Centre for Electronic Imaging

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Future Astronomical Instrument Development, Dublin, Sep 2019

Research group at the Open University involved in CCD & CMOS R&D for Space Science

- Basic research & innovation into CCD and CMOS sensors
- Involvement in key space science projects using the technology
- Increasing the fundamental understanding of the technologies
- Key research strengths in Device modelling & Radiation damage effects for space use
- CMOS design and development
- CCD & CMOS operation and optimisation

Employing about 30 people

Many industrial collaborators

- Teledyne e2v
  - Sponsorship
  - In-kind CCD and CMOS for testing
- XCAM
  - Electronics, test systems, design, etc.
- PSI, PTB/Bessy
  - Radiation testing

FUNDAMENTAL UNDERSTANDING

Radiation Damage

- Developing a physical understanding of the damage mechanisms in silicon
- Evaluation & qualification (γ, p, e, SEE)
- Radiation environment modelling (GEANT4, SPENVIS)

Device Modelling and Development

- Use of advanced 3D simulation tools and Monte Carlo code to understand device operation
- Several patents on CMOS design
  - hi-rho technology for improved NIR QE

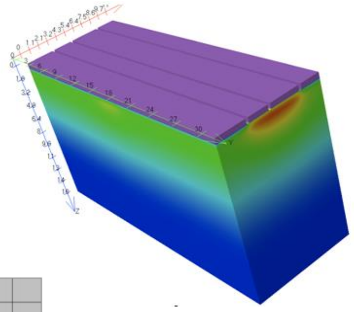
Detector Characterisation

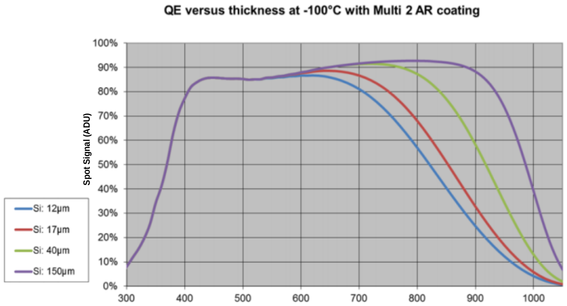
- Development of test methodologies to both provide feedback on new detectors and test techniques

Electro-optic Testing

- Using a combination of X-ray, UV, and optical techniques to enable an understanding of device operation

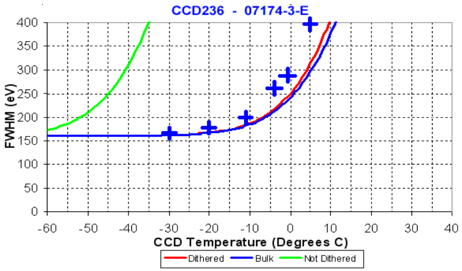
3D simulation



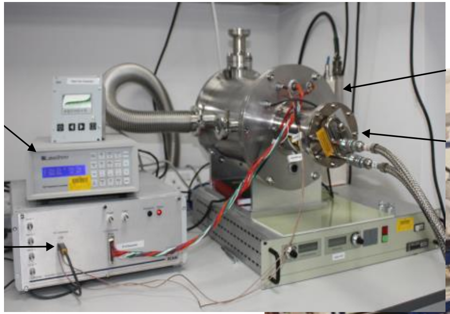


Modelling

Characterisation



RADIATION DAMAGE TESTING

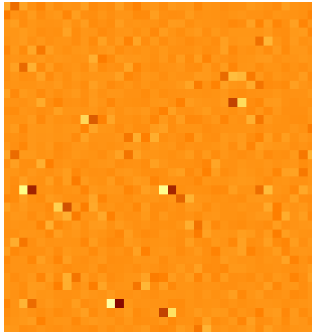


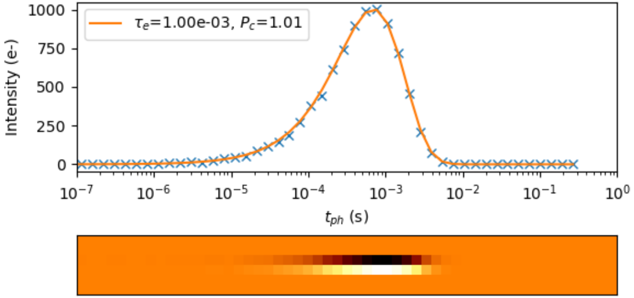
Irradiation of devices with highly energetic particles (protons, neutrons, etc)

