Proton Induced Traps within EM-CCDs

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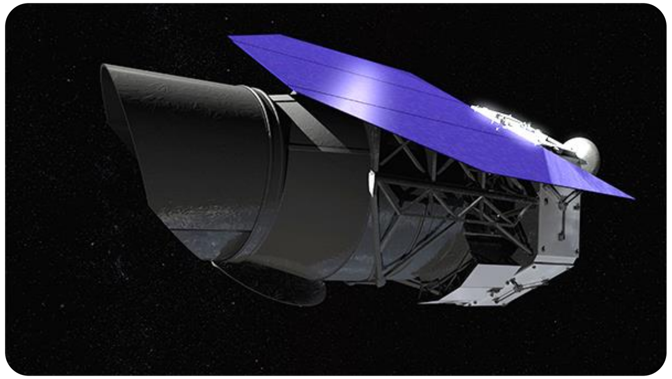
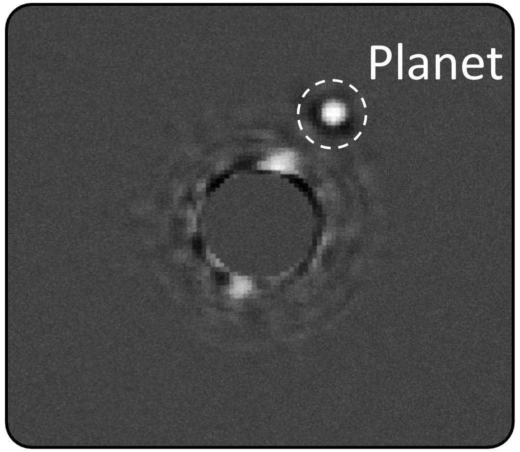
Introduction: WFIRST

- The WFIRST CGI aims to directly image and characterise extrasolar planets with properties similar to those within our own solar system.
- It will be the most sensitive optical instrument ever launched into space. Signal flux from science targets is expected to range between 10^{-4}-10^{-3} e^{-}/pix/s.
- In this regime, the impact of radiation damage is most severe. A thorough, definitive investigation into all defects that can impact CTI will help maximise the photon yield, prolonging mission lifetime.
- Here, we present the initial results from such a study.



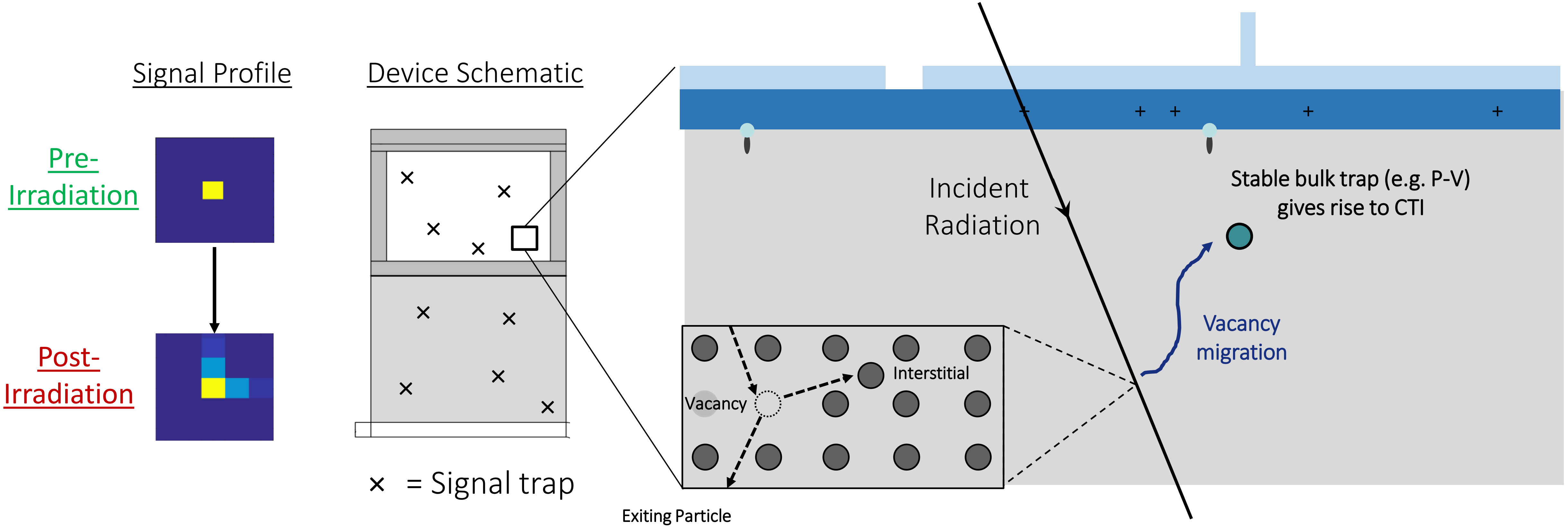
WFIRST mission concept



Example ground based coronagraph image

Radiation Damage

- Operation in a space environment subjects the detectors to radiation damage that can:
  - Increase Dark Current, Clock Induced Charge (CIC)
  - Increase Charge Transfer Inefficiency (CTI)

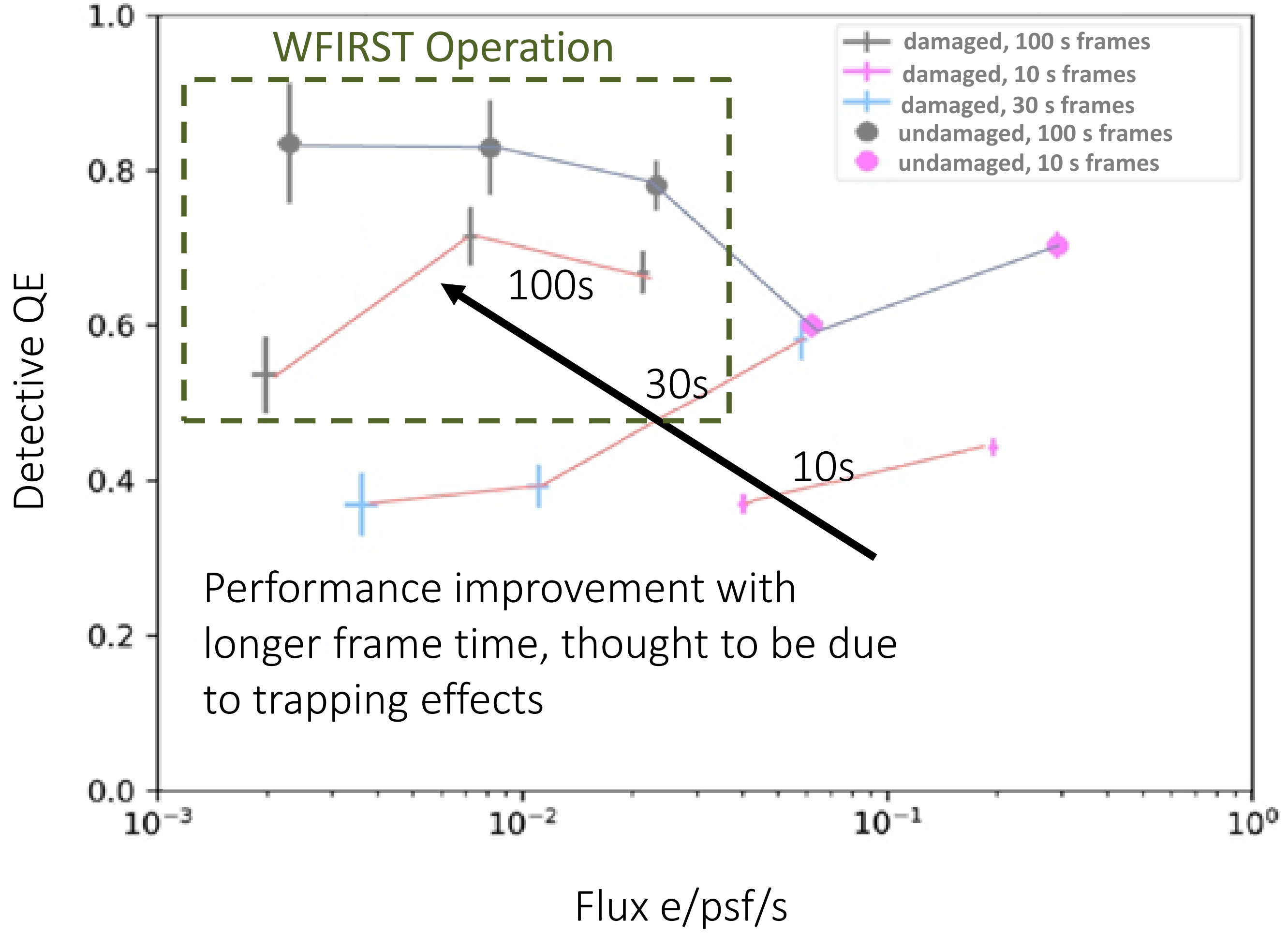


Radiation Damage for the CGI

- 2 irradiation campaigns for JPL. A total of 7 × CCD201-20 EM-CCDs have now been irradiated, with 10 proton irradiations!

- Low flux measurements at JPL using a damaged device have confirmed that The standard COTS CCD201-20 can **still detect planets following 6 years at L2** with a sufficient frame time (100s).

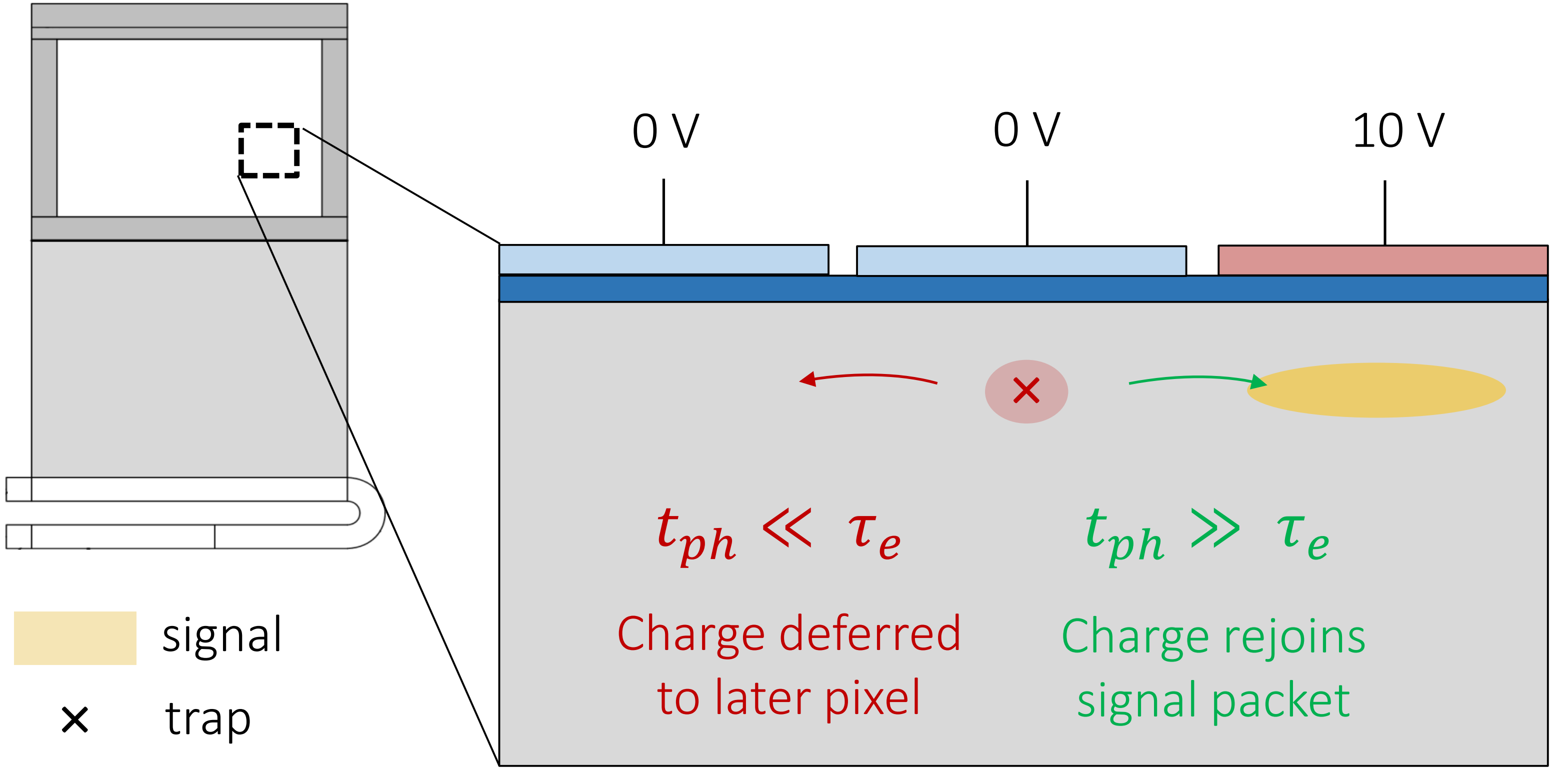
- But performance can be improved further….
  1. Narrow channel variants of the CCD201
  2. CTI optimisation through knowledge of defect properties



