L2 at Solar Maximum: Radiation Damage in the Euclid Space Telescope

8th Radiation Damage Workshop
14th of May 2025

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In collaboration with Richard Massey, Gavin Leroy, Matt Wander, James Nightingale, et al.

Durham University

Institute for Computational Cosmology

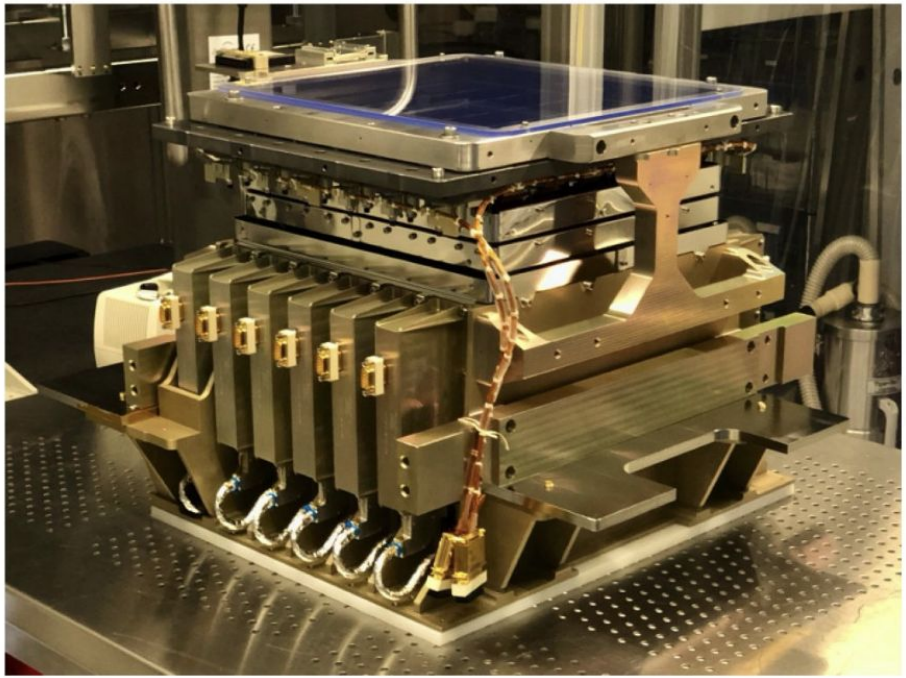
Durham Centre for Extragalactic Astronomy