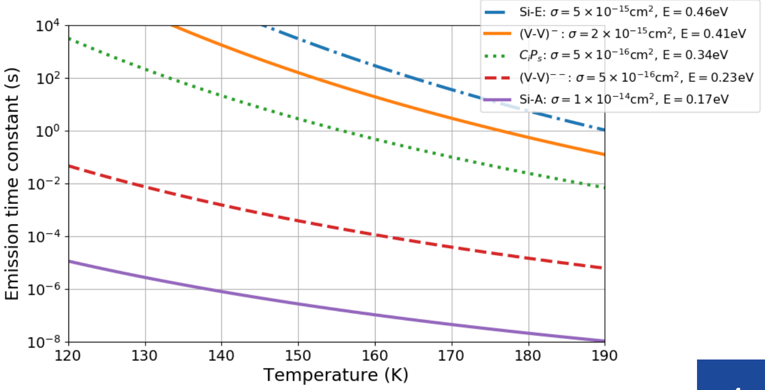
- Cryogenic irradiations to mimic conditions in Space
- ‘Keep cold’ systems to be monitored over extended periods (years)

Development of analysis methods

- Many methods employed to tests the performance
- ‘Trap pumping’ technique can identify and characterise single defects
- Can help optimise instrument operating parameters







CEIs MAJOR SPACE PROJECT ACTIVITY - 1

Gaia – Launched 2013

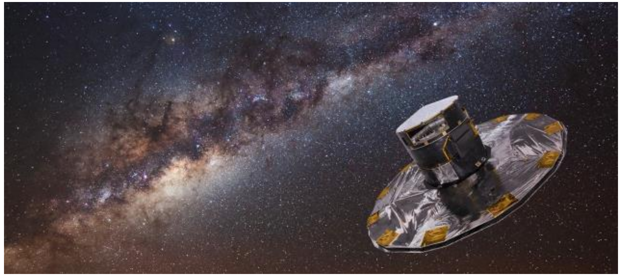
- 120 large area optical CCDs
- Contributed to the radiation damage knowledge through device modelling and data analysis

Euclid – Launch 2022

- 36 large area optical CCDs
- Detector modelling and optimisation
- Leading the CCD radiation damage evaluation & evaluating p-channel CCD technology
- Doing cryogenic irradiations and monitoring for 2+ years

JUICE – Launch 2022

- Optical CMOS sensor (CIS115)
- Providing detectors for the camera in the extreme electron environment (~1 Mrad)
- Radiation damage qualification using protons, electrons, gammas and heavy ions



CEIs MAJOR SPACE PROJECT ACTIVITY - 2

SMILE – Launch 2023

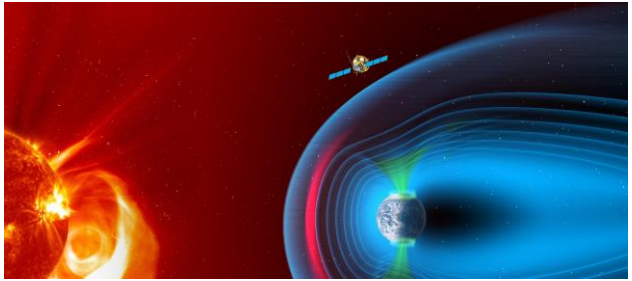
- Large X-ray CCDs
- Developing and supplying the X-ray CCDs into the SXI instrument
- Radiation characterisation, optimisation and in-flight calibration

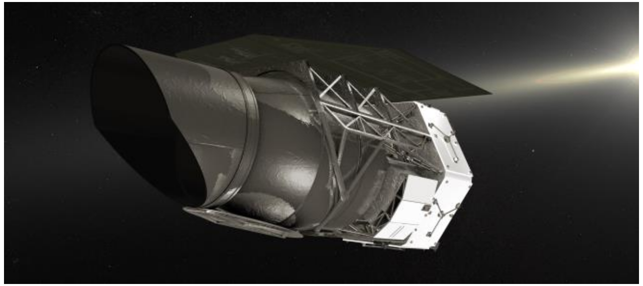
WFIRST – Launch 2023

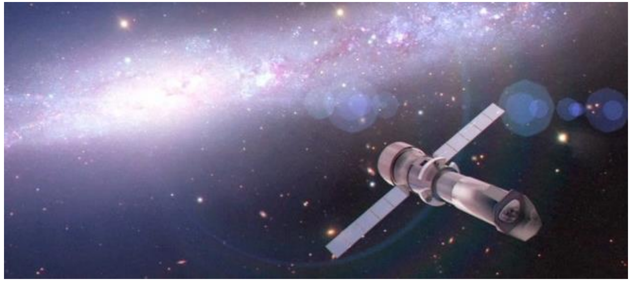
- Optical EMCCD
- Device modelling, optimisation and radiation damage testing