With thanks to Leon K. Harding and Rick T. Demers of JPL for providing this data

Characterising Traps in CCDs

- The charge lost is dependant on the relationship between the phase time (t_{ph}), and the emission time constant of the trap τ_e.
- Knowledge of τ_e is therefore crucial in order to optimise t_{ph} and minimise charge loss.



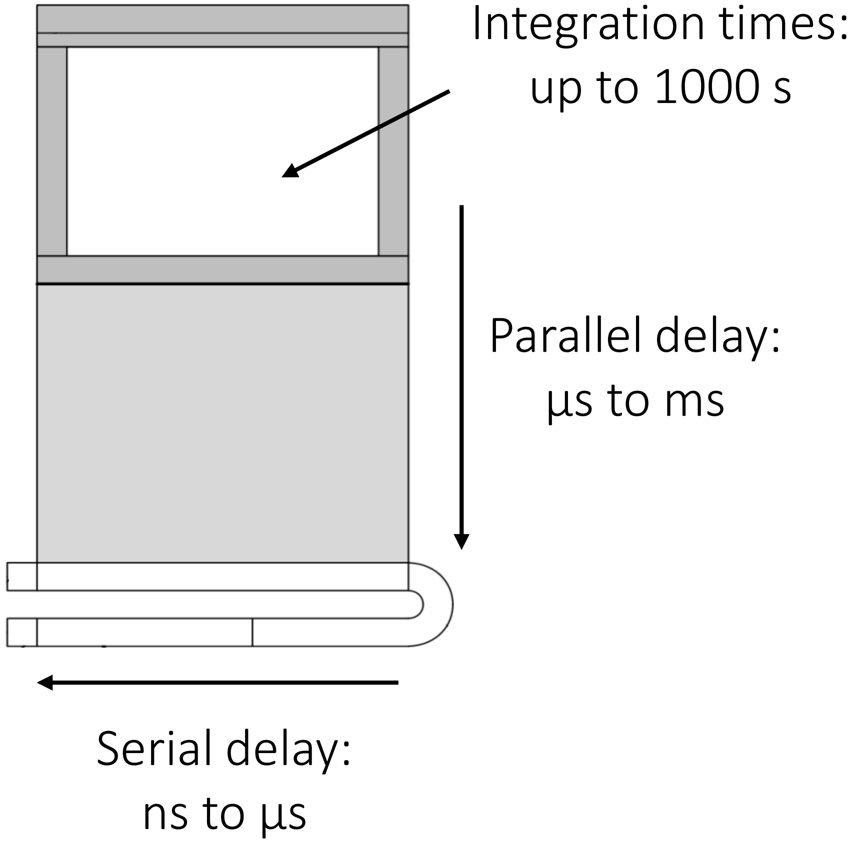
$$\tau_e = \frac{1}{\sigma N_C v_{th}} \cdot e^{\frac{E}{k_B T}}$$

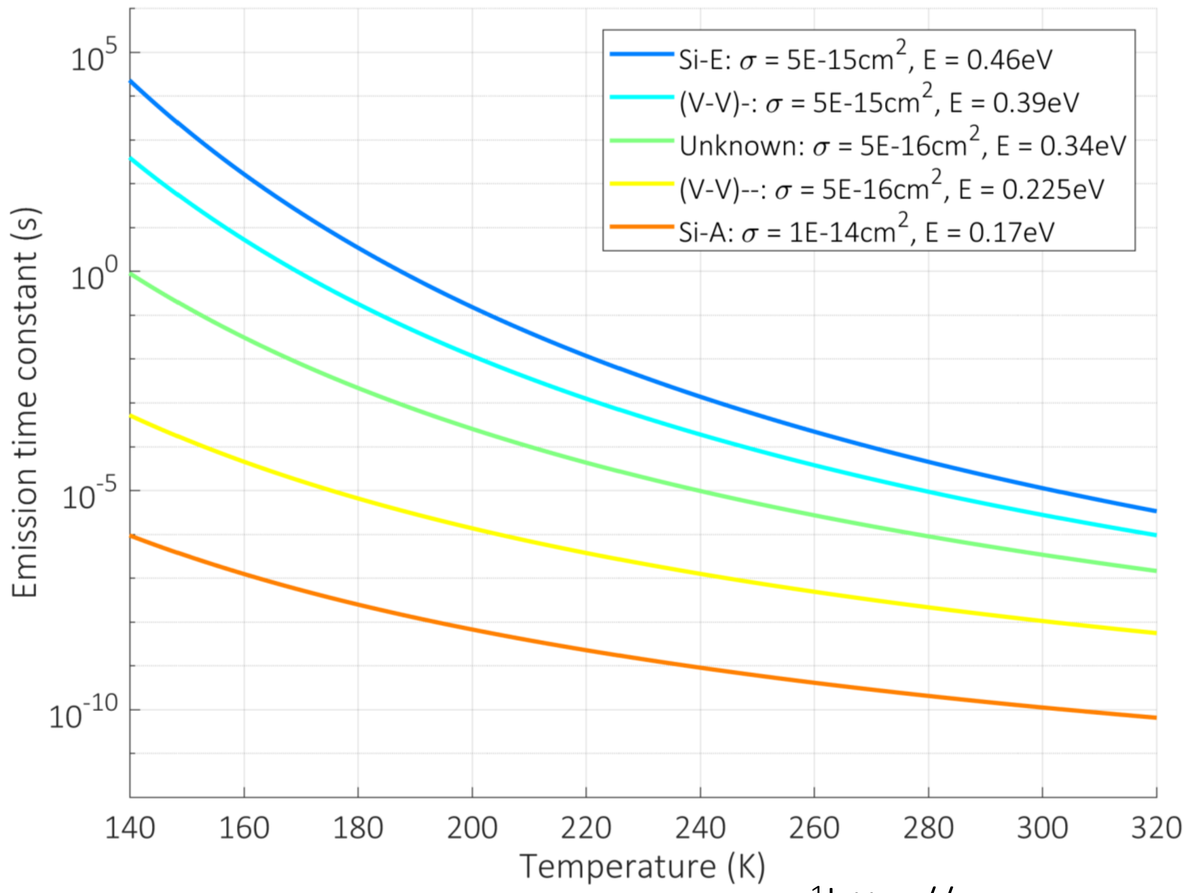
E = Energy Level
σ = Cross section
} Intrinsic to defect species

T = Temperature } CCD operation

Traps affecting CTI in CCDs

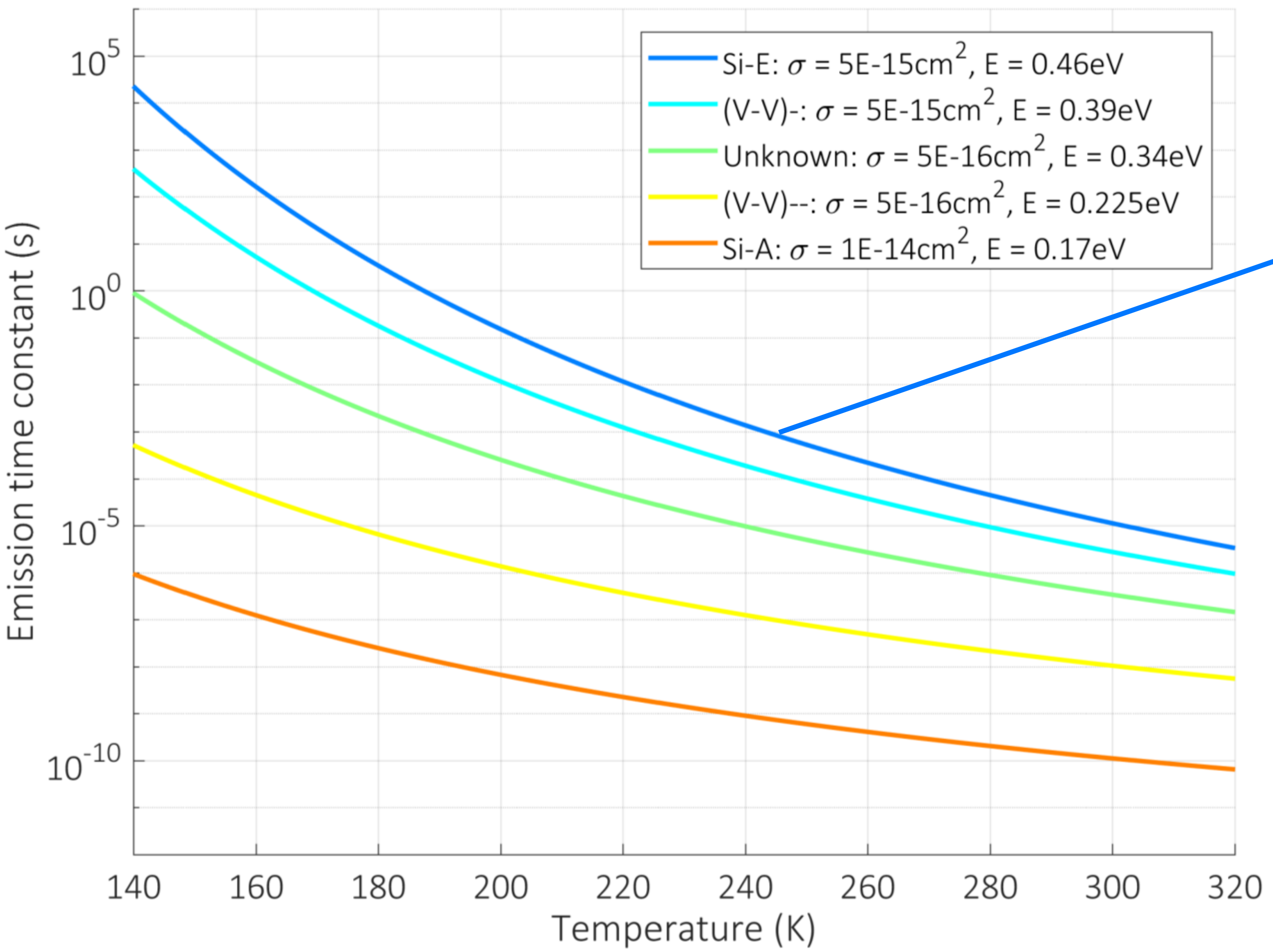
- The “trap diagram” shows τ_e as a function of temperature for each species known to affect CCD operation. The data show are a compilation of literature values, taken from Hall et al. (2014)[1]