Euclid consortium

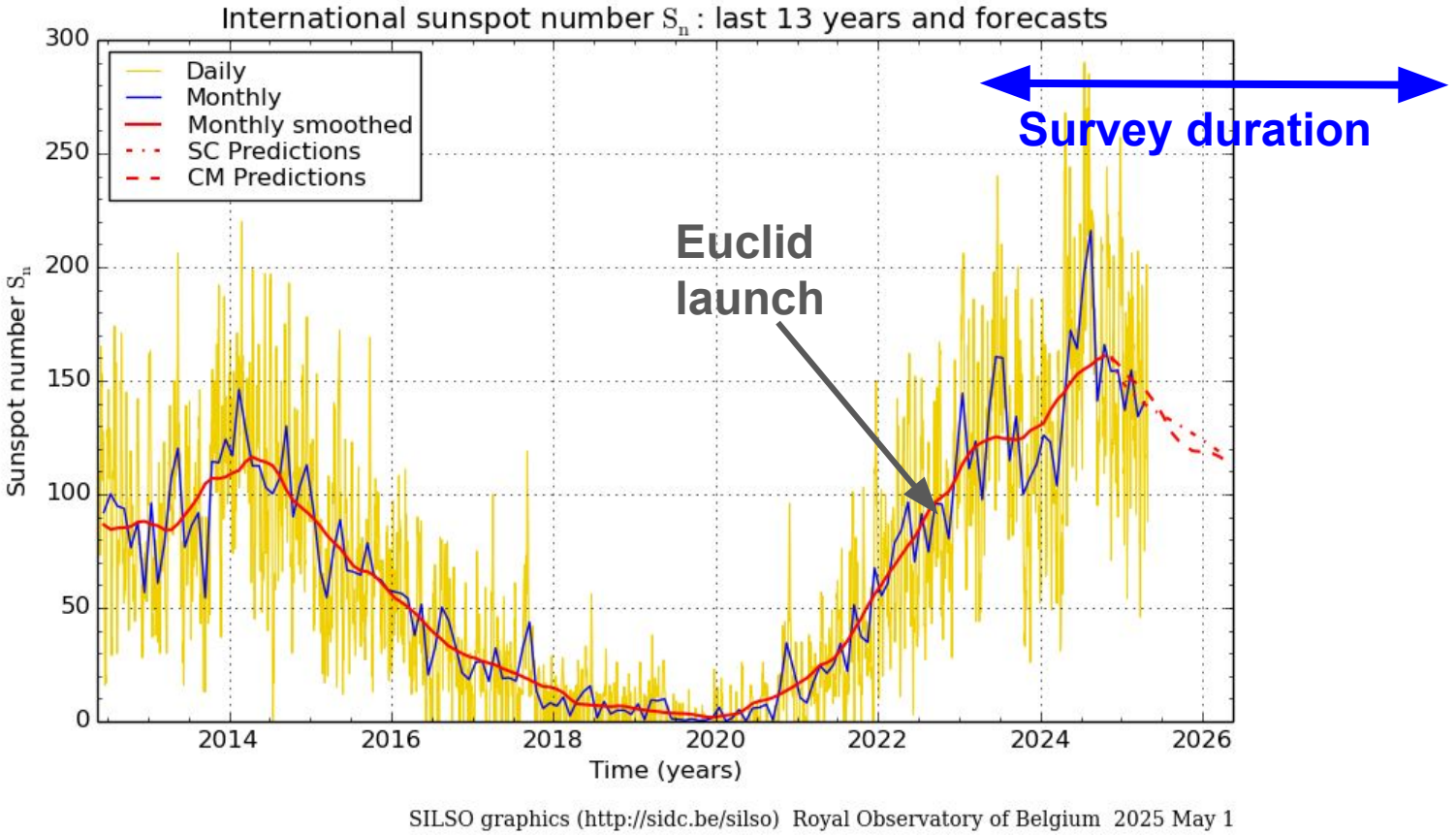
UK SPACE AGENCY

Euclid

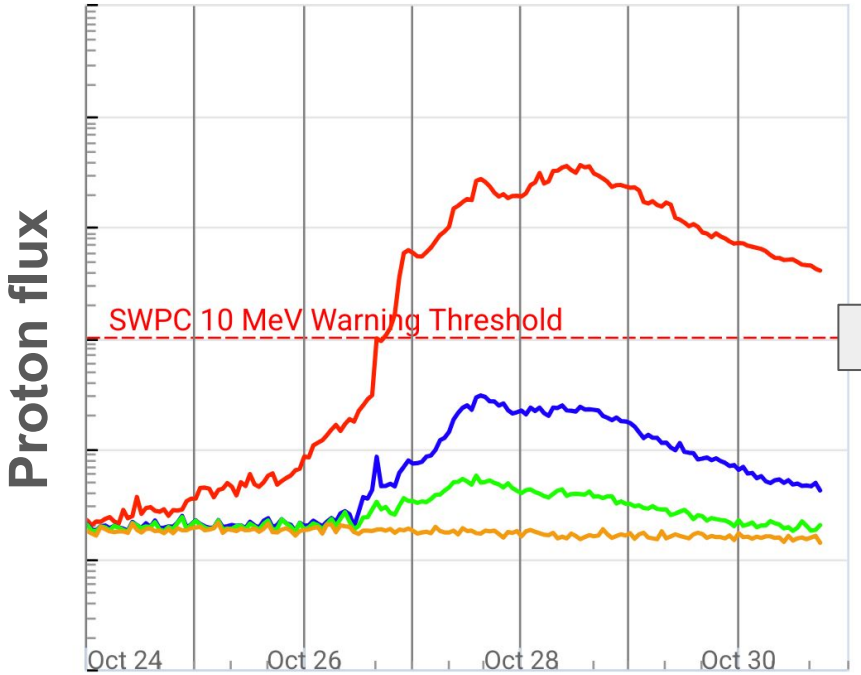
VIS instrument



Solar Activity



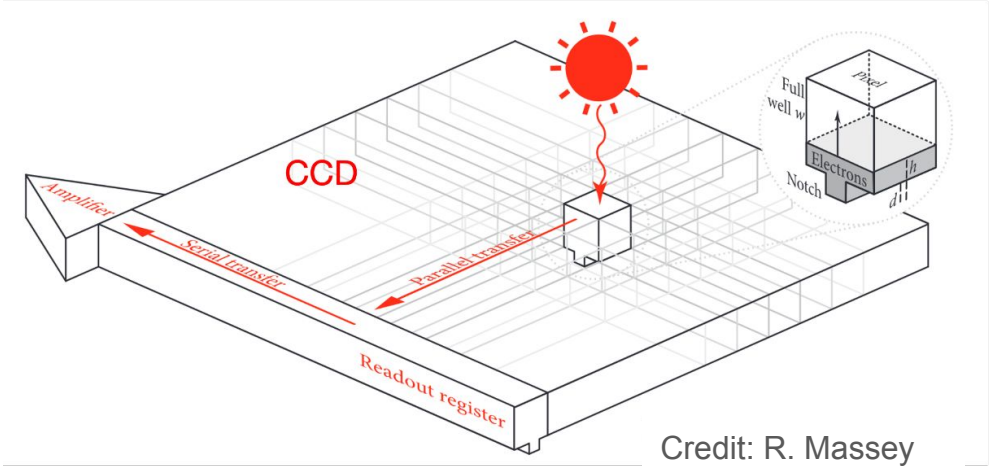
Solar Activity



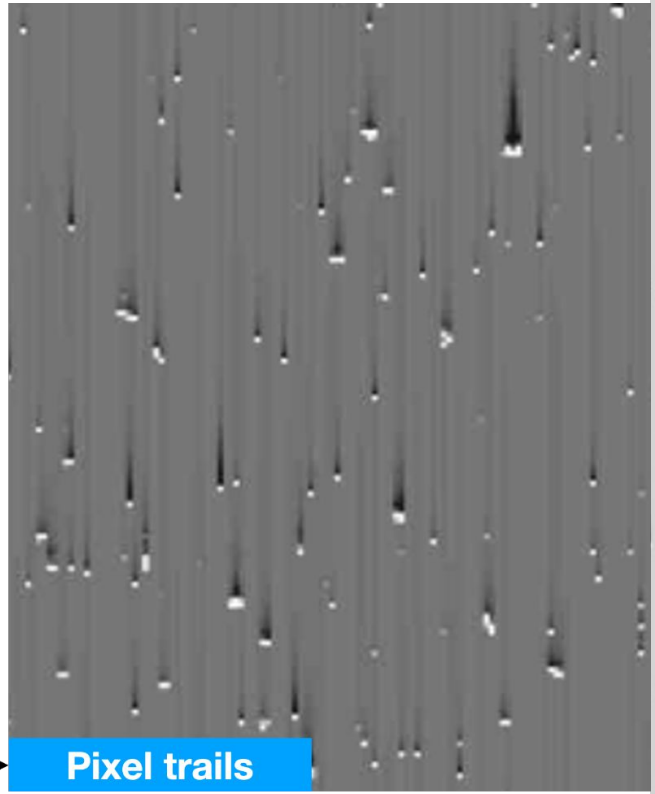
VIS images

Not to be shared outside consortium

Charge Transfer Inefficiency (CTI)



