C3TM: CEI CCD Charge Transfer Model for radiation damage analysis and testing

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The Open University

RADIATION DAMAGE

High energetic particles from the Sun can damage the silicon lattice in the CCD

- Creates defects

These defects (or traps) can capture electrons and release them later in time

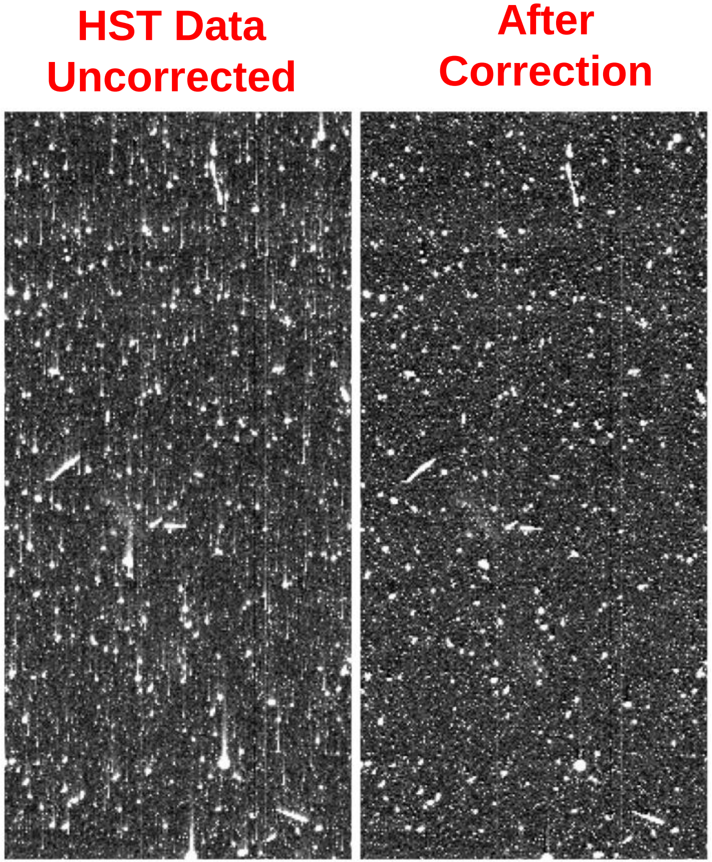
- Increases the Charge Transfer Inefficiency (CTI)
- Leads to smearing of the data
- Radiation damage is an issue for most space missions

Charge smearing can be corrected for with statistical methods

- Increasing demands on data quality means better knowledge of trap properties is needed

To further the understanding of radiation induced defects we have created the CEI CCD Charge Transfer Model (C3TM)

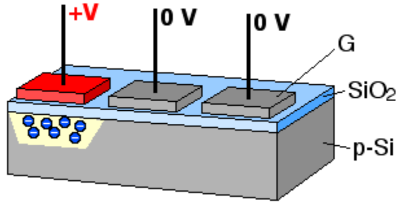
Part of the Euclid radiation damage correction efforts

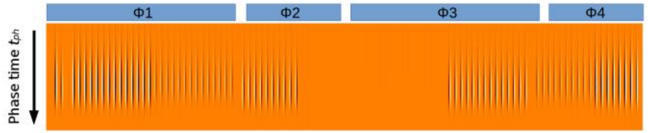


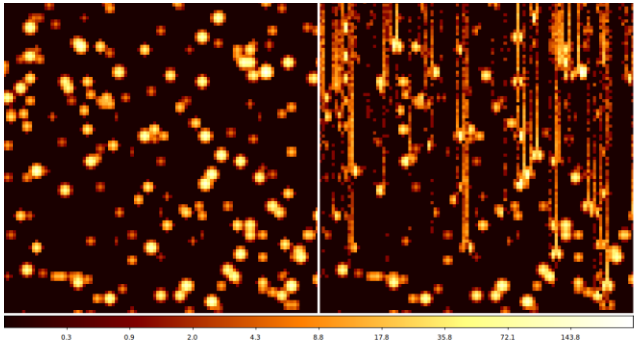
From: Massey et al. (2010)