ATHENA – Launch 2031

- X-ray DEPFET active pixel sensor
- Simulating radiation background and developing shielding







GRAVITYCAM

Proposed high-resolution wide-field instrument for NTT 3.6m Telescope in Chile

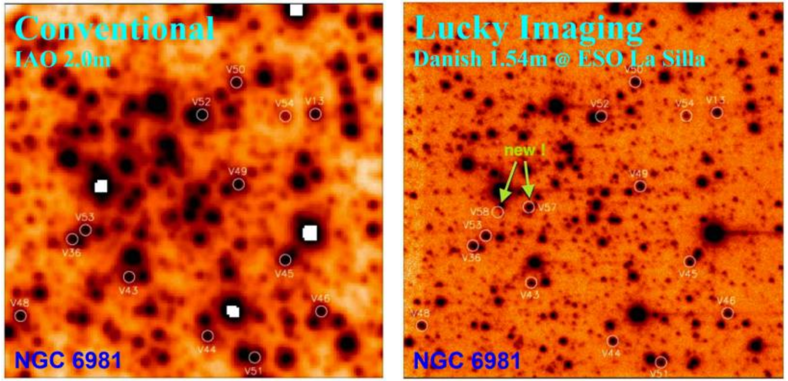
- Main collaborators: Edinburgh, Sct Andrews, Cambridge, UK ATC
- Large array of high-speed detectors
- High cadence surveys over large part of the sky
- Long list of science drivers, incl.
  - Detection of low-mass exoplanets using the microlensing method
  - Improve weak shear studies of dark matter distribution
  - Unique database of stellar variability
  - Mapping of Kuiper belt objects

High resolution obtained by doing high frame-rate imaging (~25Hz)

- Tip-tilt correction (shift-and-add) can give 2-3 times improvement
- Can be used over much larger area than conventional Adaptive optics approach

In single pointing (0.5ºx0.5º):

cadence	40 ms	1 s	1 min	1 h
# stars	~ 10^3	~ 2×10^4	~ 10^6	~ 10^7



From: Skottfelt et al. 2013

GRAVITYCAM

Instrument Design

- Field of View of 0.5º
- Simple optics - no re-imaging optics needed
  - NTT plate scale matches pixel size (20um pixel gives 0.1”/pix – close to diff limit of 3.6m telescope)
- Large focal plane (50-200 detectors) inside vacuum dewar

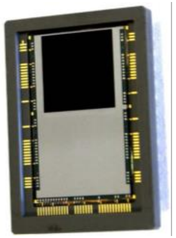
Detectors

- CMOS imaging sensors preferred option
  - Similar performance to CCDs in terms of QE
  - Sub-electron noise at high speeds, good QE, digital readout, buttable packages
- Working on direct comparison of EMCCD and CMOS sensor

Data Management and Analysis

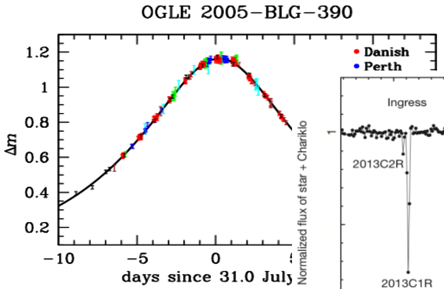
- Large amounts of data – many 100’s TB/night
- Real time analysis of data and diverse output to different science cases