Credit: R. Massey



Impurities in the silicon lattice

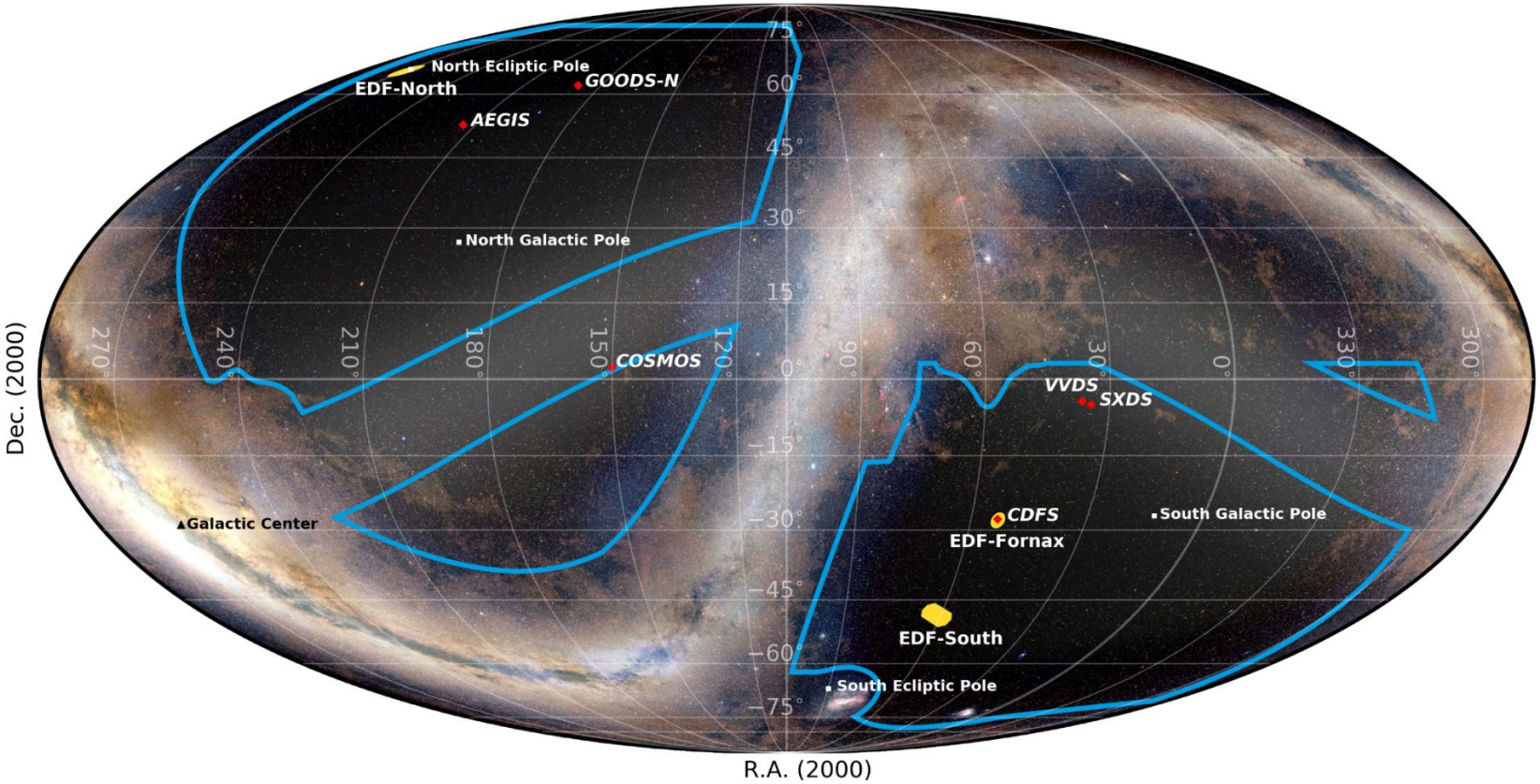
(Solar) radiation damage

Charge traps

Pixel trails

Charge Transfer Inefficiency (CTI)

Euclid Wide Survey



Euclid Wide Survey: Science

Euclid main science

- Weak gravitational lensing
- Galaxy clustering

Requires accurate

- Galaxy shapes
- Galaxy positions
- Galaxy redshifts

Euclid legacy science

- Strong lensing
- Active Galactic Nuclei
- Galaxy evolution
- Transients
- Exoplanets

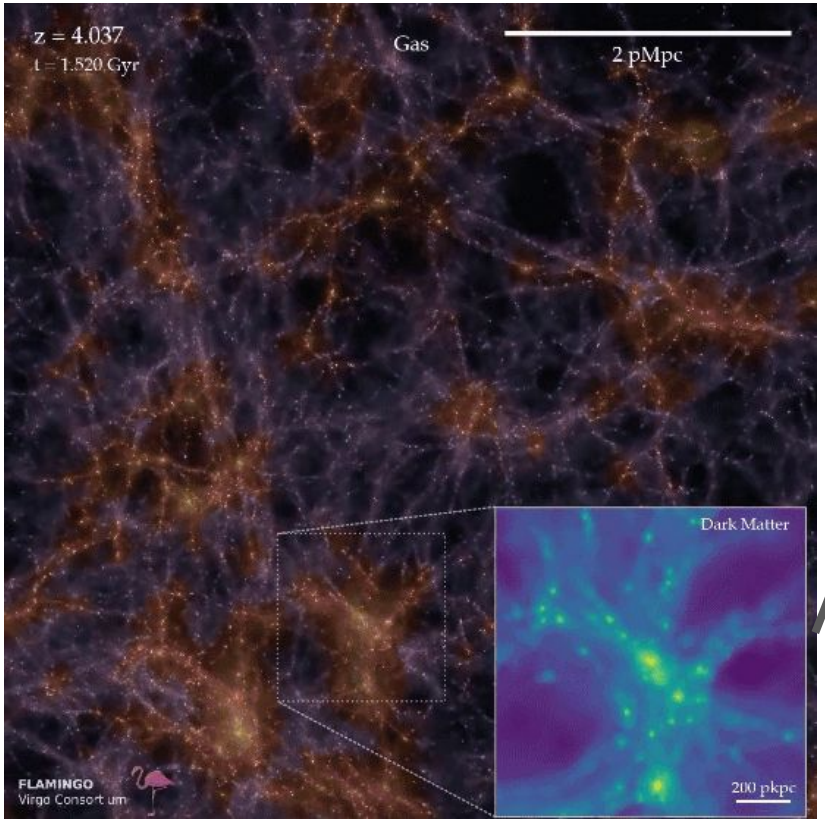
  etc.

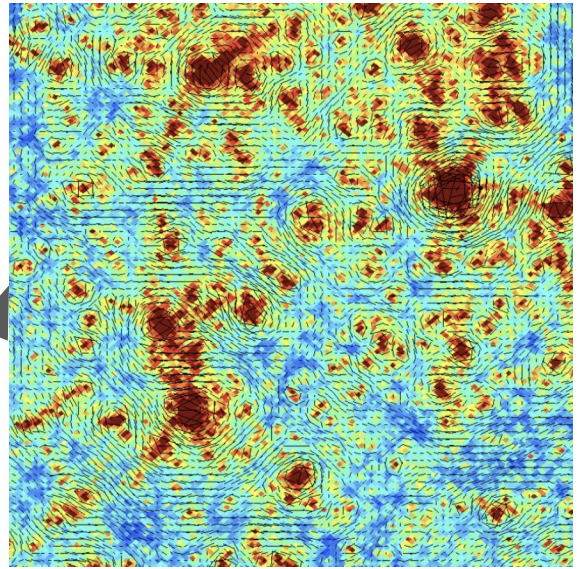
Requires accurate

- Photometry
- Astrometry

  etc.

