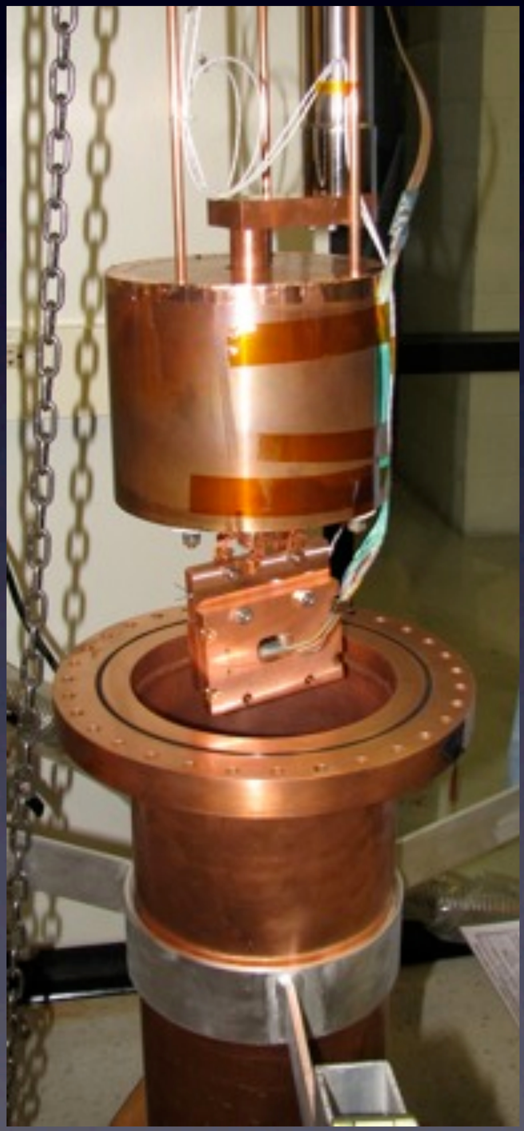
- 7.2 eV noise ➪ low threshod (~0.036 keVee)
- 250 µm thick ➪ reasonable mass (a few grams detector)

low background applications

T987 :

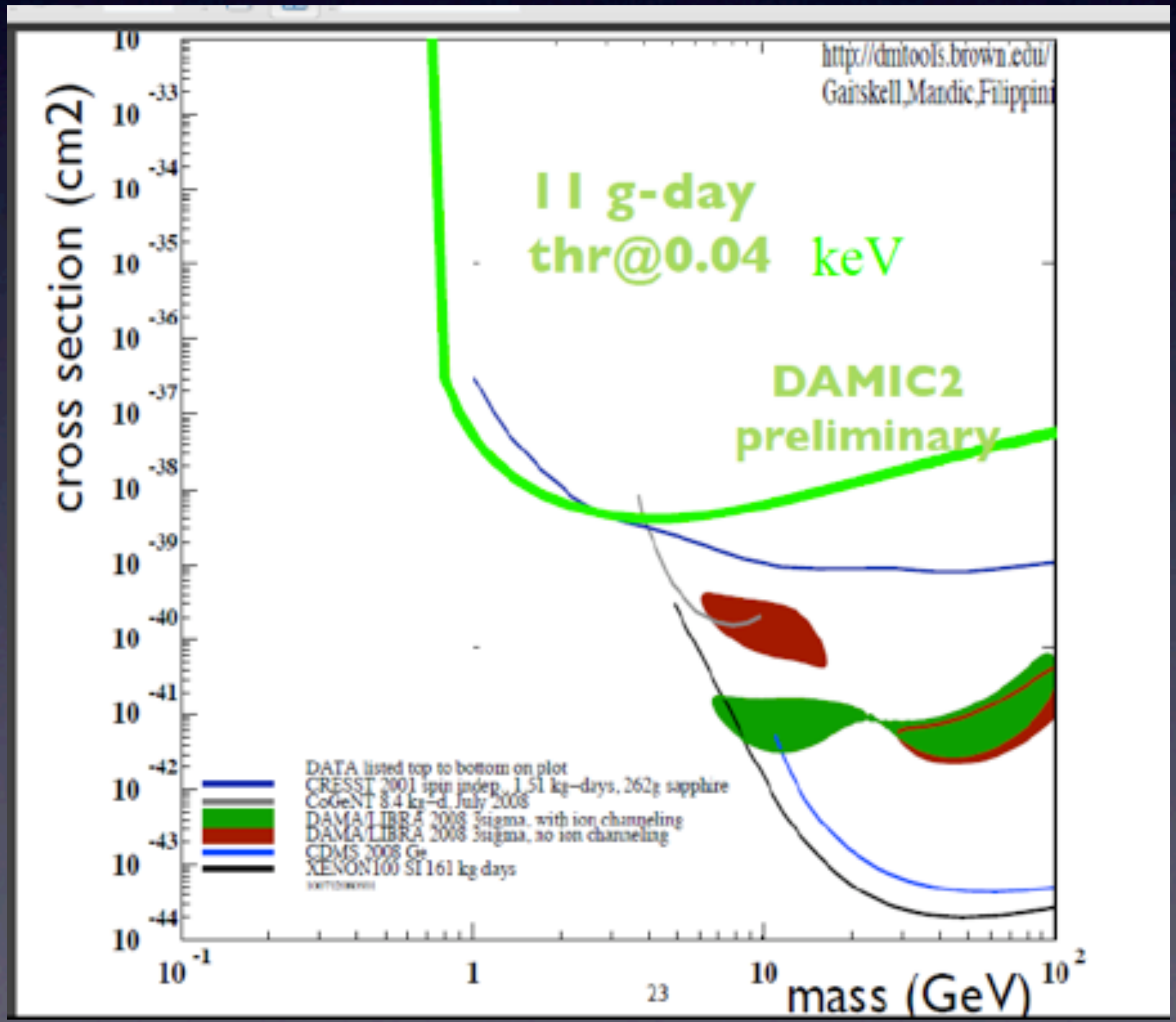
first version at NuMI near detector in 2009
second version at NuMI in near detector 2010