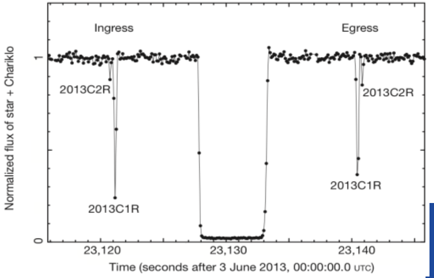
JPAS CroyCam



Te2v CCD201-20

Te2v CIS113





THANK YOU

INSTRUMENT DESIGN

GravityCam will sit on the Nasmyth port of the NTT

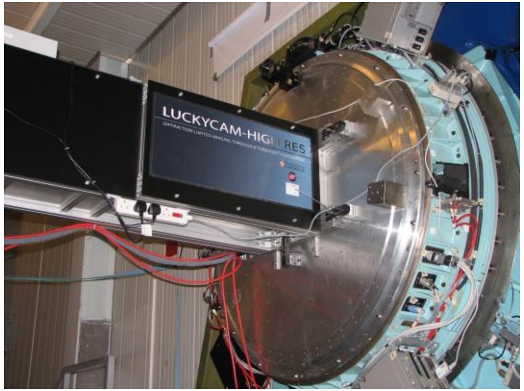
- Good optical quality and plenty of room
- Needs an atmospheric dispersion corrector to allow wide band-pass
  - Important for microlensing survey
- A filter wheel will be important for other areas

The NTT has a Field of View of 0.5º

- Important with good optical qualify over whole FoV
- Field flattening optics in front plate of cryo dewar

Nasmyth focus has plate scale of ~5”/mm

- Using a pixel size of 10 – 20 μm gives a pixel scale of 0.05’’ – 0.1’’ just around the diffraction limit of a 3.6m telescope
- Total number of pixels will thus be 100m – 1bn, depending on pixel size and fill factor
- Probably 50 – 200 devices



FOCAL PLANE

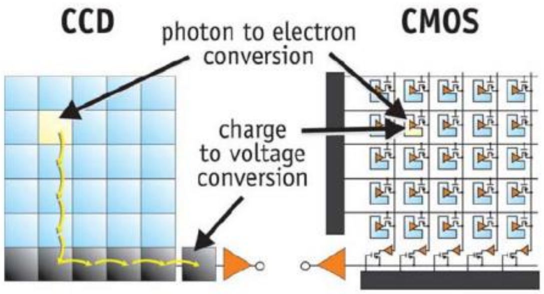
CMOS Imaging Sensors (CIS)

Initial idea was to use EMCCDs, but large package and charge transfer area means that fill-factor will only be ~ 1/6

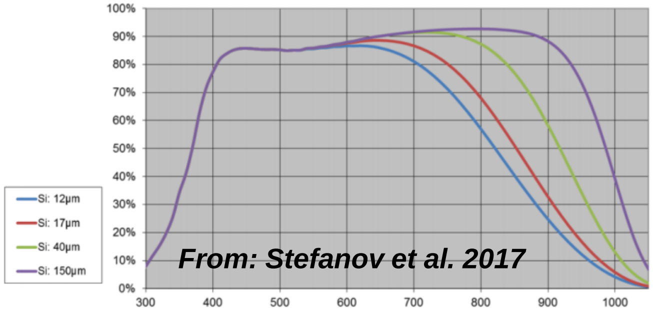
Recent developments in CIS devices have made the image quality good enough for astronomy

- Back-thinning means Quantum Efficiency comparable to CCDs
- Hi-rho technology for CIS could give big improvement in NIR QE

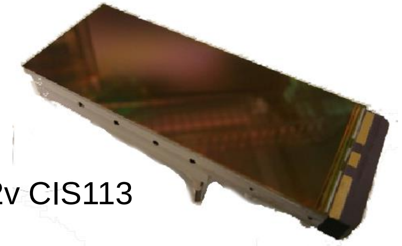
- Charge-to-voltage conversion circuit in each pixel
  - Faster readout speeds as pixels can be read out in parallel
  - Lower noise as more time can be spent on charge conversion
- Low power consumption and on-chip ADCs
  - Simplifies readout electronics, vacuum and cooling systems
- Can easily be made in buttable packages
  - Higher fill factor of focal plane
- Currently testing CIS devices for this purpose



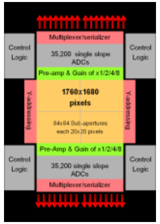
QE versus thickness at -100°C with Multi 2 AR coating