Gravitational lensing

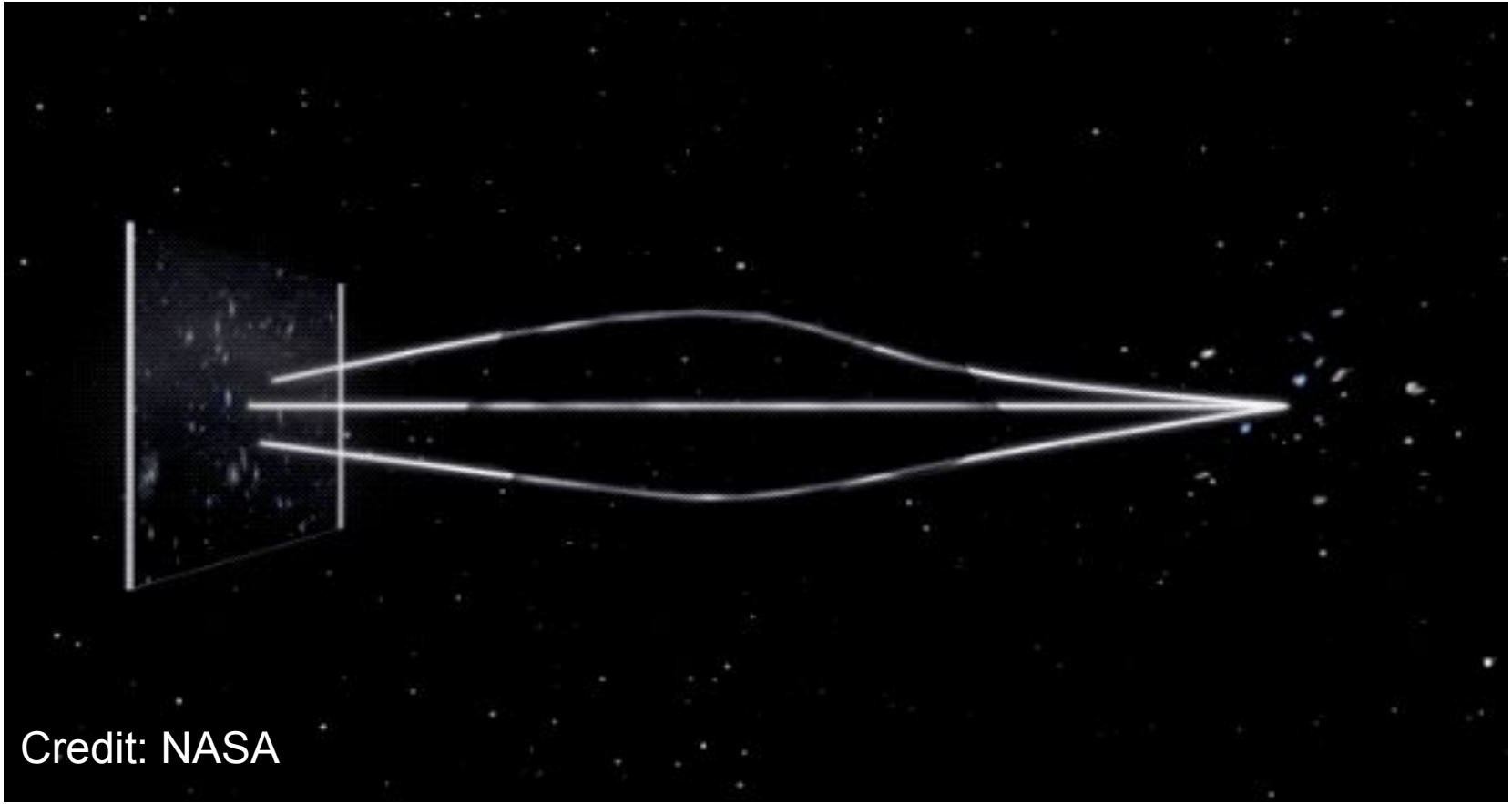




Probes the nature of:

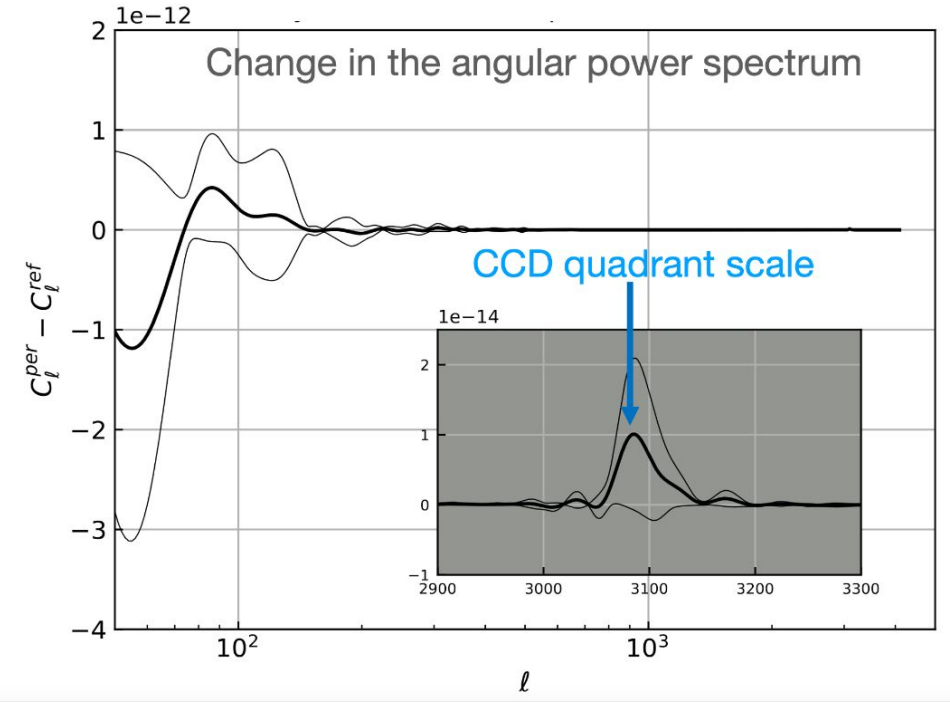
- Dark matter
- Dark energy
- Gravity

Gravitational lensing



Credit: NASA

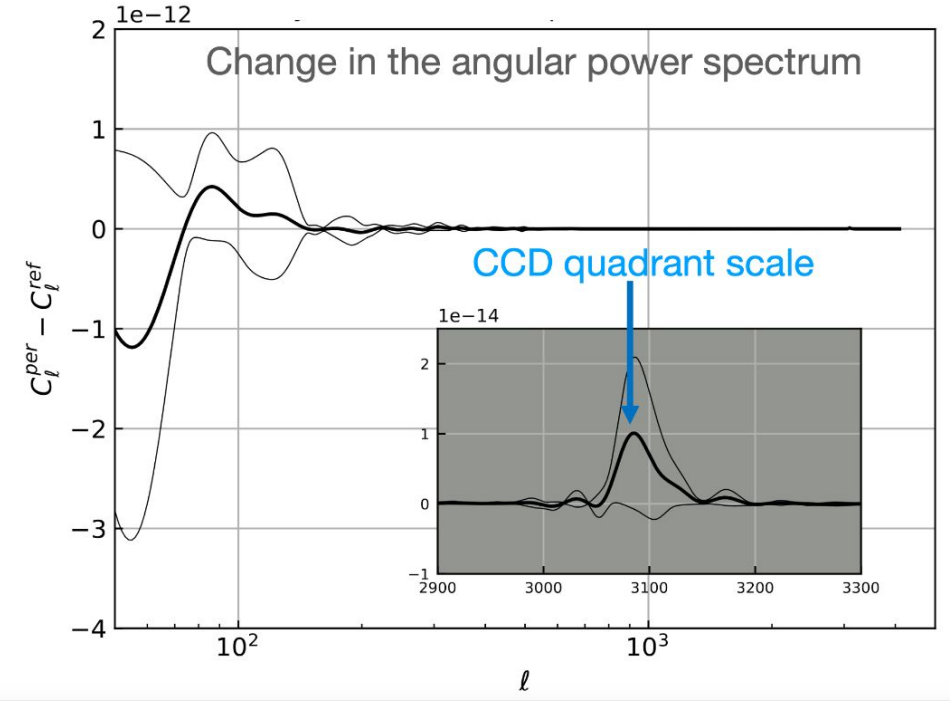
Why is CTI important?