C3TM: CEI CCD CHARGE TRANSFER MODEL

- Monte Carlo CTI simulation code
  - Mimic processes in a CCD as close as possible
  - Full 3D model
  - Electrode level simulations
    - phase-to-phase timing of transfers
    - Probability of trap status changing over each phase time (not time-sliced emission/capture)
  - Density-driven charge capture
- Using Silvaco TCAD simulations of electron density as direct input
  - Better estimation of capture time constant
- Include features such as multi-level clocking, trap pumping etc.
- Can take any array or FITS file as input, or input frames can be generated by the code
- Code is made to be highly versatile and parameterised, so it can be adapted to any CCD and a large number of operating conditions







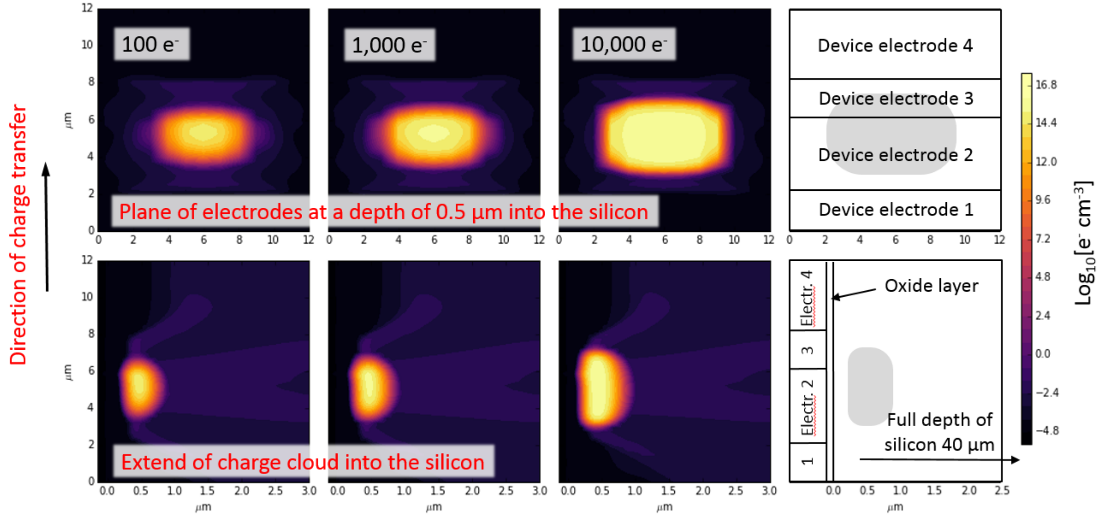
CHARGE CAPTURE

Silvaco simulations

C3TM uses Silvaco TCAD simulations of electron density to calculate capture time constants

- Silvaco is a suite of semiconductor simulation software
- Electron density simulations can be done in 3D based on
    - Pixel or register architecture
    - Materials and doping concentrations
    - Operating temperatures
    - Clocking voltages
        - Including multi-level clocking

Simulation needs to be done for a range of signal levels



From Skottfelt et al. JATIS 3(2), 028001 (2017)