[1]http://oro.open.ac.uk/41458/

Traps affecting CTI in CCDs

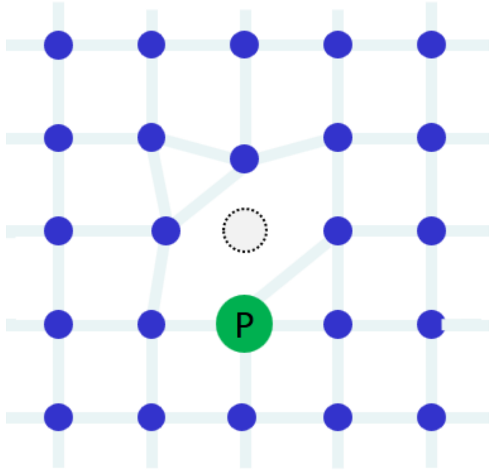


PV – (Si-E) Phosphorus Vacancy complex

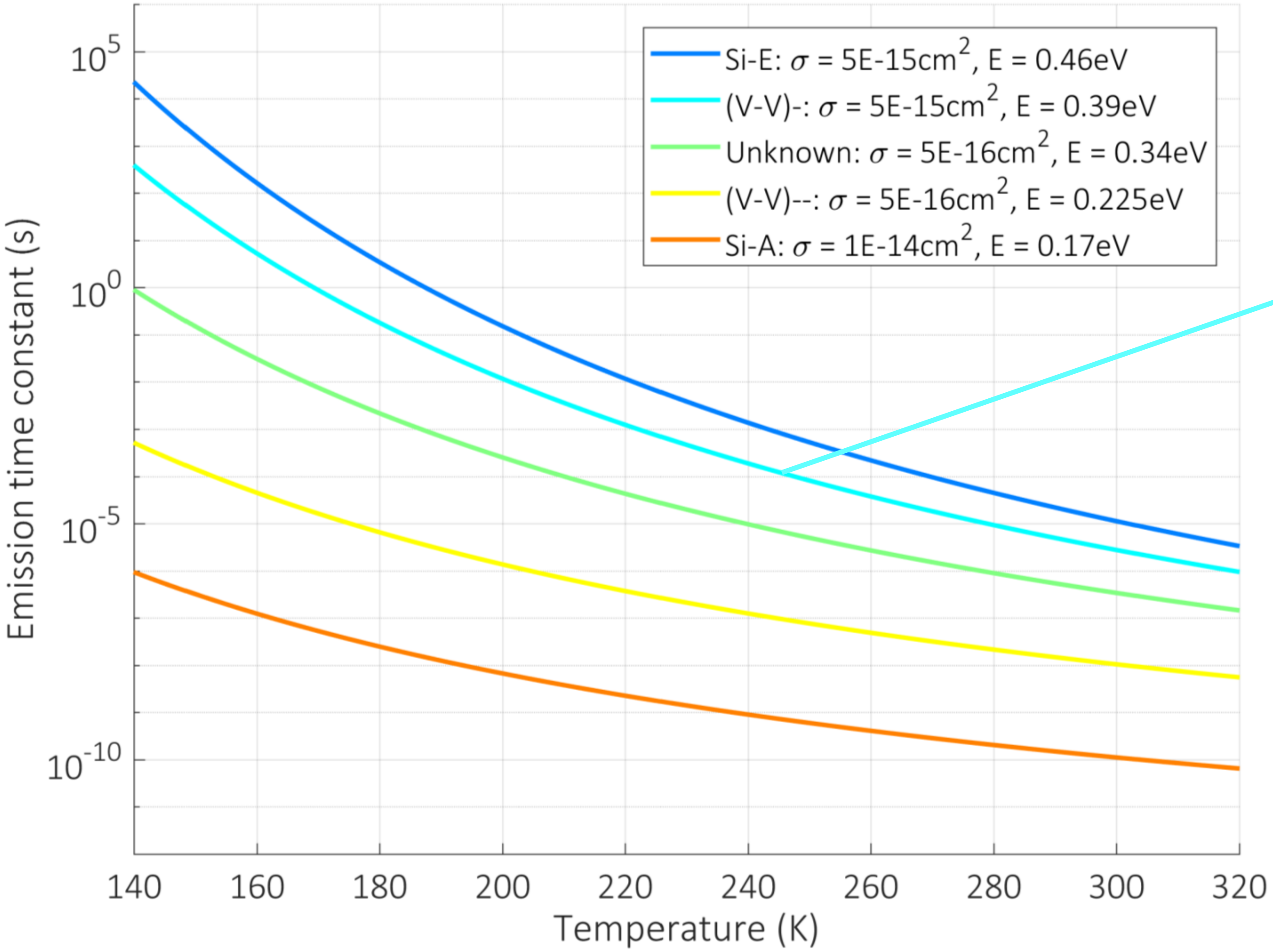
Phosphorus is a common buried channel dopant present in high concentration. Forms PV centres following irradiation. Impacts CTI and generates hot pixels.

Lattice view

$\tau_e \approx 100$ s at 160 K



Traps affecting CTI in CCDs

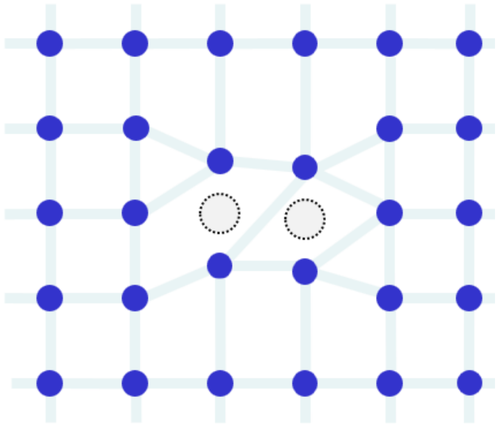


Single Acceptor Divacancy (V-V)$^-$

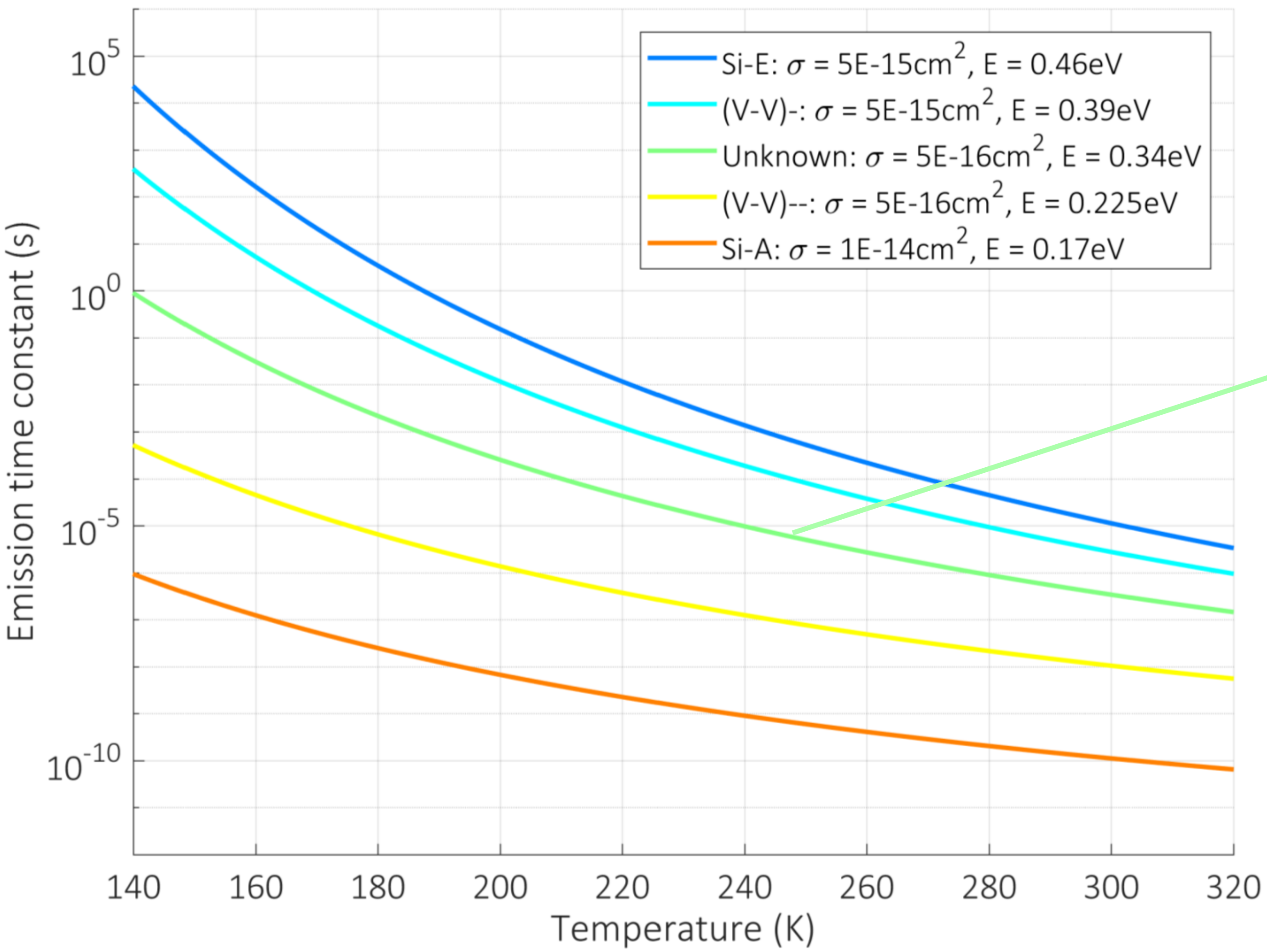
Present primarily following irradiation. typically within a few nm of the proton interaction site. The single acceptor state has also been linked to hot pixel locations.