Paykari et al. 2019

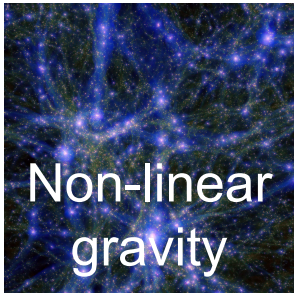
As CTI distorts galaxy shapes, additional “structure” appears at CCD scales.

Why is CTI important?



Paykari et al. 2019

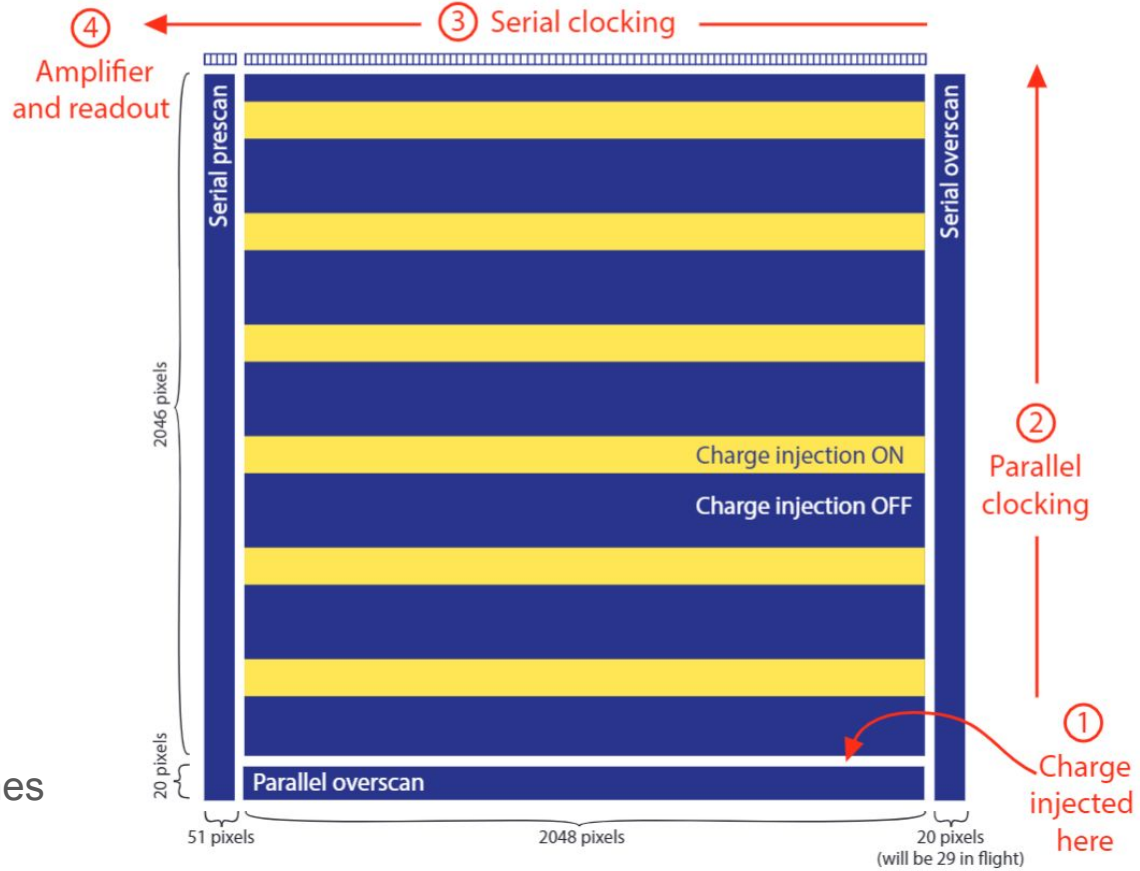
At these scales, other physically interesting effects may be detected:



\+ **other systematics**

Data: Charge Injection Frames

For a given quadrant out of 144:



Credit: James Nightingale

Data: Charge Injection Frames

8 charge injection line (CIL) images are taken daily during the nominal survey

Cycle through 4 groups (A, B, C, D) of sets of 8 CILs with different patterns

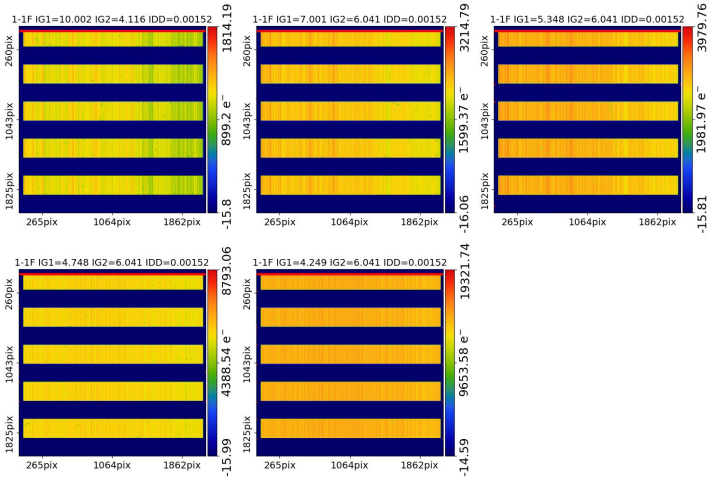
Cycle resets after 4 days

A given CTI model is calibrated on the data from a single group of up to 8 CILs

#Number	Day	Pattern	CHG_INJ_ON	CHG_INJ_OFF	ID_Delay [ms]	IG1 [V]	IG2 [V]	IG2-IG1 [V]	30us_DWELL(CHINJ_RoDly)
1	1	CIR3	420	100	2.5	4.25	6	1.75	on
2	1	CIR1	214	200	2.5	4.75	6	1.25	on
3	1	CIR1	214	200	2.5	6.25	6	-0.25	on
4	1	CIR1	214	200	1.5	4.25	6	1.75	on
5	1	CIR1	214	200	1.5	4.75	6	1.25	on
6	1	CIR1	214	200	1.5	7	6	-1	on
7	1	CIR1	214	200	1.5	10	**4**	-6	on
8	1	CIR1	214	200	1.5	5.35	6	0.65	on
9	2	CIR1	214	200	1.5	4.75	6	1.25	**OFF**
10	2	CIR2	260	1500	2.5	4.75	6	1.25	on
11	2	CIR2	260	1500	2.5	6.25	6	-0.25	on
12	2	CIR2	260	1500	1.5	4.25	6	1.75	on
13	2	CIR2	260	1500	1.5	4.75	6	1.25	on
14	2	CIR2	260	1500	1.5	7	6	-1	on
15	2	CIR2	260	1500	1.5	10	**4**	-6	on
16	2	CIR2	260	1500	1.5	5.35	6	0.65	on
17	3	CIR3	420	100	2.5	4.25	6	1.75	on
18	3	CIR3	420	100	2.5	4.75	6	1.25	on
19	3	CIR3	420	100	2.5	6.25	6	-0.25	on
20	3	CIR3	420	100	1.5	4.25	6	1.75	on
21	3	CIR3	420	100	1.5	4.75	6	1.25	on
22	3	CIR3	420	100	1.5	7	6	-1	on
23	3	CIR3	420	100	1.5	10	**4**	-6	on
24	3	CIR3	420	100	1.5	5.35	6	0.65	on
25	4	CIR3	420	100	2.5	4.25	6	1.75	on
26	4	CIR2	260	1500	1.5	4.25	6	1.75	**OFF**
27	4	CIR4	53	50	2.5	6.25	6	-0.25	on
28	4	CIR4	53	50	1.5	4.25	6	1.75	on
29	4	CIR4	53	50	1.5	4.75	6	1.25	on
30	4	CIR4	53	50	1.5	5.35	6	0.65	on
31	4	CIR4	53	50	1.5	7	6	-1	on
32	4	CIR4	53	50	1.5	10	**4**	-6	on