From: Stefanov et al. 2017



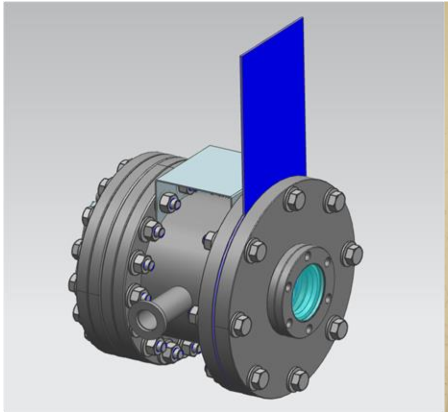
Te2v CIS113

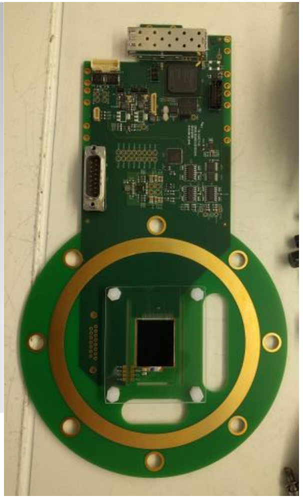


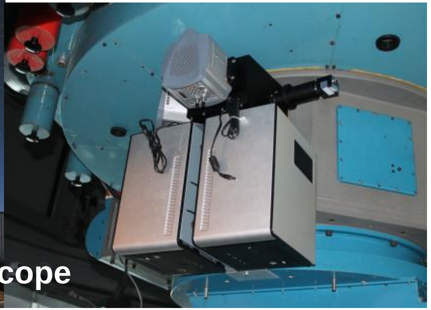
TESTING CIS120

Building test camera to test and characterise Te2v CIS120

- New all-purpose CIS detector
  - 2k x 2k pixels, 10 µm pixels, 20 Hz frame rate
  - 3-side buttable package in development
- Compare with EMCCD systems already available at OU
  - Gain, noise, inter-pixel responsivity, image lag, etc.
- Plan to install (a copy of) the test camera on the Danish 1.54m telescope at La Silla, Chile
  - EMCCD instrument installed since 2013
  - 2x Andor iXon cameras 10-30 fps (Te2v CCD97)
  - Direct on-sky comparison between EMCCD and CIS
  - Same site as the NTT
  - Current plan is to test this summer (2019)
- Main purpose is to test which detector is best for GravityCam
  - Will also establish the readiness of CIS for high-speed astronomical imaging







Danish 1.54m Telescope

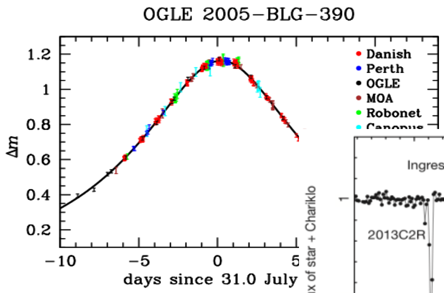
DATA MANAGEMENT AND ANALYSIS

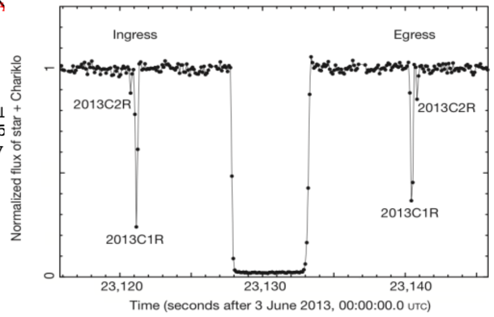
Large focal plane and high speed imaging will produce vast quantities of data ~ many 100's TB/night

- Software needs to analyse data in real-time and produce a diverse output to fulfil the need of all the science cases
- Each detector can be run on its own high-performance PC or on a powerful server
    - Analysis tasks well-suited for GPU processing
- Fixed reference frames created for each pointing
- Detector-related corrections (flat fielding, vignetting or extinction corrections etc.) will be handled on full output images.
- Processing then done in ~1024 x 1024 blocks. Each sub image is co-added into the appropriate resolution bin
- Light-curve of each star is created
    - For microlensing surveys alerts will be generated if a change in brightness occurs
    - For occultation events a high time-resolution light-curve needs to be saved

Nvidia Tesla

3584 cores
Up to 21 teraFLOPS
732 GB/s memory bandwith





SUMMARY

- Initial work on GravityCam has started
    - Paper published in PASA: Mackay et al. (2018) doi: 10.1017/pasa.2018.43
    - Test camera for on-sky comparison of detector technologies being developed
- Next step will be proper Phase A study
    - Better idea of instrument design and number of detectors
    - Currently identifying funding sources for this
    - Relatively simple instrument design, but large number of detectors
    - Biggest effort will be software development for real-time data analysis
- Projected timescales and costs
    - Estimate 3 years to build and produce software for GravityCam
    - Plus 1 year for commissioning
    - Estimate £15m for 3 years development and 1 year commissioning
        - Detectors will be driving the costs
    - £500k/year in running costs
        - Mainly team to manage data analysis outputs