Lattice view

$\tau_e \approx 10$ s
at 160 K



Traps affecting CTI in CCDs

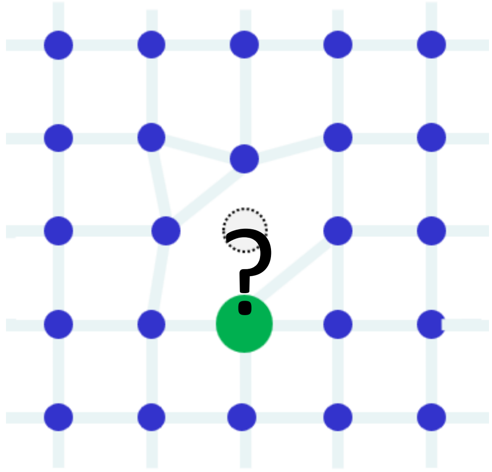


Unknown Trap Species

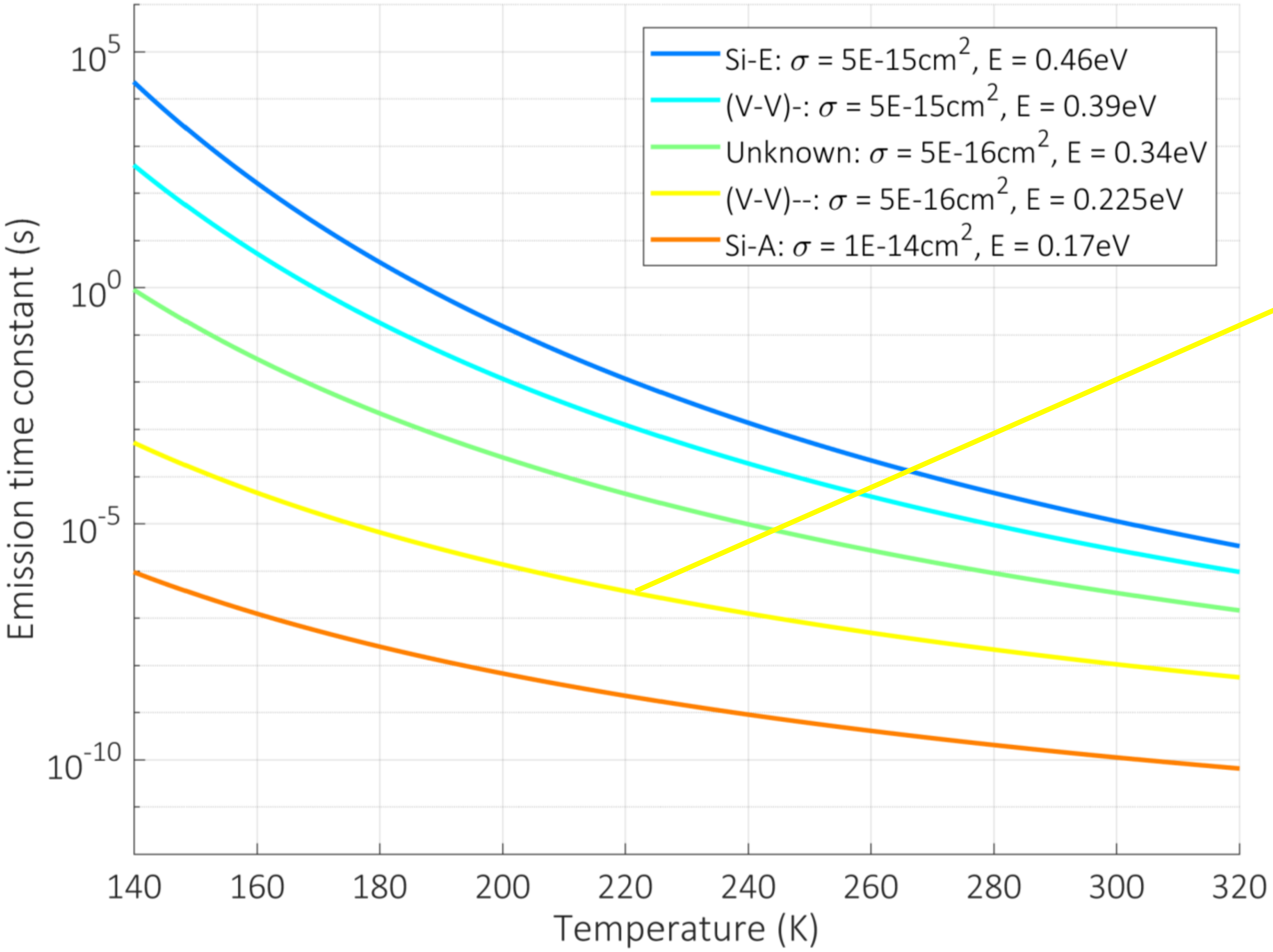
Observed following irradiation in some studies but not recent ones. If it exists it is likely due to an impurity that was present in some device batches but not others.

$\tau_e \approx 10^{-2}$ s at 160 K

Lattice view



Traps affecting CTI in CCDs

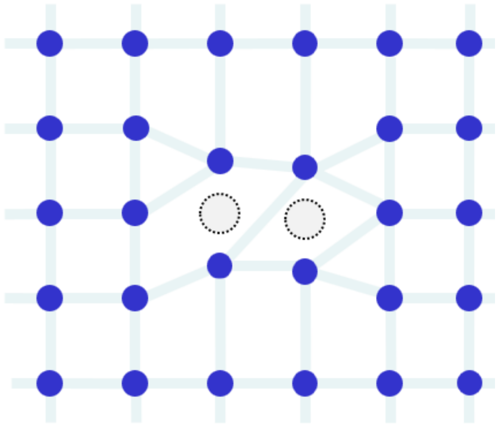


Double Acceptor Divacancy (V-V)$^{--}$

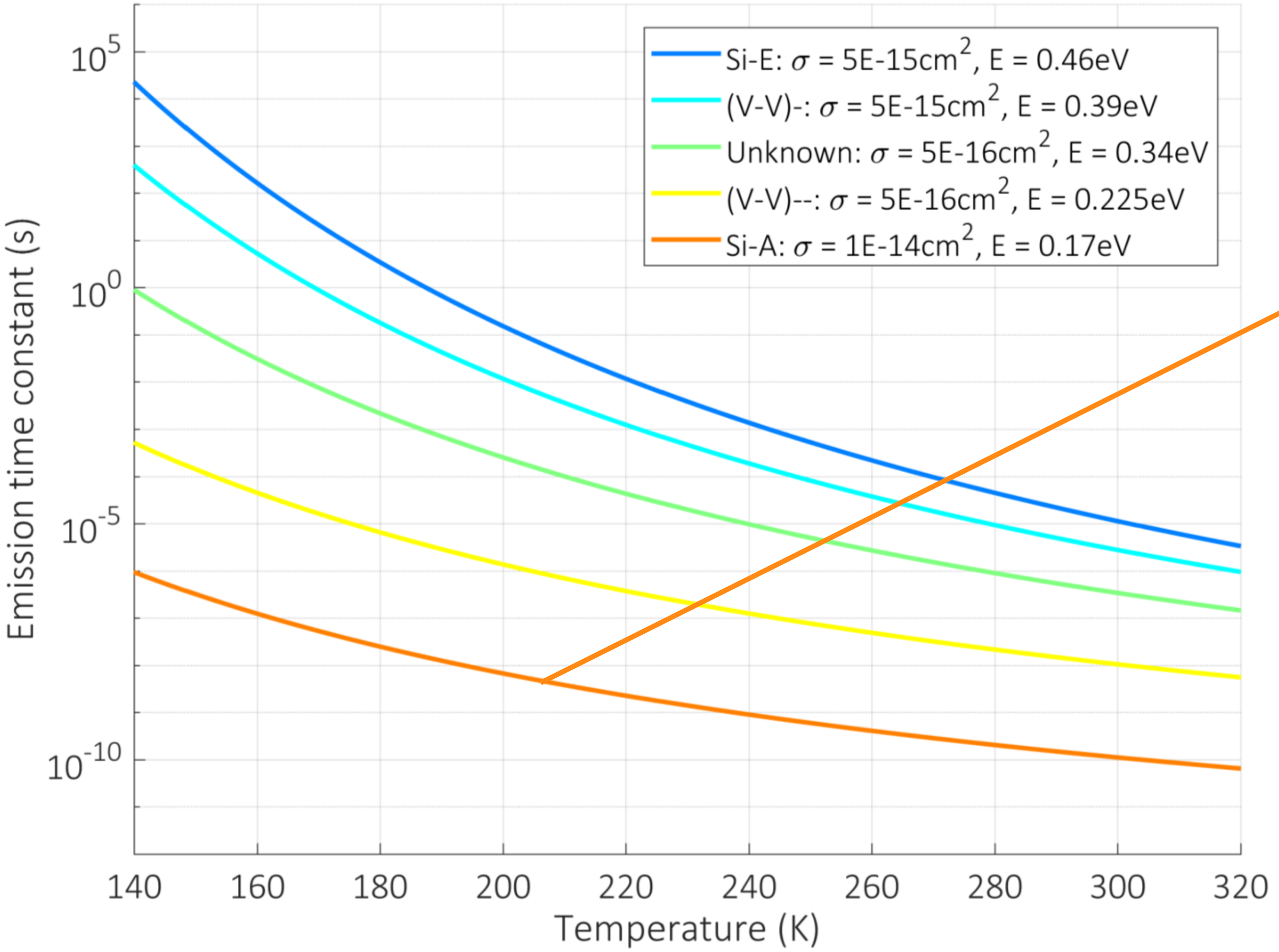
Present primarily following irradiation. typically within a few nm of the proton interaction site. Thought to be same introduction rate as VV^{-} (single acceptor).

Lattice view

$\tau_e \approx 10^{-4}$ s at 160 K



Traps affecting CTI in CCDs

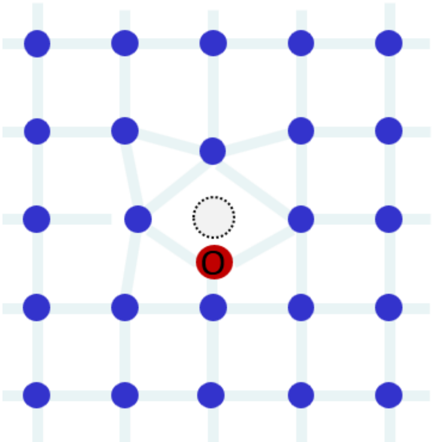


A-Centre (Si-A)