CHARGE CAPTURE

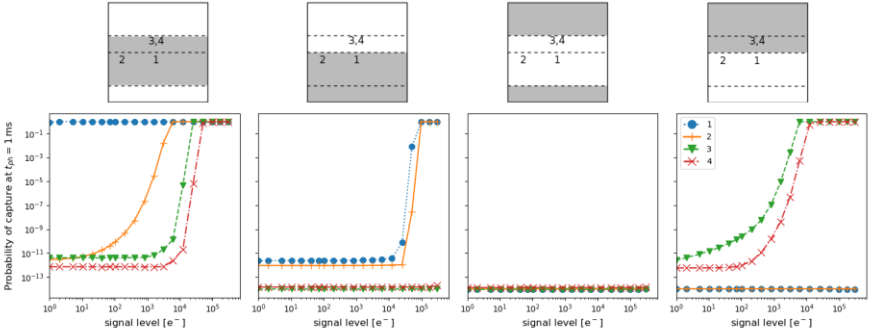
Capture time constants

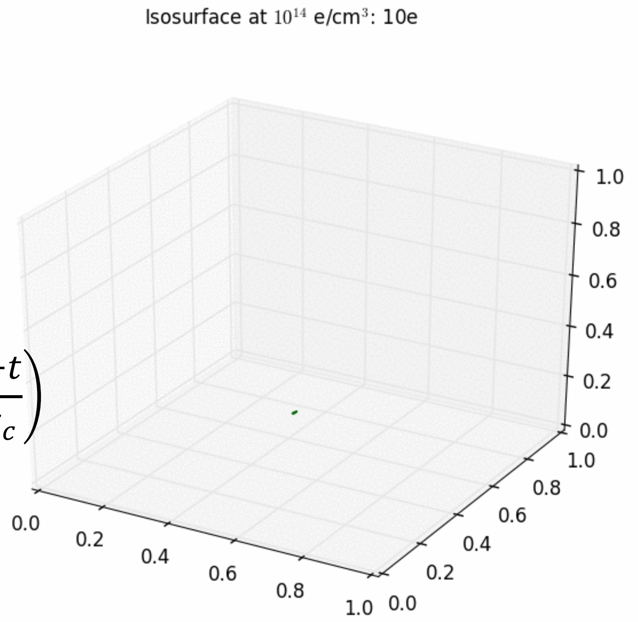
- Trap positions can be inserted manually or generated randomly
- The electron density n_e of each trap at a specified signal level is found by interpolating the electron densities at the simulated signal levels
- From this the capture time constant can be found

$$\tau_c = \frac{1}{\sigma n_e v_{th}}$$

- Physical solution instead of the approximations previously made for capture (i.e. no analytical fitting)
- Using the capture time constant and the phase time, the probability of capture of each trap can be calculated

$$P_c = 1 - \exp\left(\frac{-t}{\tau_c}\right)$$





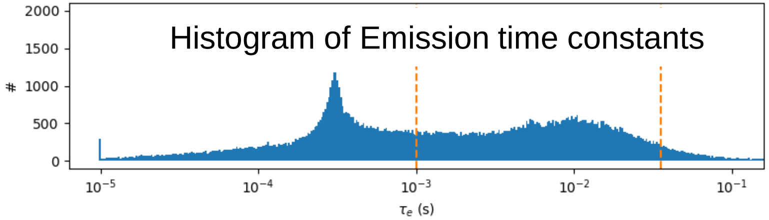
Fractional depth (12µm)

Fractional pixel widths (12x12µm)

CHARGE EMISSION

Emission time constants are not well defined, but better described as broad distributions

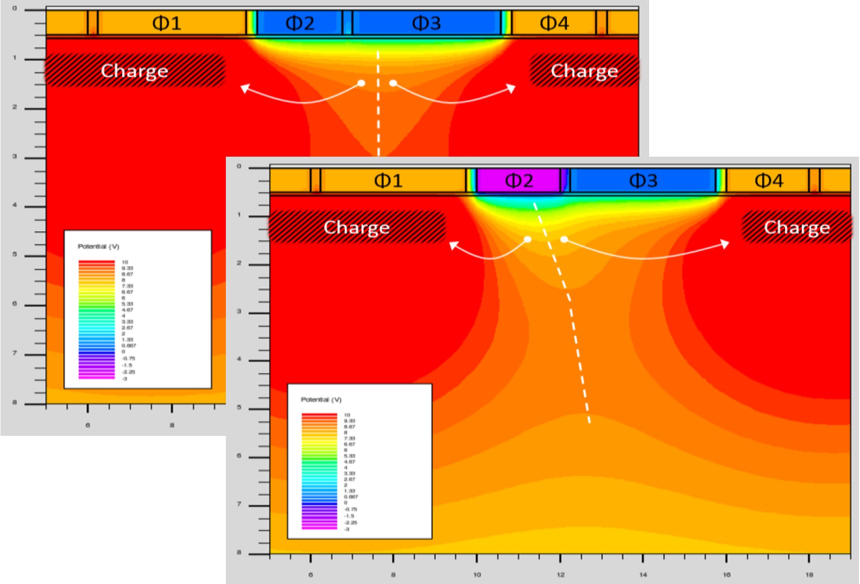
- In C3TM emission time constants can therefore be
    - Input manually, or
    - Generated from an energy level and a spread on that energy level