Data: Charge Injection Frames

n_{image} = up to 8 (after cleaning)

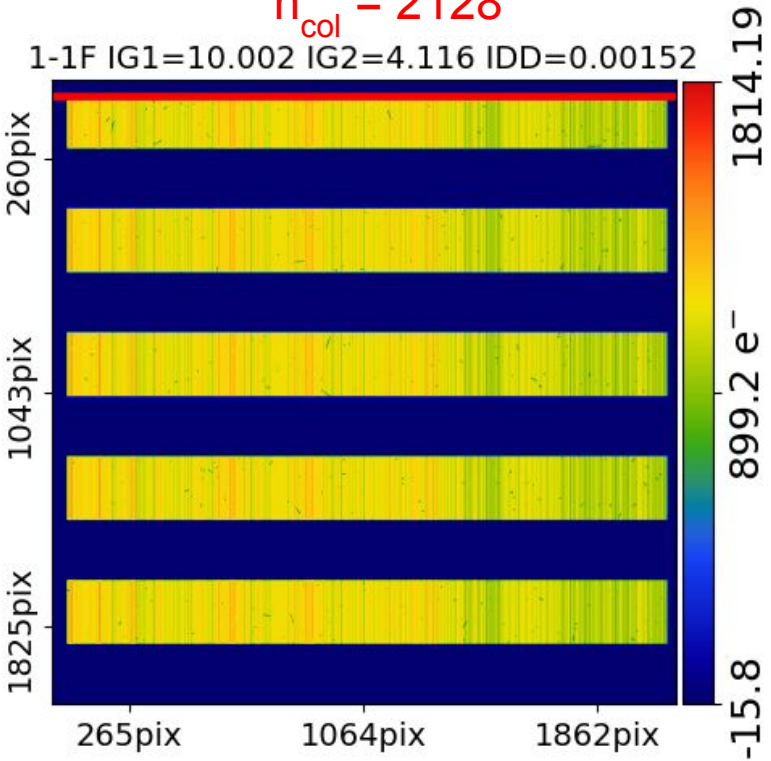


$n_{data} = n_{image} \times n_{row} \times n_{col}$

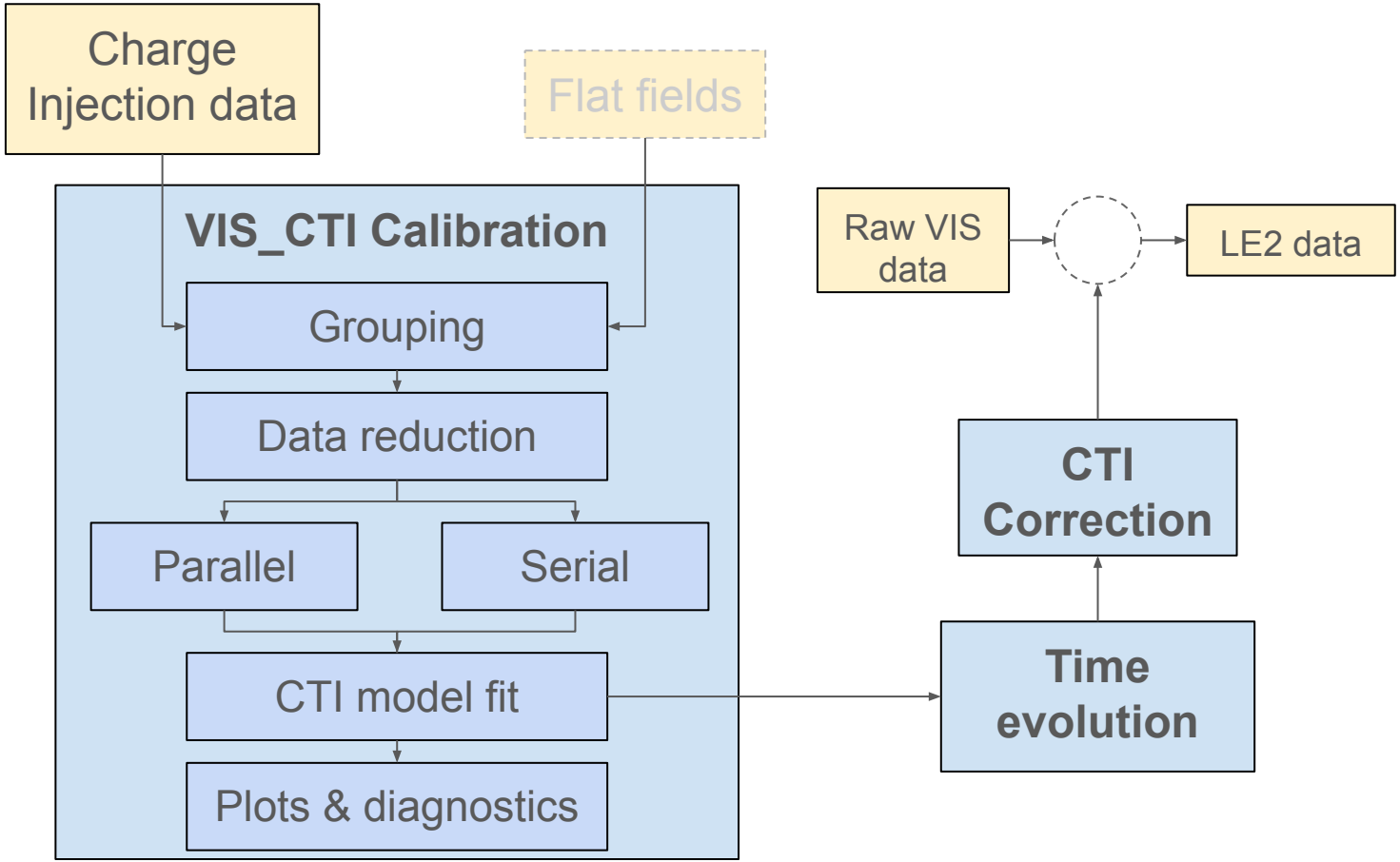
$= \text{up to } 3.55 \times 10^7 \text{ per day}$