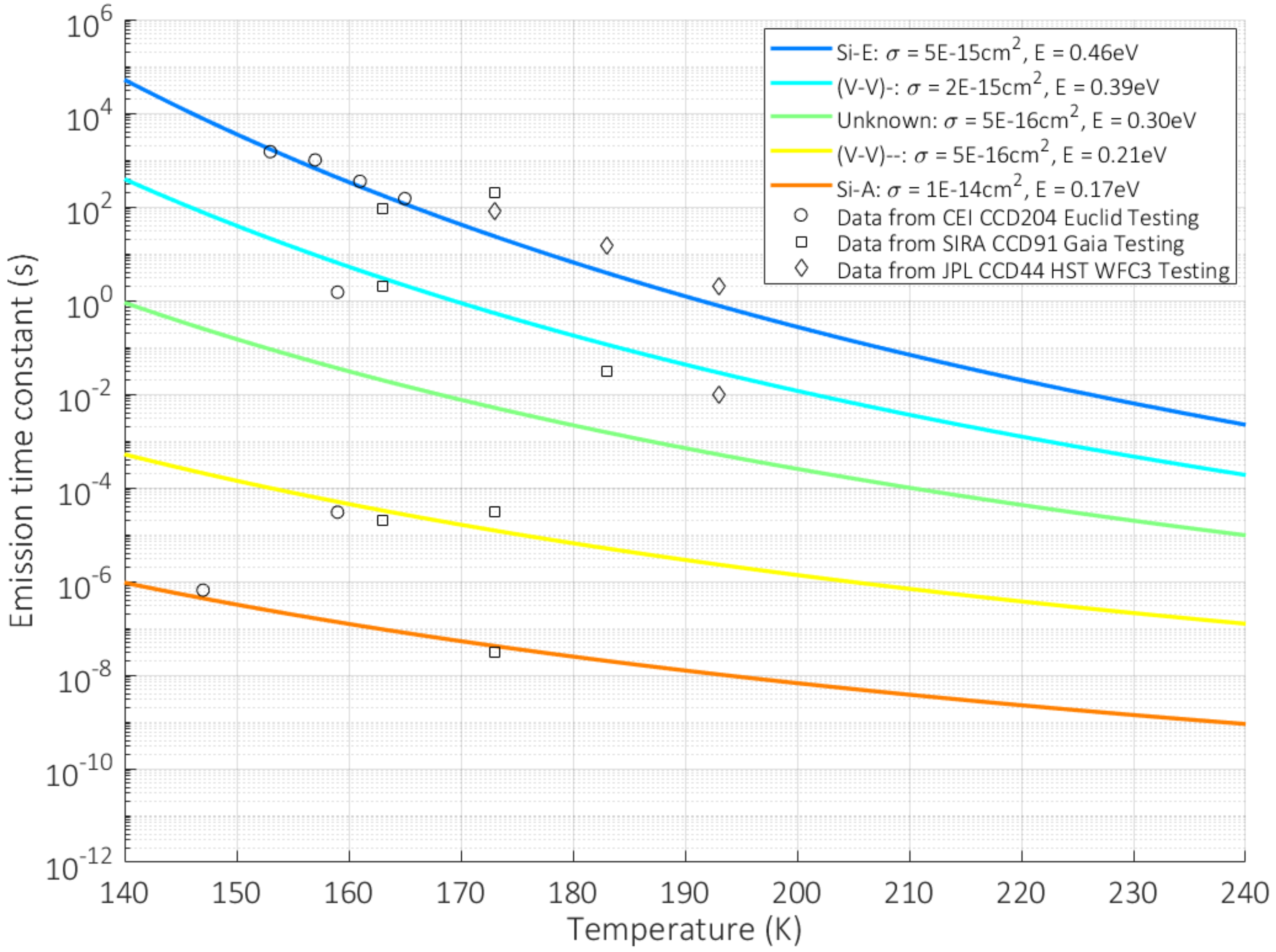
Background oxygen concentration in starting silicon is high, leading to high concentration of Si-A following irradiation.

$\tau_e \approx 10^{-7}$ s at 160 K

Lattice view



Knowledge of defect properties

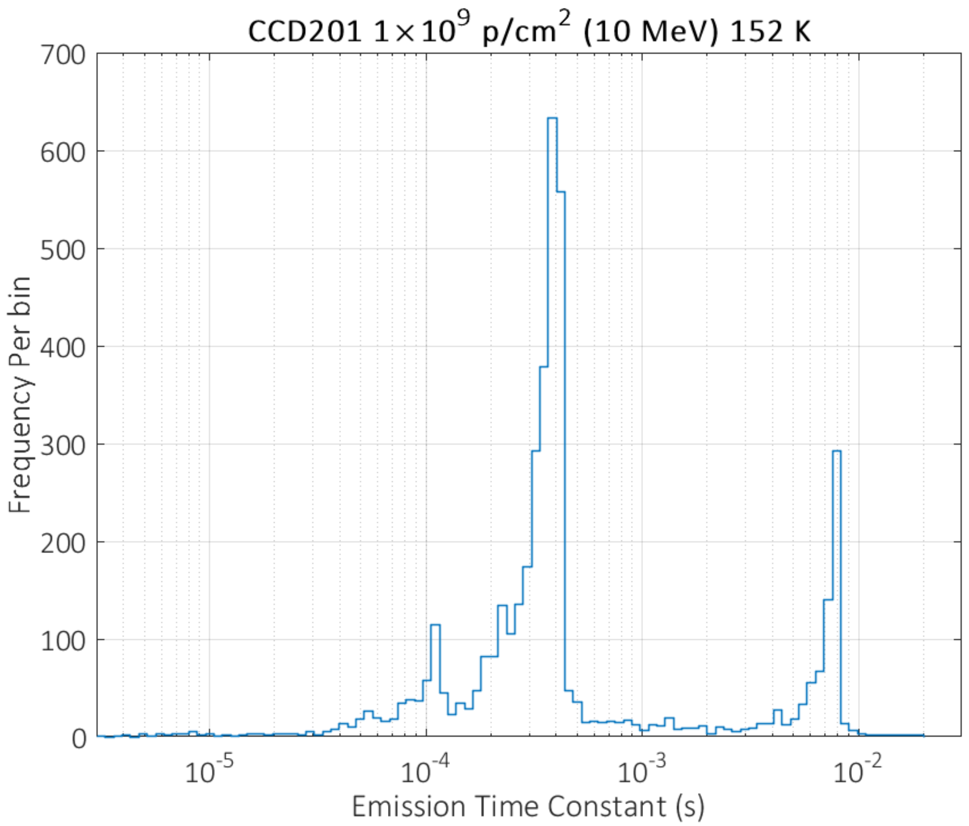


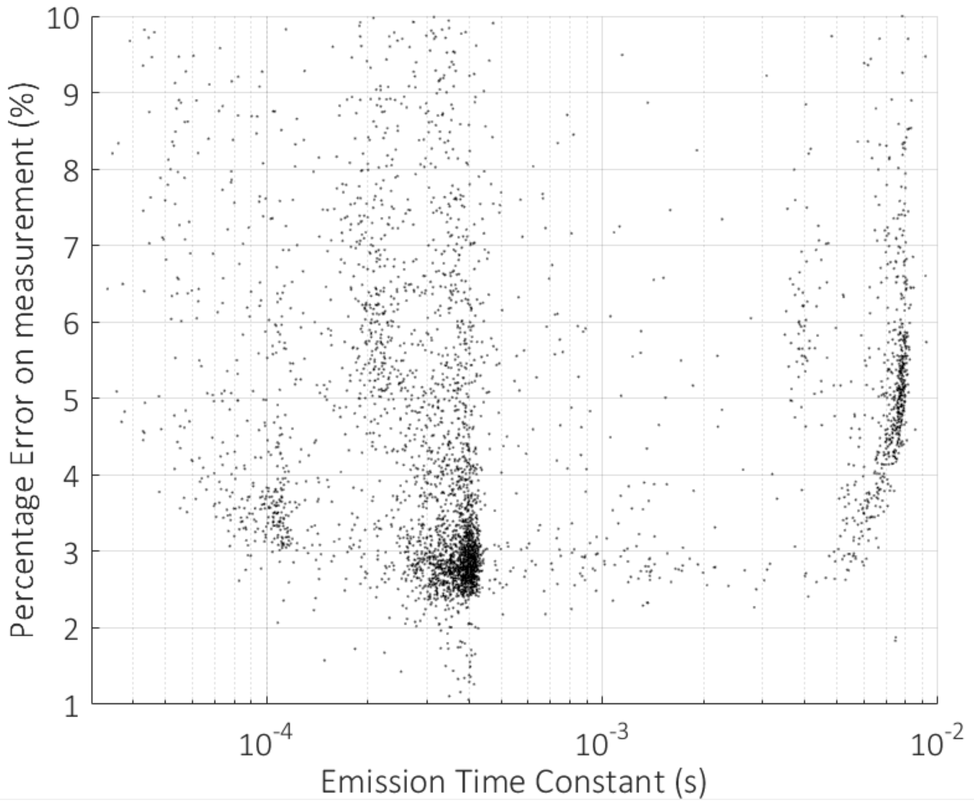
- Reasonable scatter in literature data, because extracting the properties of traps is hard!
  - Multiple trap species typically contribute to a single measurement.
  - Parallel and serial charge transfer effects are hard to separate.
  - Differences in signal distribution distort charge tails, including "re-capture" effects.
  - Electronic effects can influence the apparent shape of the tail.

With thanks to David Burt of Teledyne-e2v for providing this data

Extracting Defect Properties: Trap pumping

- For accurate CTI mitigation for the CGI, we need higher accuracy.
- “Trap pumping” provides the opportunity for the **characterisation of individual defects** to very high accuracy, giving τ_e for each individual trap.

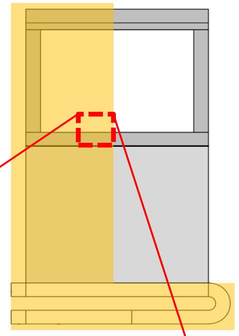




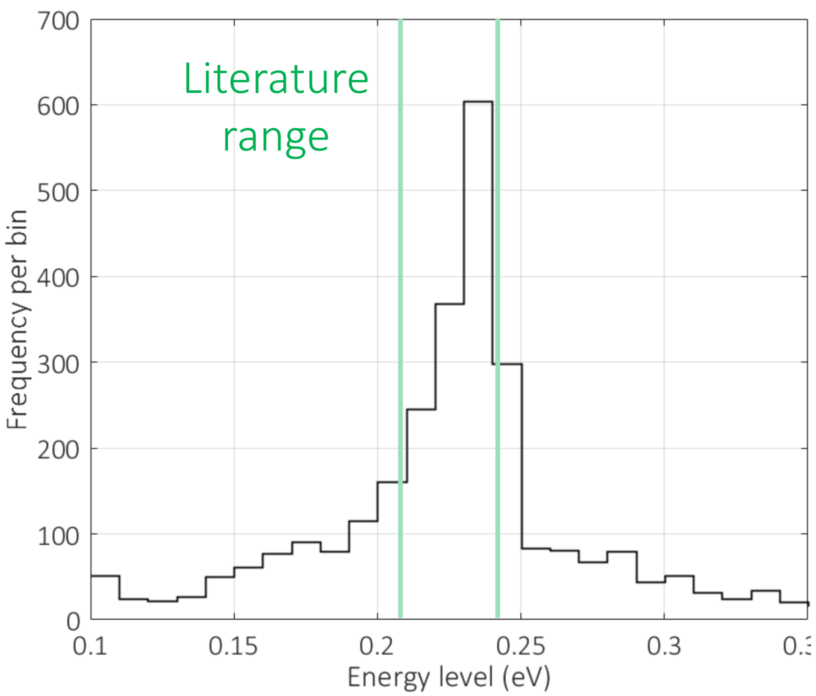
Extracting Defect Properties: Trap pumping

- In addition, the technique can provide energy levels, cross sections and locations.
- Related talk: “*Trap pumping Method: Importance of charge capture in interphase regions*” Jesper Skottfelt 14:40