From Euclid CCD273 cryogenic irradiation campaign

Potential structure determines in which direction an emitted electron will go

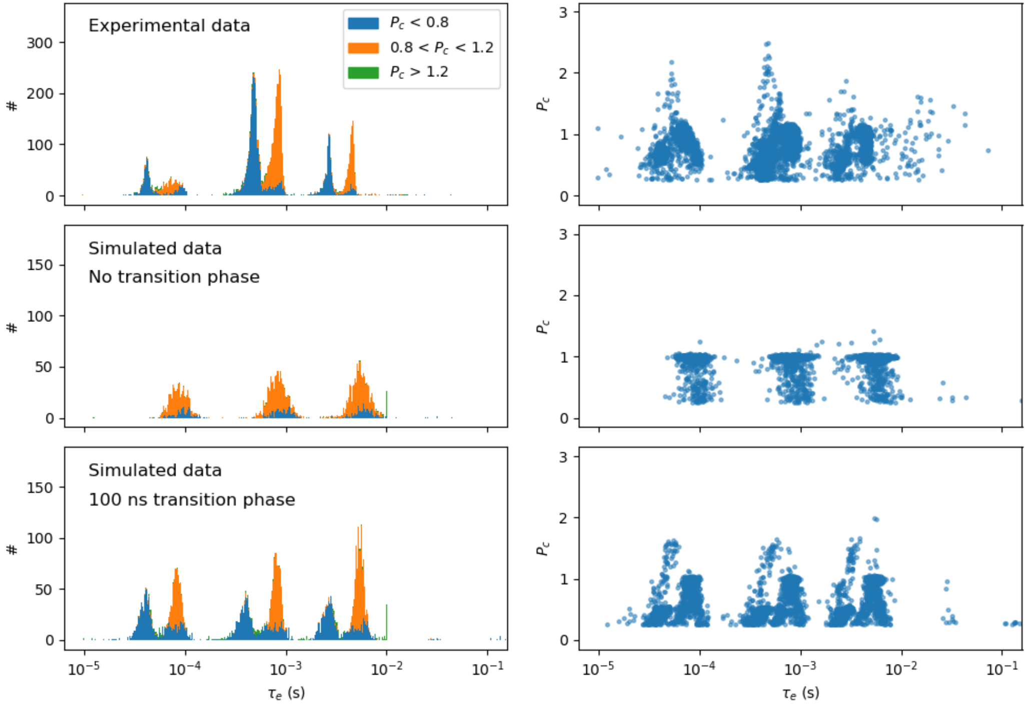
- With two-level clocking and even phase widths, this can normally be estimated using symmetry considerations
- In more complex situations Silvaco simulations of the potential structure can be useful
- With uneven phase widths the position of the trap in the phase becomes important.
- With multi-level clocking the direction of the electron depends on the distance of the trap to the electrode.



INTER-PHASE TRAPPING

It was commonly assumed that trapping only occurs when charge sits under the phase during the t_{ph} time, i.e. that inter-phase trapping does not occur.

- Pseudo-3-phase pumping scheme initial chosen for Euclid irradiation testing
- Experimental data did not match theoretical predictions or simulations
- An analysis of this issue, helped by C3TM simulations, showed that the best explanation was that inter-phase trapping can actually occur
- Adding a 100 ns transition phase to the simulated data improved the results substantially
- Presents a very strong case for inter-phase trapping
- Following this work an alternative pumping scheme was chosen for Euclid irradiation tests