n_{col} = 2128

n_{row} = 2086

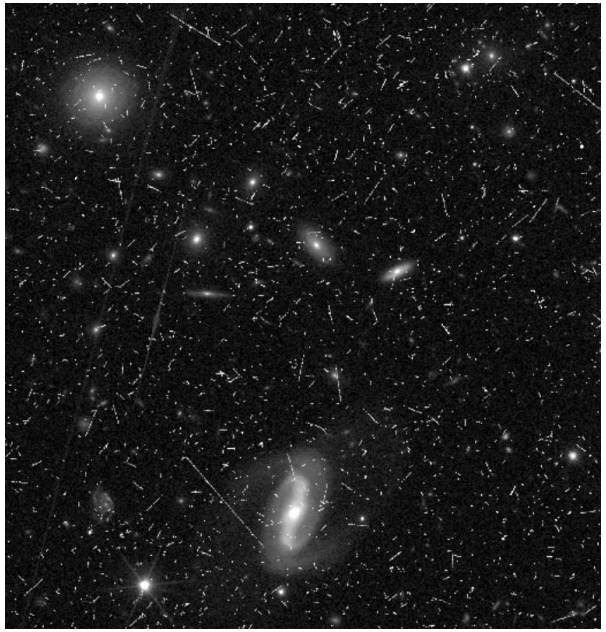


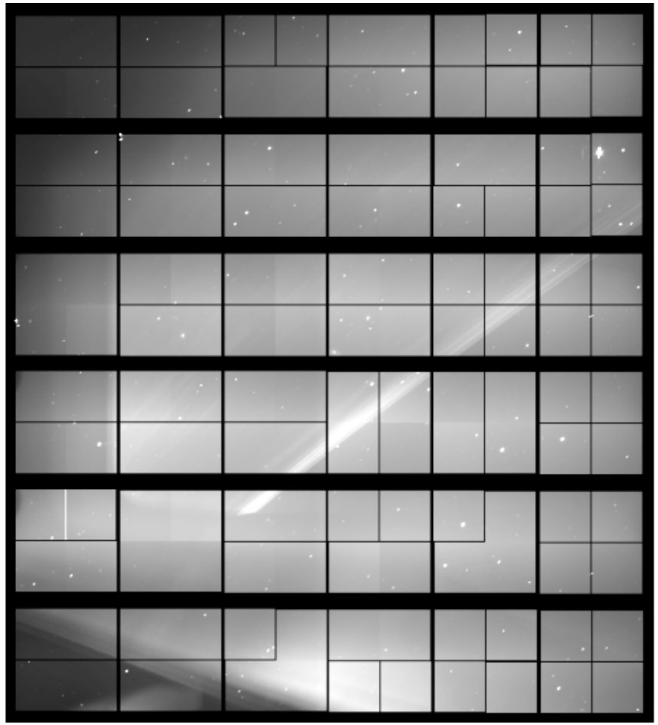
CTI Calibration Pipeline Outline



Data Preparation

- Mask cosmic rays
- Mask readout noise persistence
- Remove constant bias
- Apply stray light correction





Parallel CTI - Model

Pixel, i

Measured trail: $T_i(n_e) \equiv I(p_i) - I(p_{-i})$

Release timescales

Model with 2 trap species: $T_i = A_1 e^{-i/\tau_1} + A_2 e^{-i/\tau_2}$

Conservation of displaced charges: $\frac{A_1}{e^{1/\tau_1} - 1} + \frac{A_2}{e^{1/\tau_2} - 1} \left[= n_q \right] = \rho_q V$

Charge density

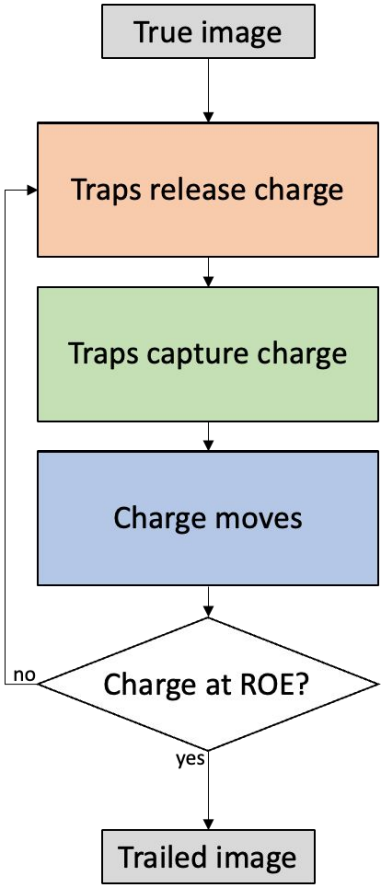
→ Fit parameters independently for each quadrant based on each CI group