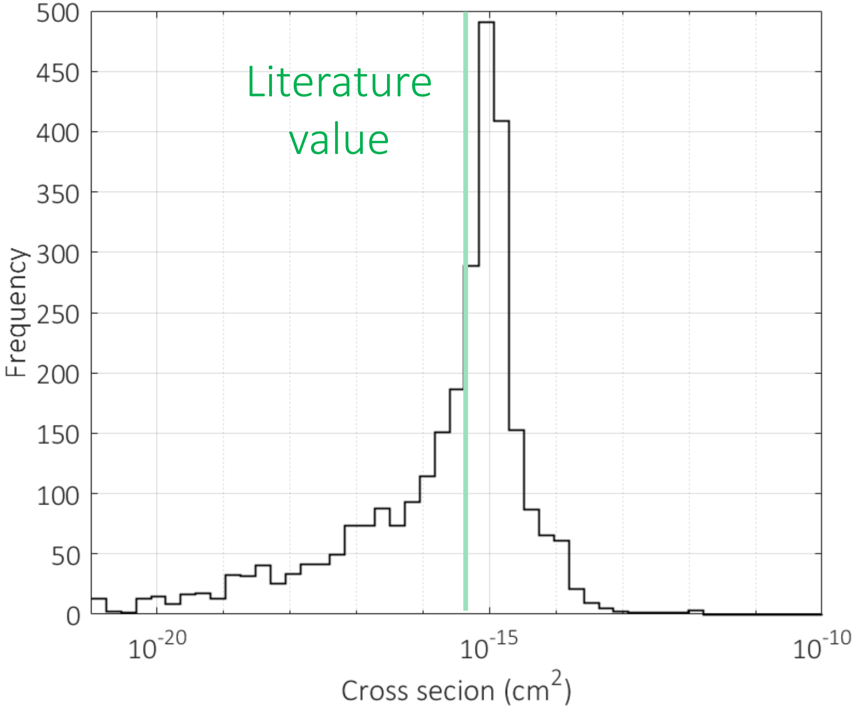
CCD201-20
Irradiated to
1.0×10^{9} p/cm^2



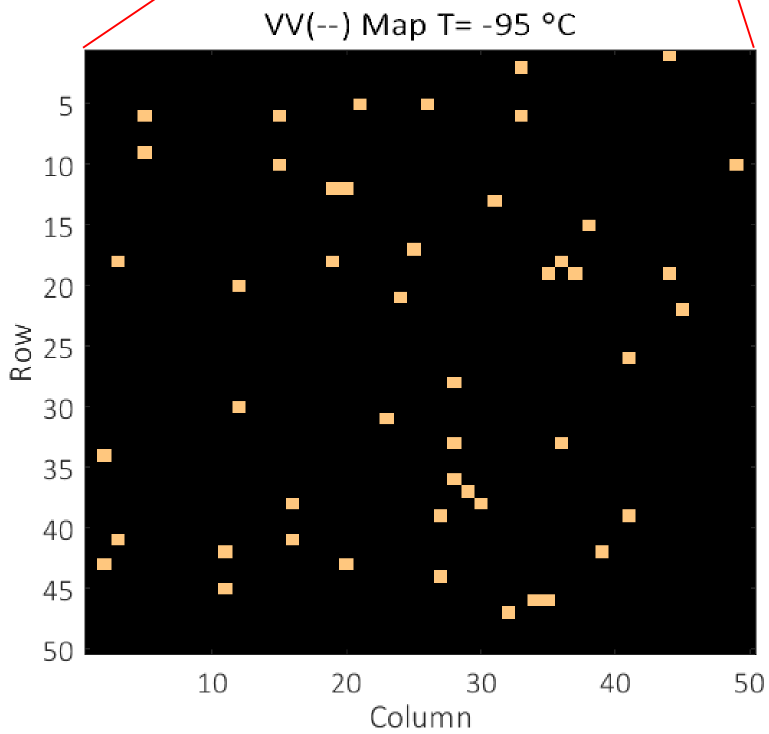
Energy Levels (VV^{--})



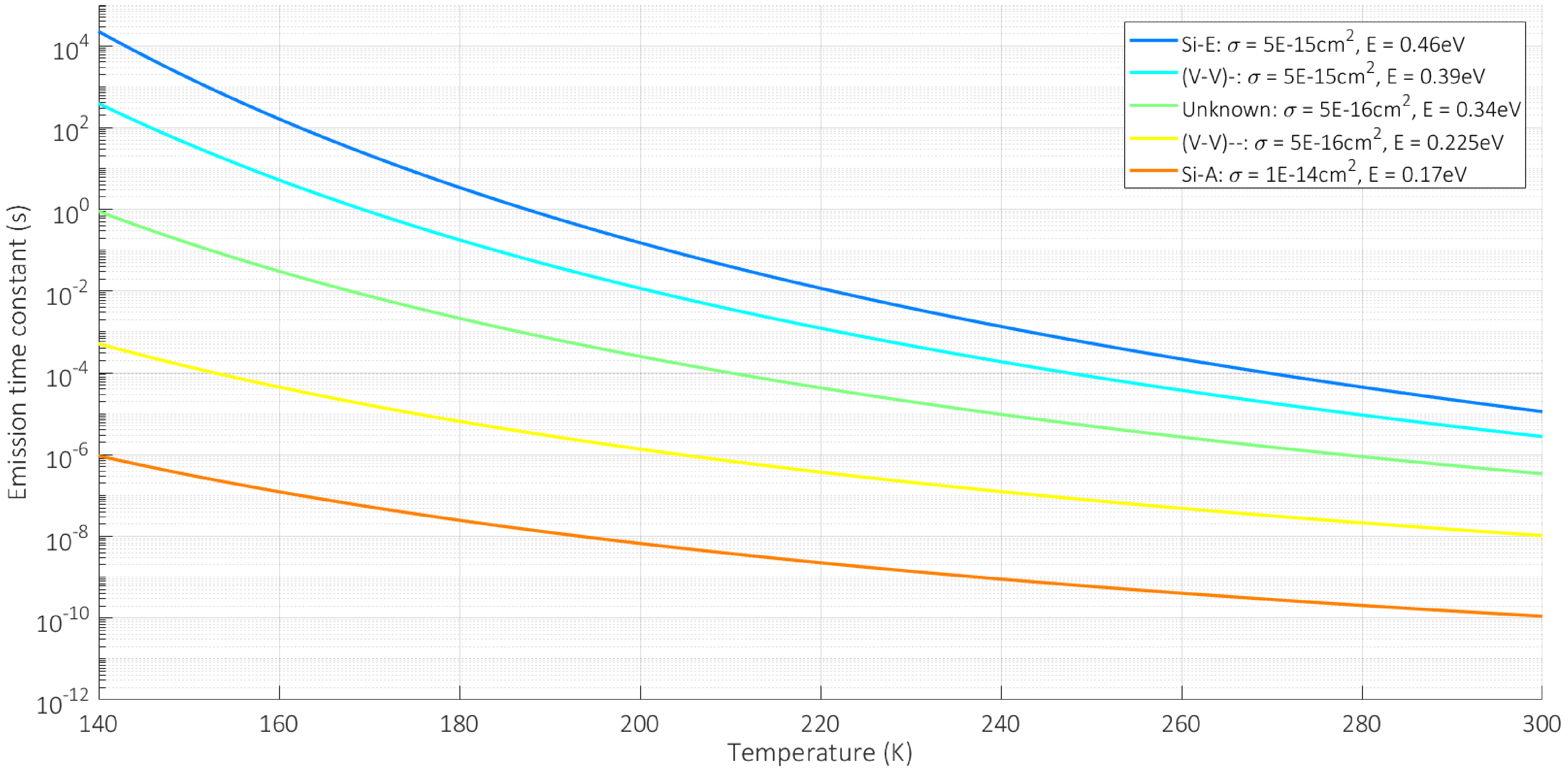
Cross sections (VV^{--})