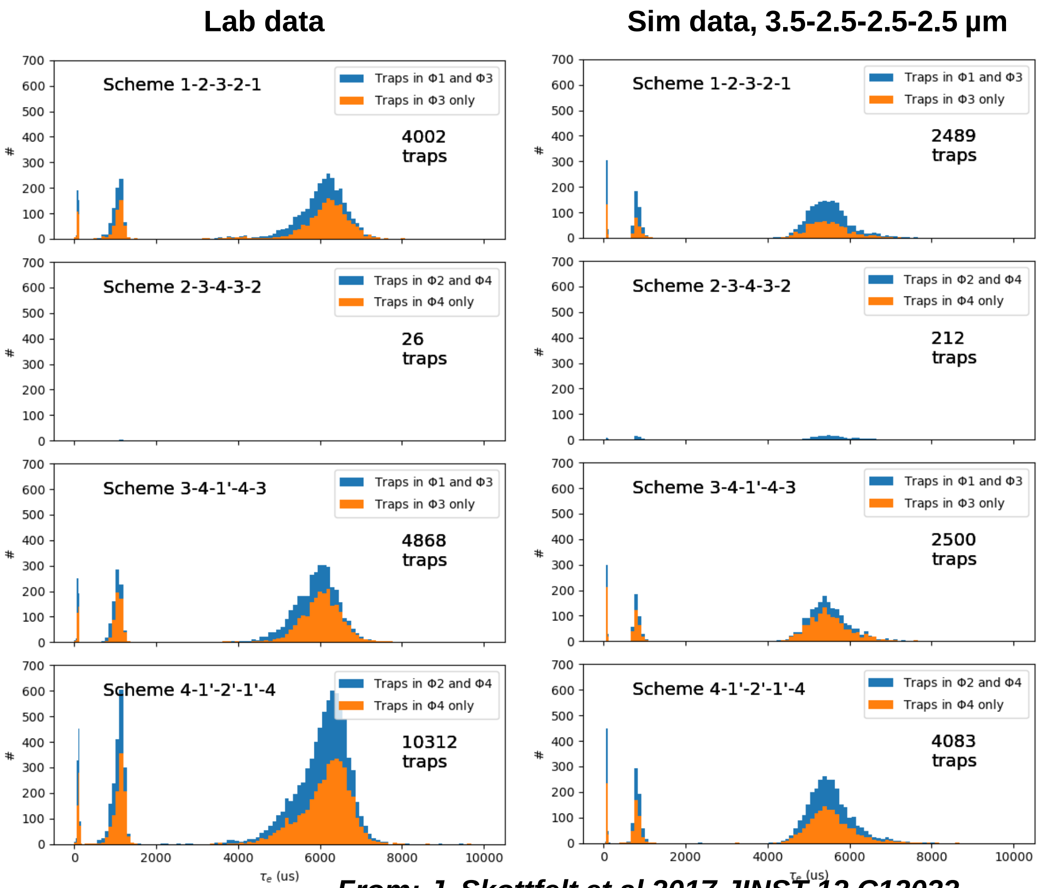


From Skottfelt et al. JATIS 4(1), 018005 (2018)

EFFECTIVE ELECTRODE WIDTHS

Comparing experimental trap pumping data with simulations can reveal **effective** widths of CCD electrodes

- Trap pumping scheme used for Euclid CCD273 will pump very well-defined regions of the device determined by the electrode widths
    - Design width of CCD273:
      3.5-2-3.5-2 µm, with 0.25µm spacing
- Lab data looks very different
- Possible explanation could be that the **effective** electrode widths are different from the design
- Simulating different electrode widths and comparing to experimental data
- Best match is found to be electrode widths of 3.5-2.5-2.5-2.5 µm

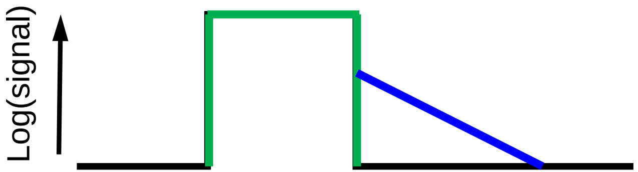


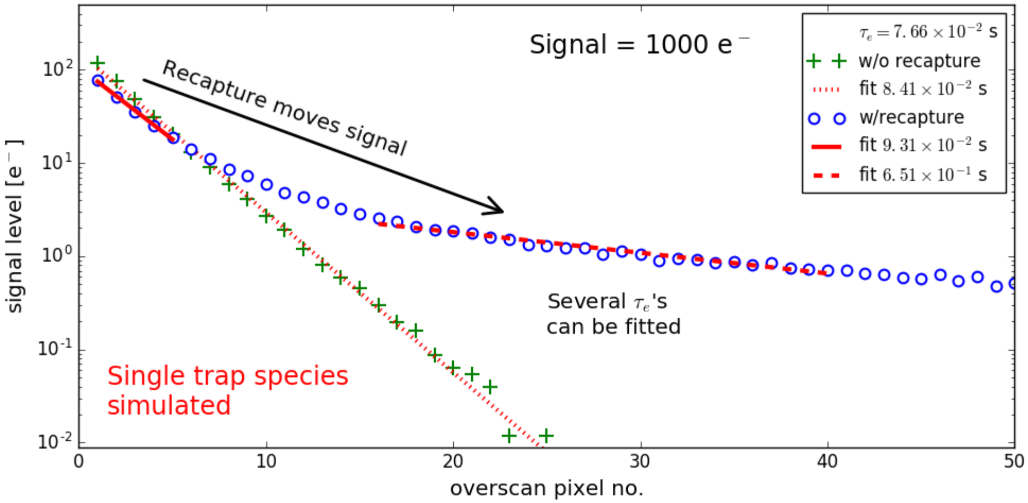
From: J. Skottfelt et al 2017 JINST 12 C12033