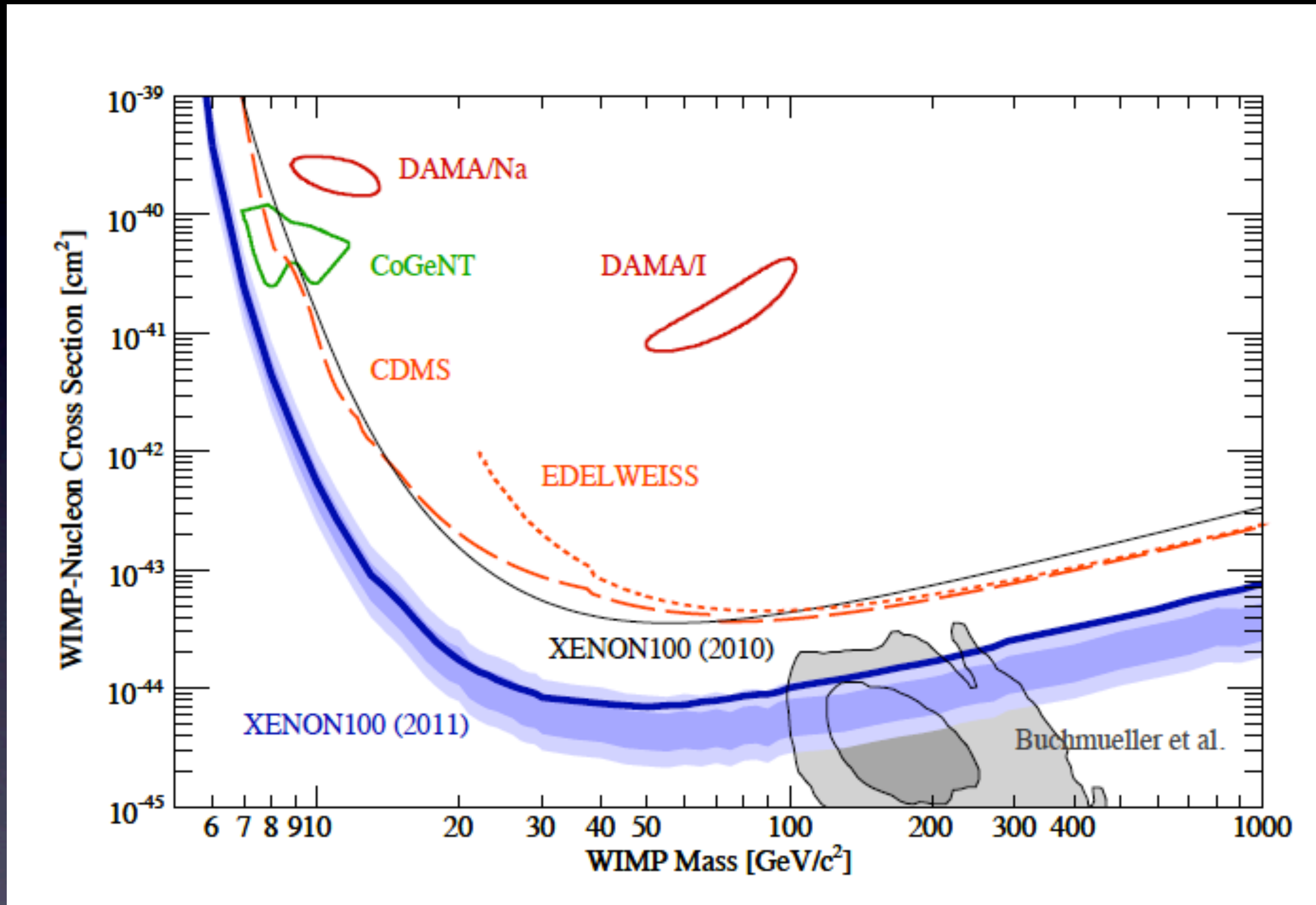
copper dewar with lead shield



low background CCD package.

One application: Direct Dark Matter Detection with CCDs (DAMIC) with 40 eV threshold.





low mass DM is very interesting these days

low background applications : future

DAMIC:

benefited from the CCD R&D, now we are at a point where we would like to do a real experiment using demonstrated technology. Build a detector with a few CCDs and take it to a deep underground site (with low cosmogenic neutron background).

Plan:

> currently designing the new detector with ~10 grams