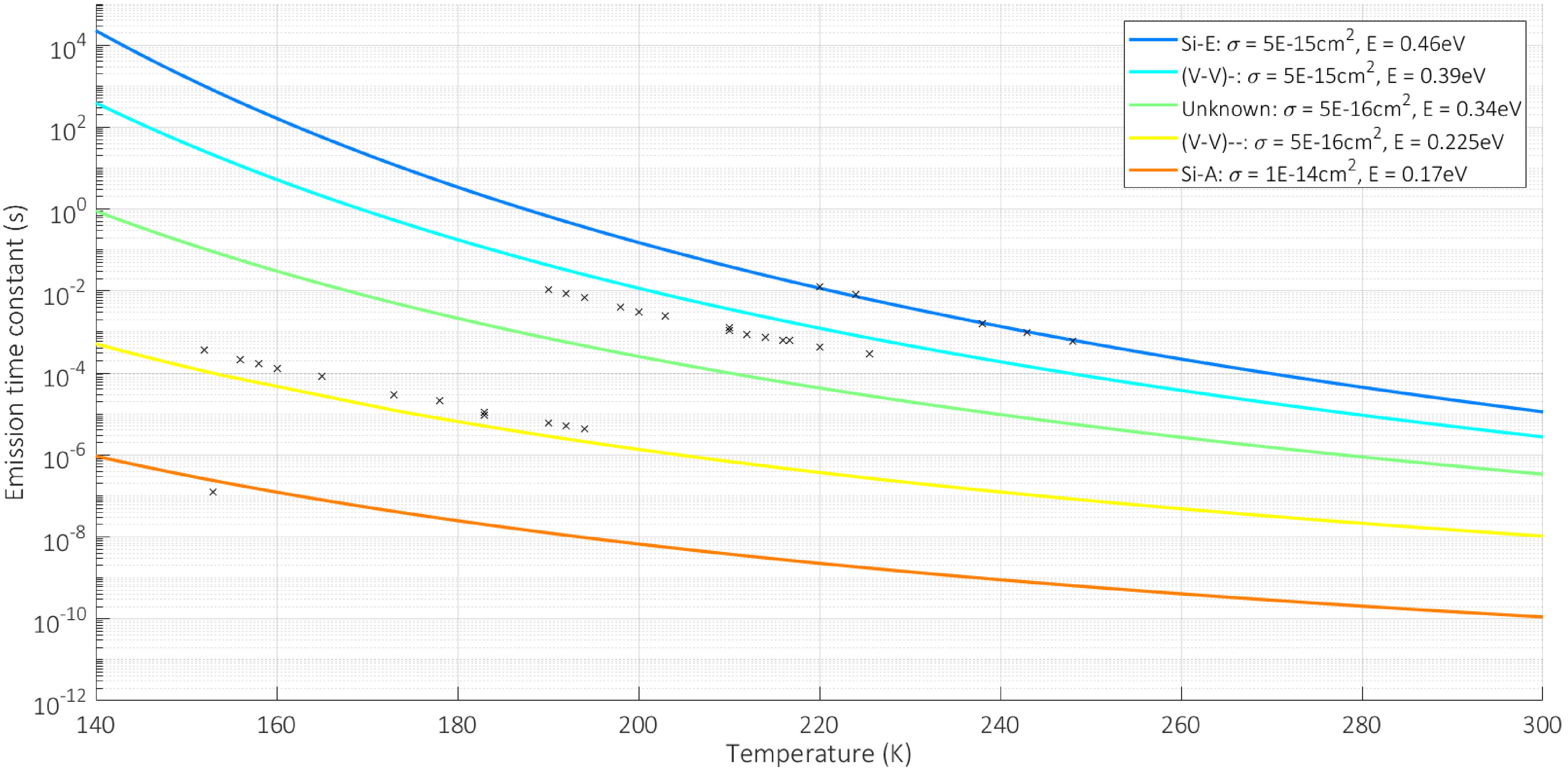
Locations



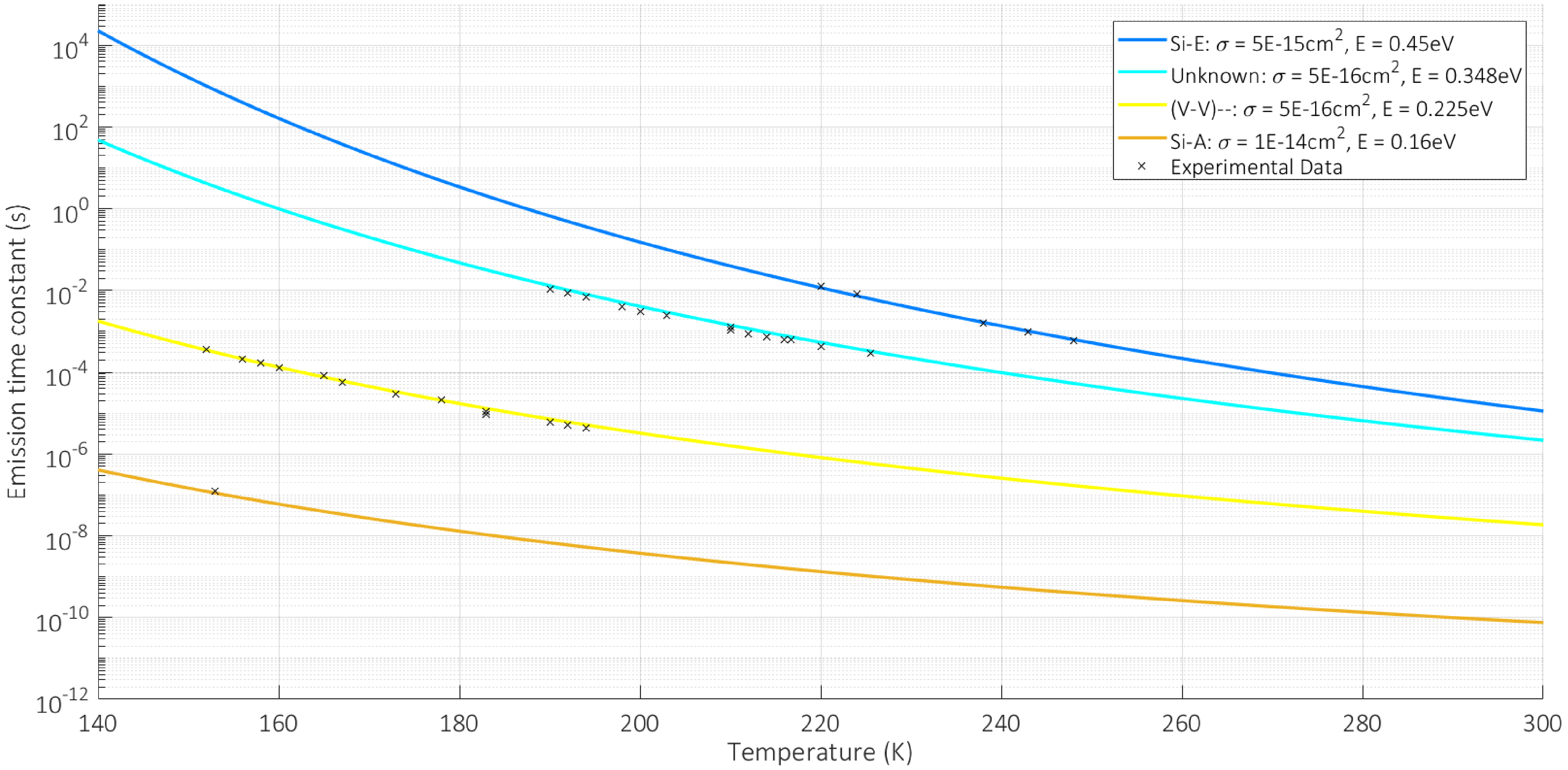
Data Obtained



Data Obtained

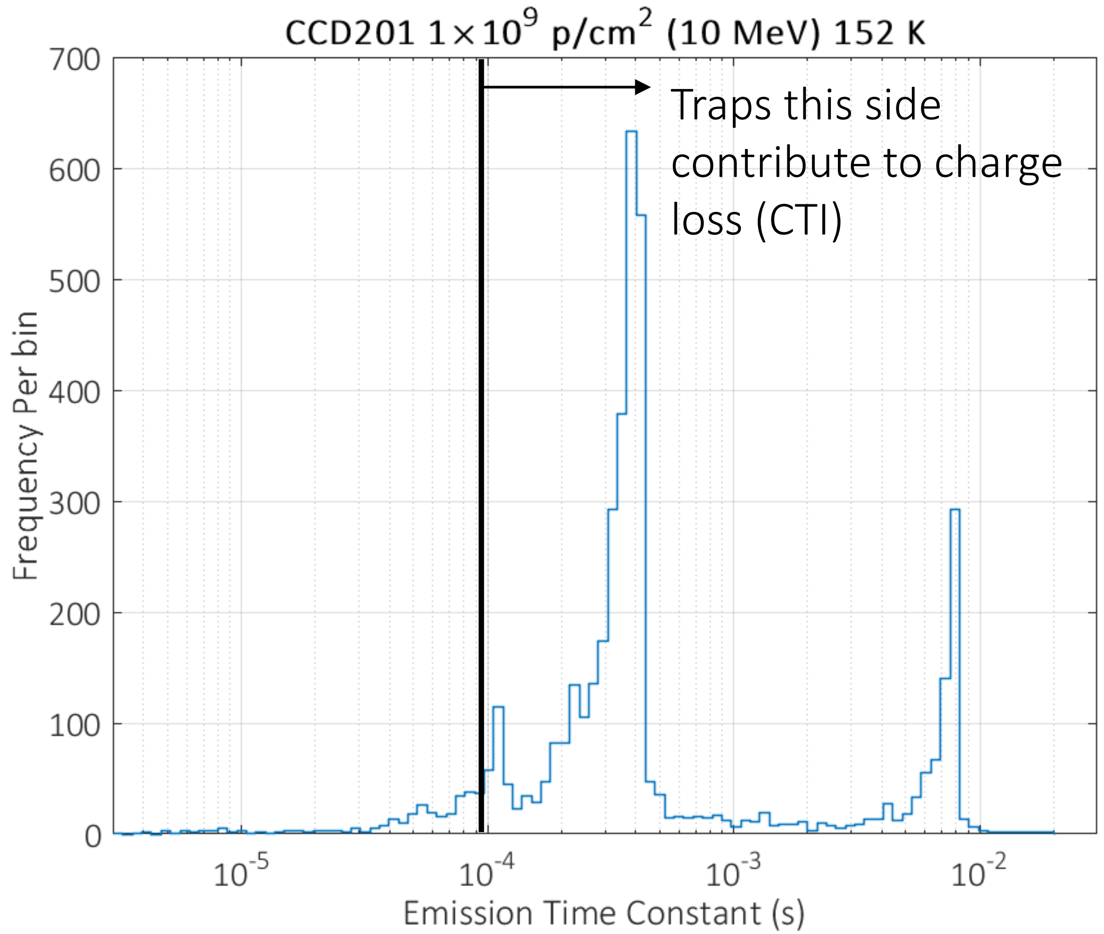


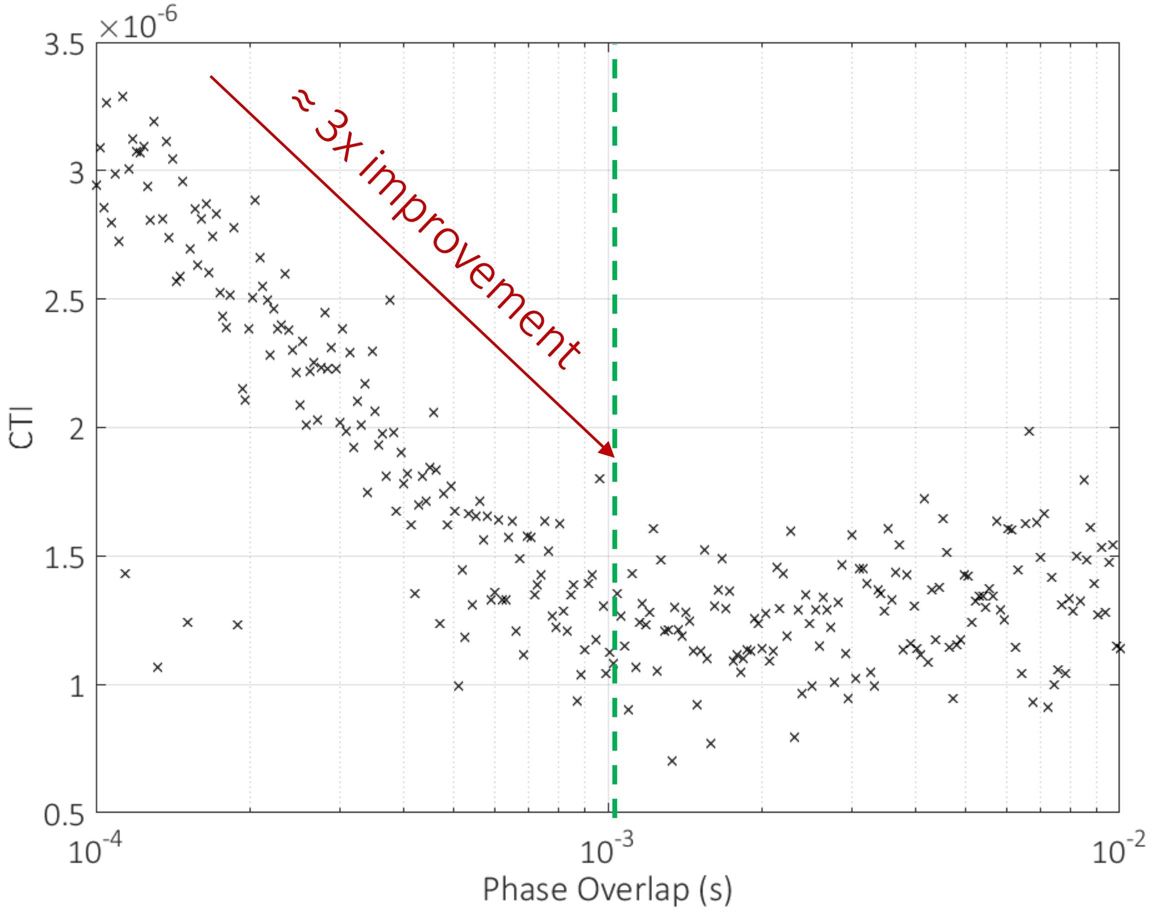
Our "new picture" of known traps



Applying the results: CTI optimisation

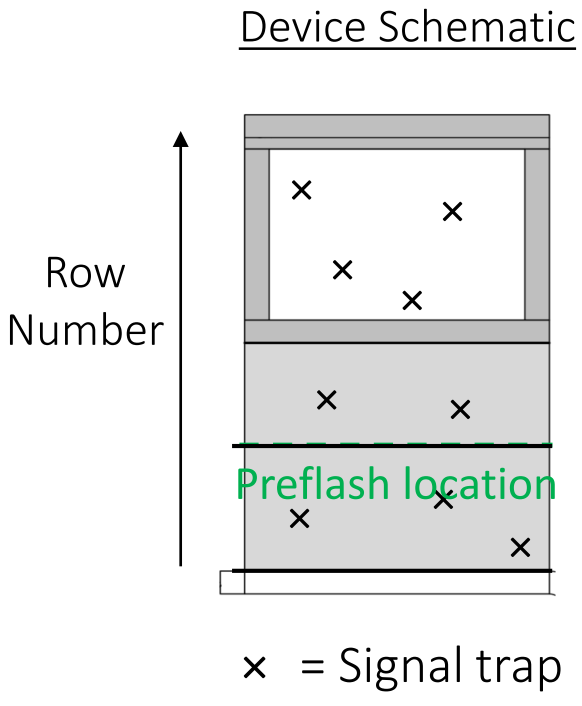
- E.g. against the VV⁻ at 152 K; the phase time is increased so that the maximum amount of charge can re-join the signal packet. The improvement in CTI correlates with the trap-pumping results.