FITTING CHARGE TAILS

Emission time constants can be acquired by fitting charge tails with sum of exponentials, however

- Fitting sum of exponentials needs very tight boundaries
- Recapture in the tail pushes charge further down the charge tail
  - It is possible to incorrectly fit several τ_e's to a single trap species

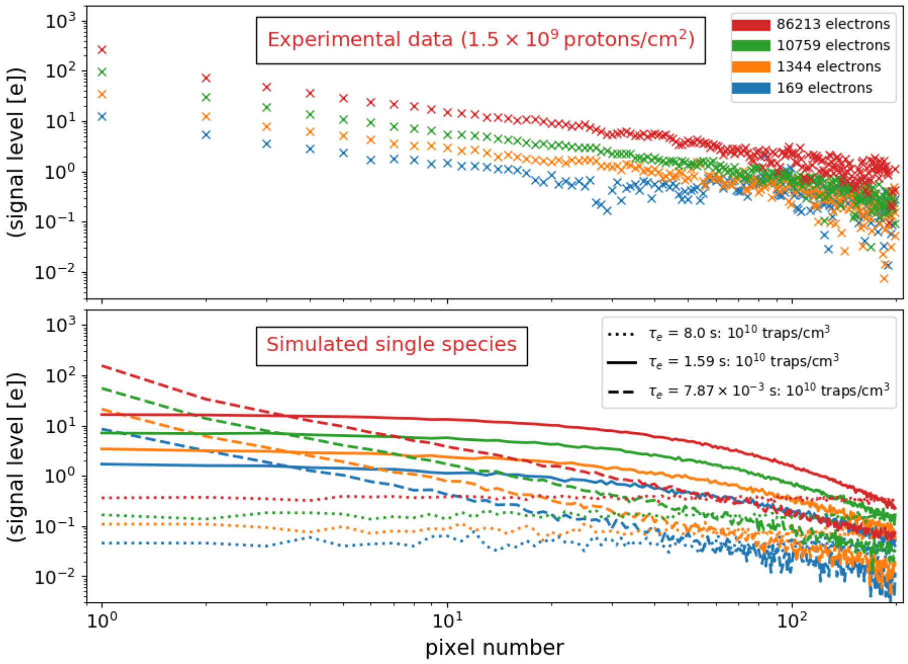




FITTING CHARGE TAILS

Alternative method using C3TM

- Experimental data from Euclid irradiation campaign
- Simulating a single traps species and signal level at a time



From Skottfelt et al. JATIS 3(2), 028001 (2017)

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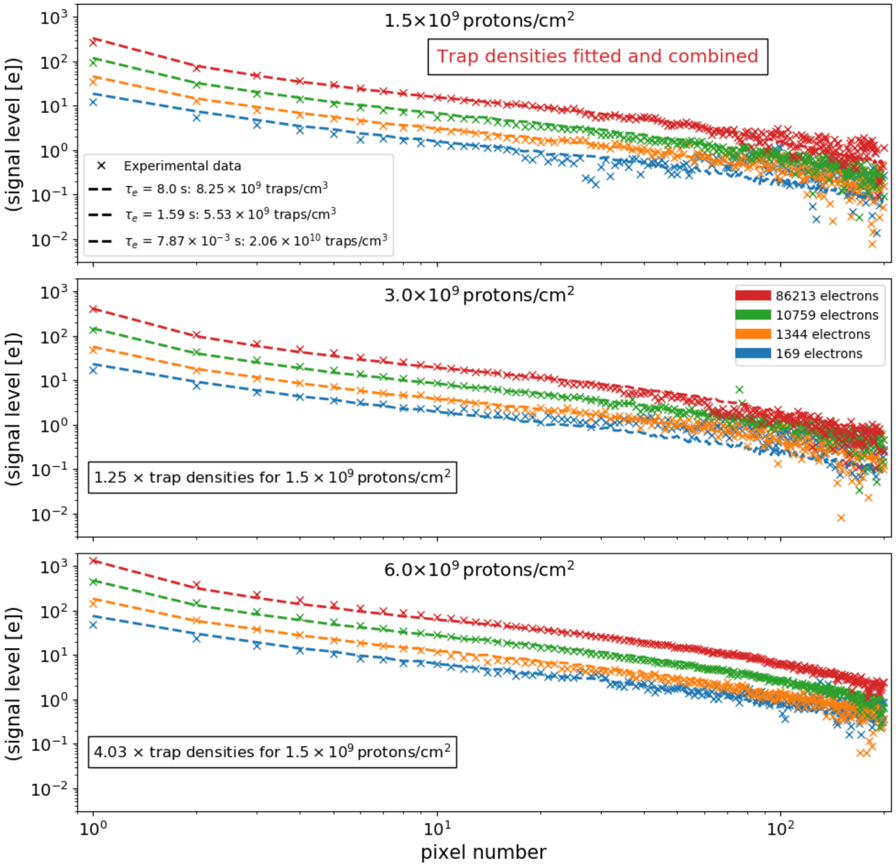
- Simulating a single traps species and signal level at a time
- Fitting density of simulated charge tails and summing them to match experimental charge tails
    - Done over all irradiation and signal levels at the same time
- Gives info about
    - Energy levels of traps
    - Capture cross section of species
    - Trap density at different irradiation levels