> plan to build it and test at FNAL before the end of the year
> move to deep site early next year and run for 1 year (3.5 kg-day @ 40 eV thr)

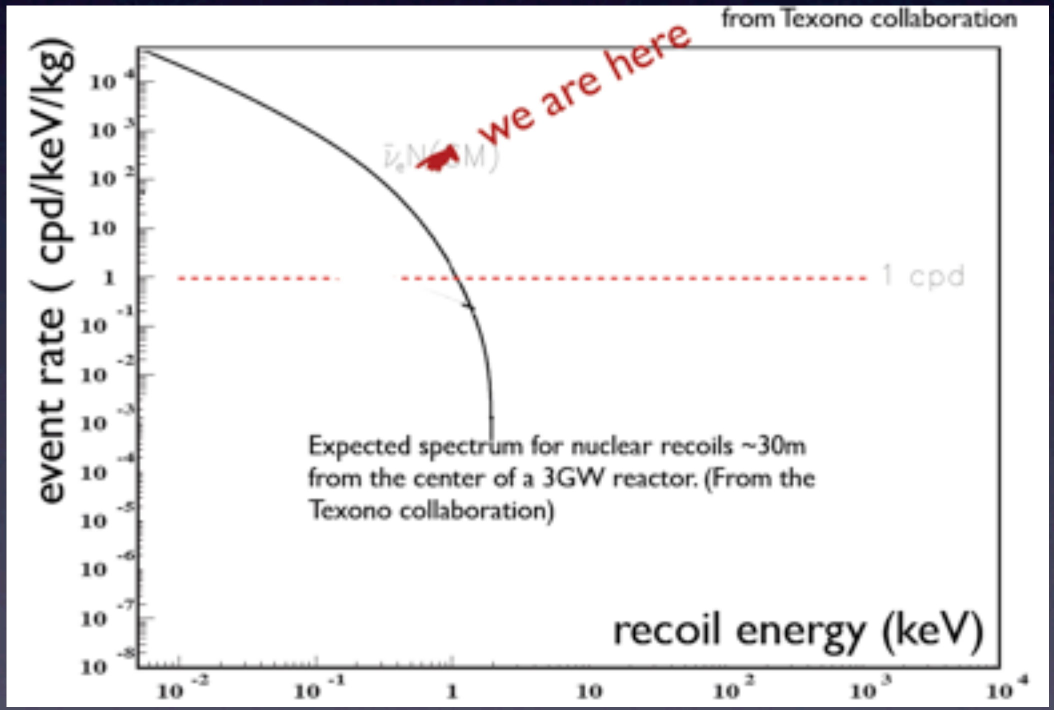
> we have to perform the calibration (efficiency and energy) for low energy nuclear recoils

low background applications : future

Neutrino Detection with CCD:

A detector for nuclear recoils with a low threshold could be used for detection of neutrino coherent scattering. This process is predicted by the standard model with a very large cross section, but not detected because of the lack of appropriate technology.