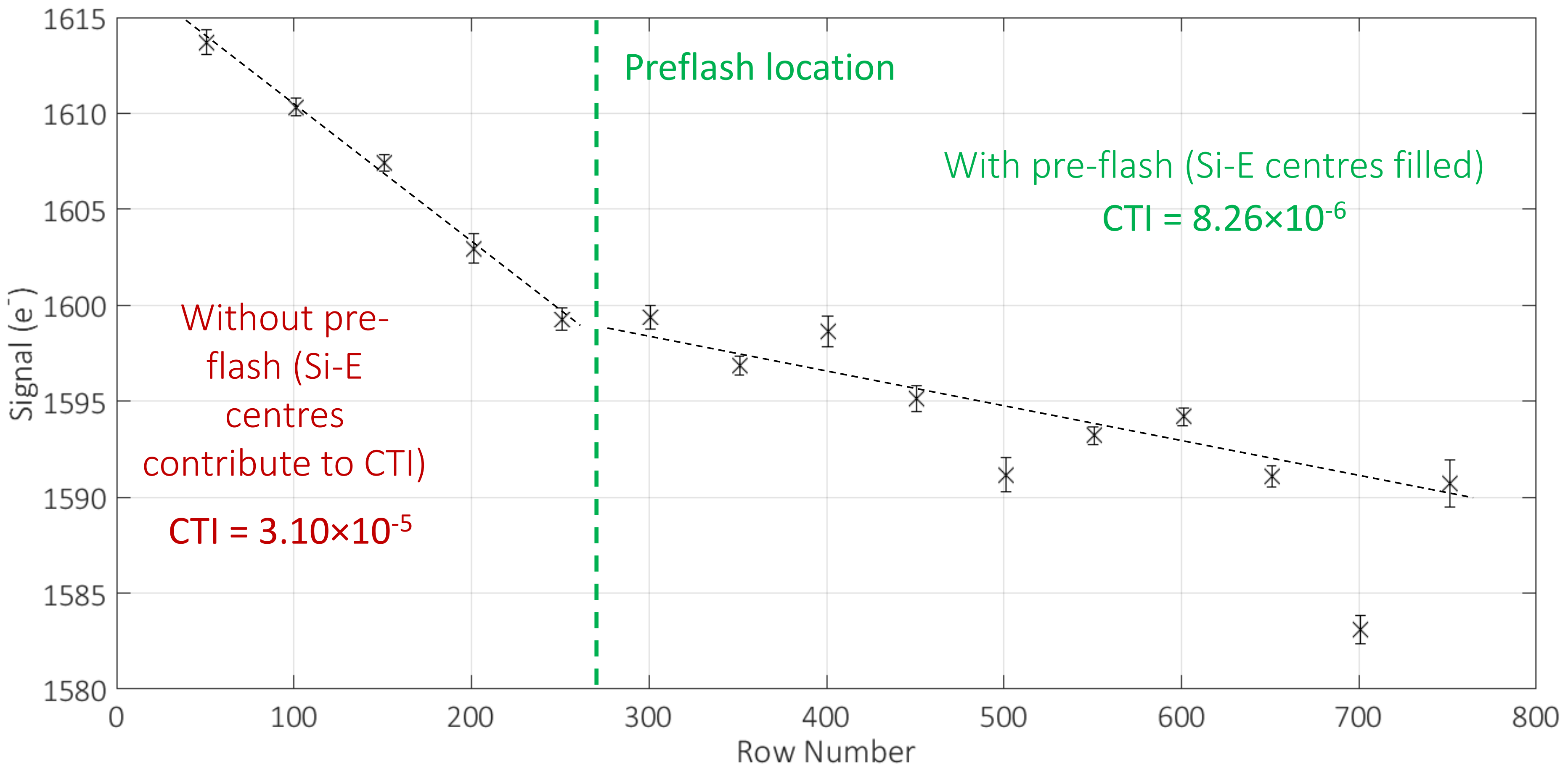




Applying the results: CTI optimisation

- E.g. against the Si-E at 165 K. An optical pre-flash keeps these traps filled for the duration of frame readout. According to the trap pumping results; the pre-flash should be repeated every 30s at this temperature to keep traps filled. After 200s, over 99% will have emptied - the impact on CTI is greatest for long integration time and low flux.

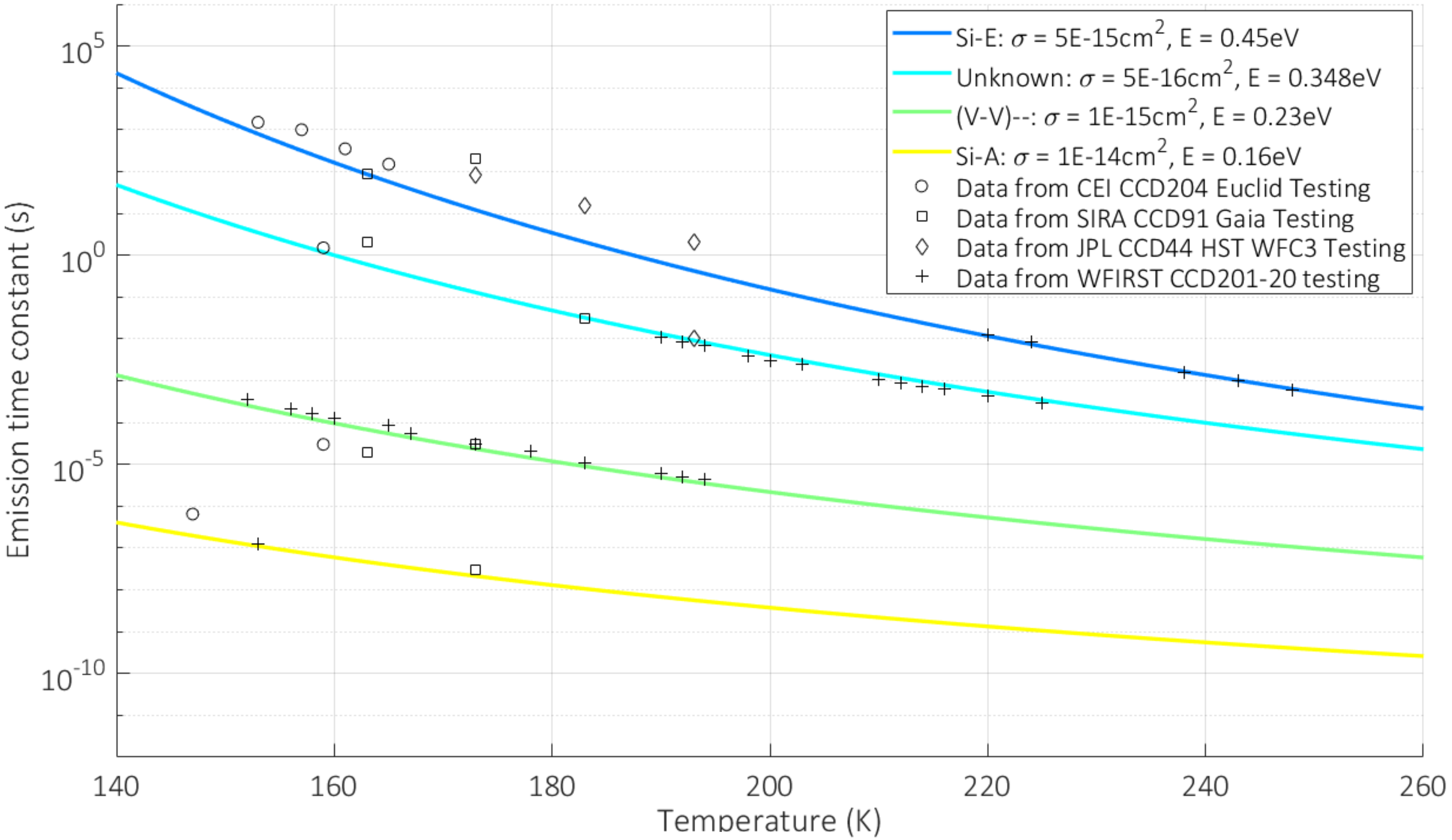




Implications of the results

- The results from this campaign show good consistency with those from past investigations on other devices.

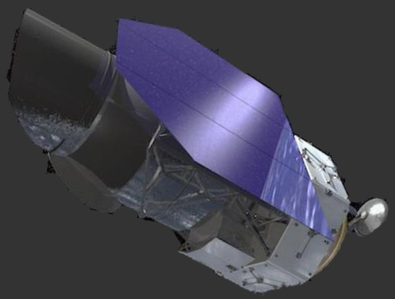
- The same four primary defects appear in each investigation at similar locations.



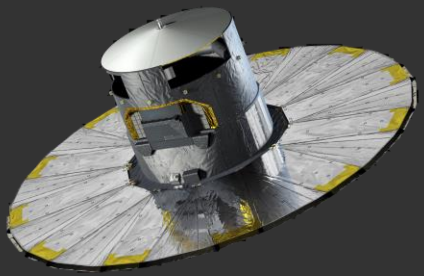
Outlook

- So far, the results are consistent with those obtained from a wide variety of Teledyne-e2v CCDs for use on large scale space missions, **but with much higher accuracy due to the trap-pumping technique.**
- **The results will be instrumental for CTI mitigation for the Coronagraph and help maximise the photon yield.**
- The results may be useful for CTI mitigation and correction for current and future observatories, through refined information on the defect landscape following exposure to irradiation.

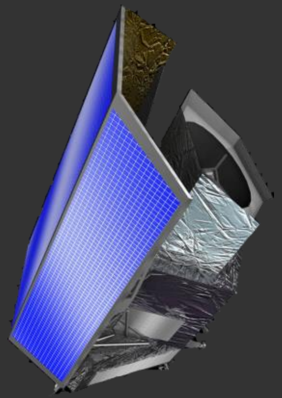
WFIRST: CCD201-20



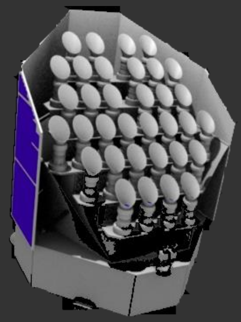
Gaia: CCD91



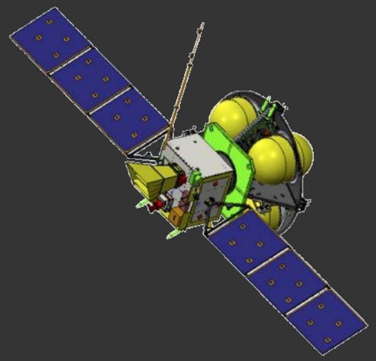
Euclid: CCD273



PLATO: CCD270



SMILE: CCD270 variant



Questions

Special thanks to the CEI, JPL & Teledyne e2v teams who have supported this work.

Related talk:
"Trap pumping Method: Importance of charge capture in interphase regions" Jesper Skottfelt 14:40

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