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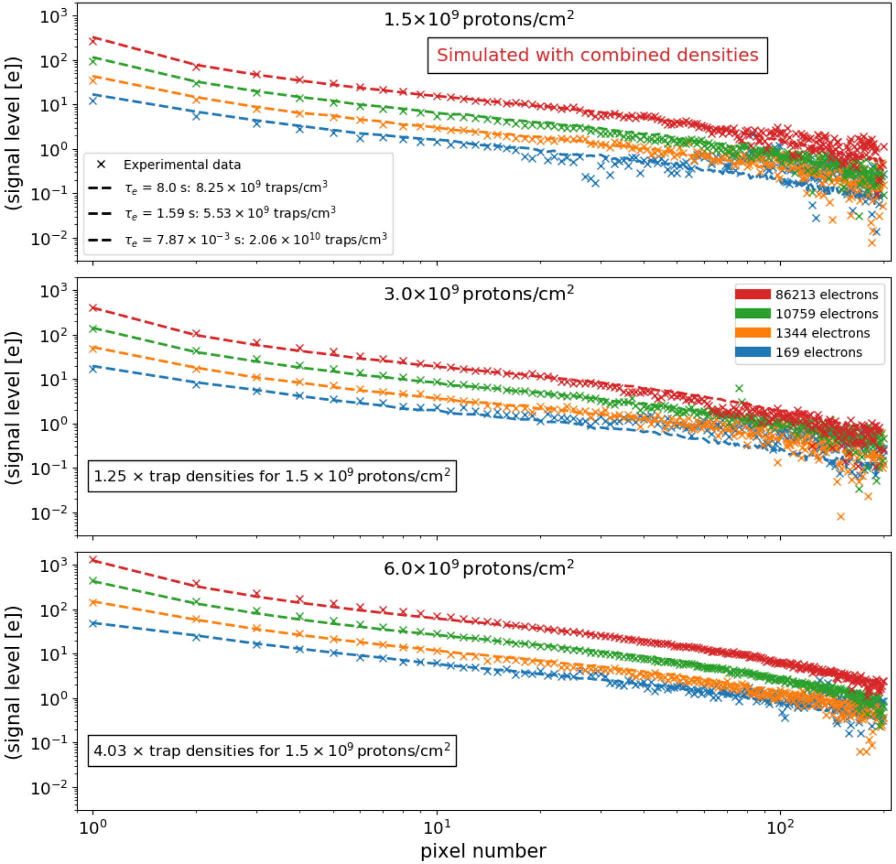
- Note: This is a first approx. as the capture and emission continues within the tails from other traps species
    - Running simulation using combined species improves result



SUMMARY

- The CEI CCD Charge Transfer Model (C3TM) is presented
- C3TM is a Monte Carlo model that takes charge density simulations as direct input
- It is running on a single electrode level which means that multi-level clocking and trap pumping etc. can be simulated
- It is shown how comparing experimental data to C3TM simulations be used to test assumptions on device performance and improve our knowledge on radiation induced defects in CCDs.
- Using C3TM to fit charge tails over large range of parameters can provide crucial information that will help inform the Euclid radiation damage correction efforts
- Can be an important tool for any space mission that depends on correction radiation damage effects to high precision
- Hope to port C3TM to Pyxel in the near future

THANK YOU