We want to investigate this possibility by installing skipper CCDs next to a reactor.



NEUTRINOS ANGRA Project

now in negotiations on how to use this reactor in Brazil.

still a detector R&D project, success could open the door for a wide new set of low energy neutrino experiments. Maybe even some useful application (reactor monitoring).

infrastructure + people

- ➡ equipment and expertise at FNAL
- ➡ collaborators outside FNAL
- ➡ sources of funding

equipment at FNAL

- CCD lab to test up to 4 CCDs independently at the same time with LN2 cooling (SiDet)
- optical equipment for full characterization of CCDs from 400nm to 1080nm (SiDet)
- 7 CCD controllers (MONSOON + LEACH)
- 2 cold boxes for running detectors at -40C
- “T” with cryocooler currently used for neutron imager
- Multi-CCD test vessel (can operate a focal plane of up to 72CCDs)
- 100+ engineering package CCDs from DECam available for test.

- most of it belongs to DECam but now that construction is finished is available for other things (at least until we start with the DECam upgrade).

expertise at FNAL

- electronic engineering group in PPD (T.Shaw) that built the CCD electronics for DECam and several components of the R&D effort.
- electronic engineering group in CD (G. Cancelo) contributing to the R&D efforts.
- mechanical engineers in PPD (H. Cease and G. Derylo) who have build DECam and the CCD R&D systems. This includes the design of the cooling system, vacuum vessels and packaging for the detectors.
- Wire bonding and packaging experts from PPD with extensive experience developed during DECam construction.
- technicians with extensive experience operating CCD test stations
- Donna Kubik from PPD (the only person that I know that has tested +300 CCDs)
- several software experts for CCD controllers

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we have the team and the equipment at FNAL to do anything with CCDs, and to do it as least as well as anyone else.

collaborators outside FNAL

- LBNL
  - established excellent relation during DECam
  - now benefiting from that relation and getting new R&D detectors from them
  - essential partner in this effort
- BNL
  - they are in charge of the LSST CCD effort
  - they are interested in some of our capabilities
  - hope to quickly establish a productive working relation

- Brazil: very interested in the nuCCD project (H.daMotta, CBPF)
- Mexico: interested in building their own low background experiment with 100 CCDs (C.D'Olivo, UNAM).
- Paraguay: DAMIC collaborator from very early (J.Molina + students, UNP)
- Argentina: collaborators in the neutron imager, interested in getting the imager installed in their experimental reactor (J.Blonstein, Instituto Balseiro)

additional funding

- Dark Energy R&D : Grant for which Tom Diehl is the PI. Used for equipment for low noise experiments, high-res spectroscopy and 1/2 Ph.D. student.
- PECASE : Support for equipment for low background experiments and travel (DAMIC + nuCCD)
- CONICET, Argentina : 1/2 Ph.D. student
- Paraguay : Support for annual visit from Jorge Molina

- in planning:
  - Argentina (Raices) : proposal submitted for some money for collaboration on readout electronics (C. Cancelo + collaborators).
  - Brazil : support for operations in the reactor
  - Mexico : equipment for low background experiment

conclusion

- Thanks to a big investment in equipment and training done by the DECam project, now FNAL is in a good situation to do significant R&D with CCDs.
- Good relation with LBNL is key ingredient of this.
- I think we should make use of this opportunity, but we can only do tit if we have a way of supporting the equipment and facilities that we have now (CCD lab). In the future they could become production facilities again when we start a new big project (DESpec, LSST).
- I hope that I have convinced you that we have a very exciting R&D program that could have significant impact in DM, neutrinos, imaging, spectroscopy.
- We would benefit from more scientist working on this