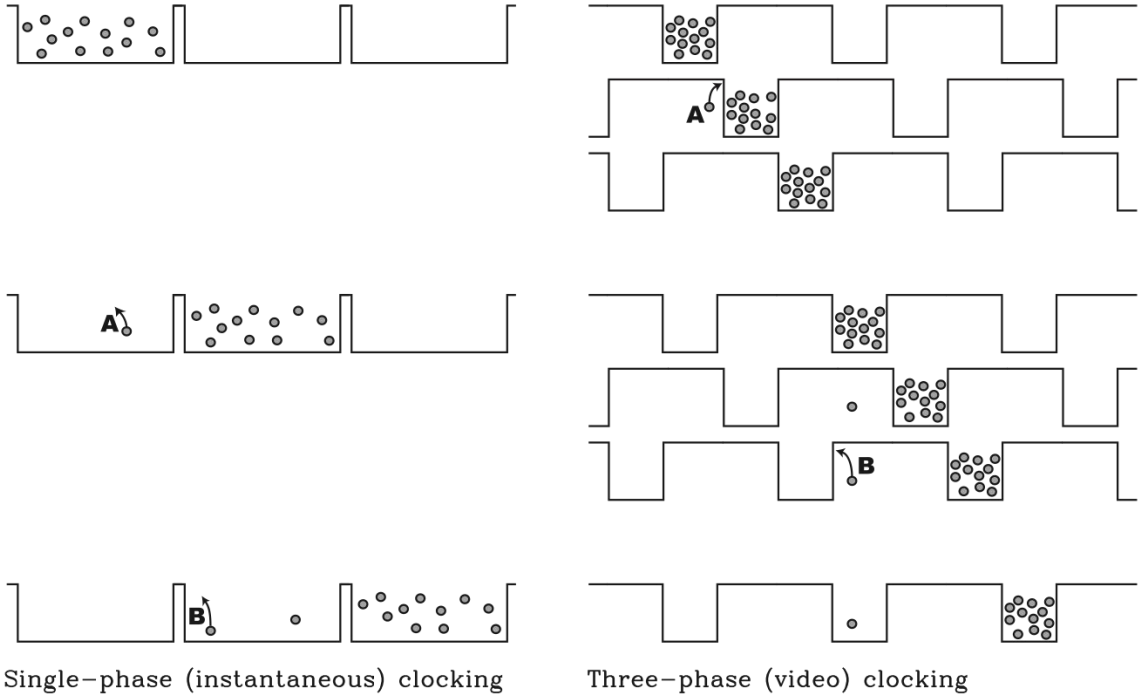
Modelled with **arCTIc**

arxiv:0909.0507

arCTIc

Runs in 0.5s

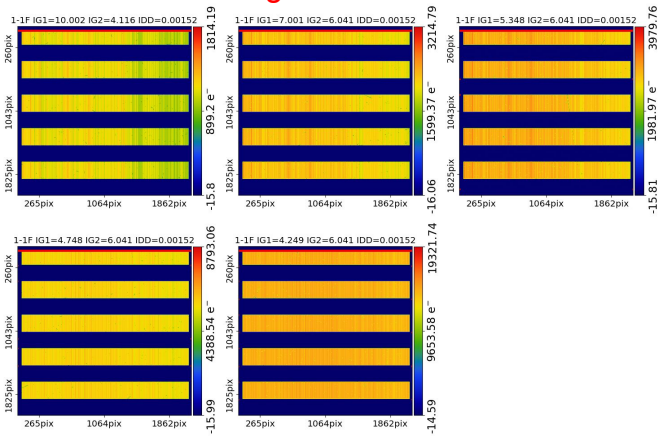




CTI Model Likelihood

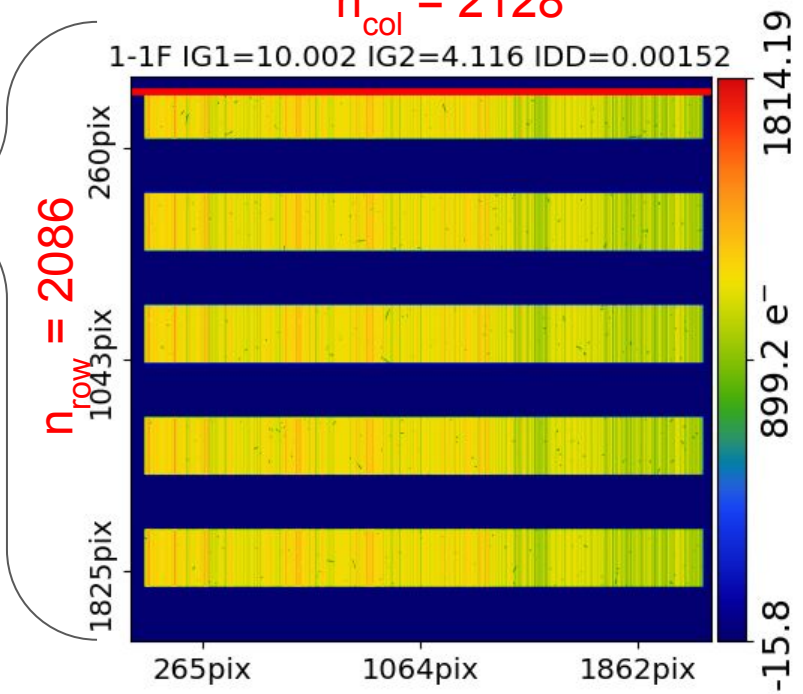
$$\ln \mathcal{L} = -\frac{1}{2} \sum_{k=1}^{n_{\text{image}}} \sum_{j=1}^{n_{\text{col}}} \sum_{i=1}^{n_{\text{row}}} \left(\left[\frac{m_{i,j,k} - t_{i,j,k}}{\sigma_{i,j,k}} \right]^2 + \ln \left[2\pi (\sigma_{i,j,k})^2 \right] \right)$$

n_{image} = 5 to 8



n_{col} = 2128

n_{row} = 2086



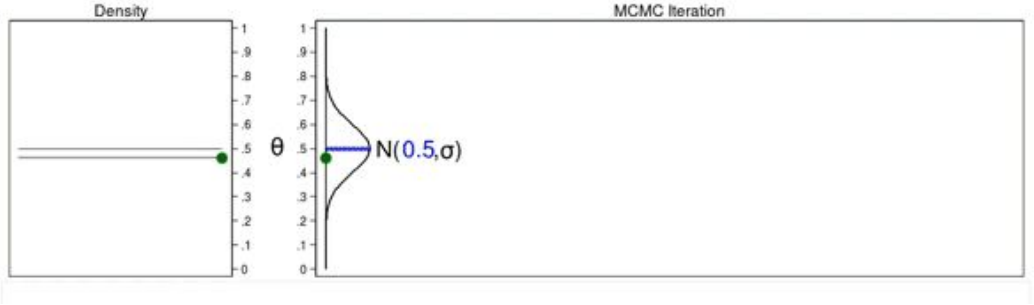
Core calculation is done in C++

CTI Model Fitting

Bayesian Algorithms

+ Robust to overfitting
+ Incorporates prior knowledge (allowing for future computational savings)
+ Handles complex likelihoods well
+ Accurate up to 30 dimensions
+ Full uncertainty quantification
  + Allows for rigorous testing
  + Allows for time evolution pipeline (reducing necessary number of calibrations)

- Slow to converge
- Resource intensive



CTI Calibration from CI

CTI Calibration from CI

CTI Calibration from CI

CTI Calibration from CI

Parallel CTI - Model independent

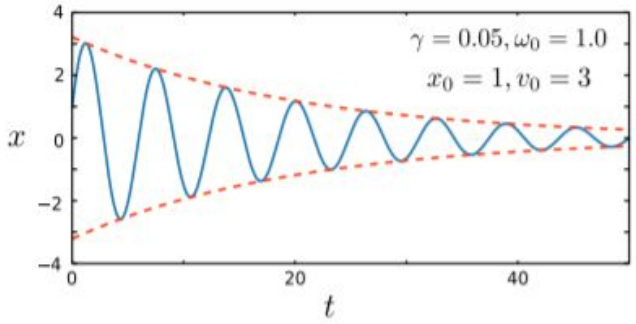
Absolute level of CTI

Relative change over 6 months

Serial CTI + Pixel Bounce - Model

Model with 2 trap species: $T_i = A_1 e^{-i/\tau_1} + A_2 e^{-i/\tau_2}$

$V(t) = e^{-\gamma t}(k_A \cos(\Omega t) + k_V \sin(\Omega t))$



→ Fit parameters independently for each quadrant based on each CI group

Modelled with **arCTIc**

arxiv:0909.0507

Serial CTI - Model

During PV

Serial CTI - Model

6 months later

Serial CTI Calibration

Serial CTI Calibration

Summary

- **Euclid has been enjoying a nice Sun bath**
- **CTI in Euclid is lower than forecast, but uneven**
- **CTI calibration is robust and scalable** (at least in parallel direction)
- **Pixel bounce?**