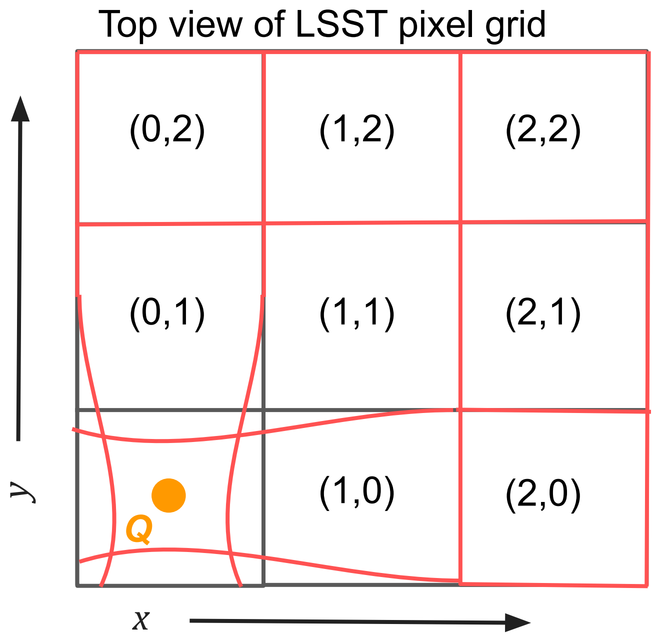
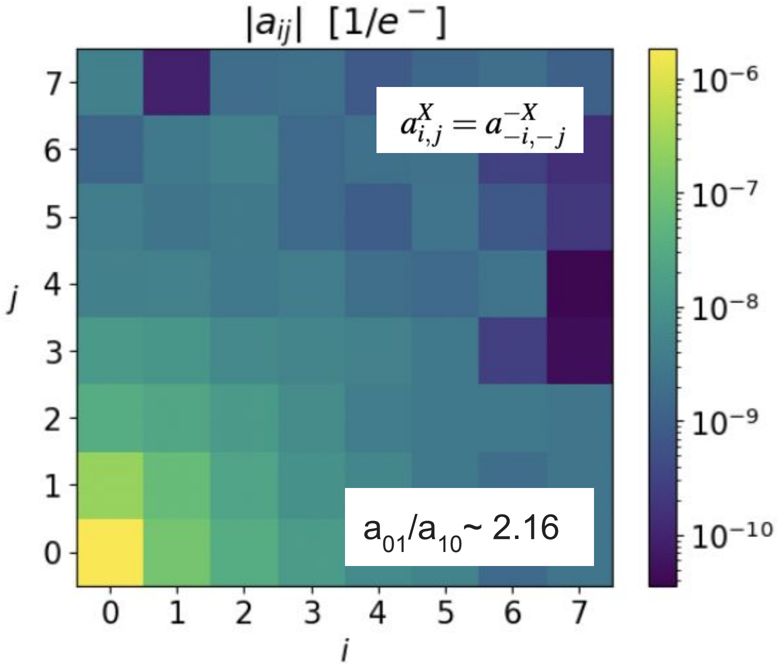
ISR Roadmap for the Brighter Fatter Effect in LSSTCam

Alex Broughton

Science Pipelines Meeting
1/31/2024

Pixels are distorted in LSST Sensors due to charge accumulation



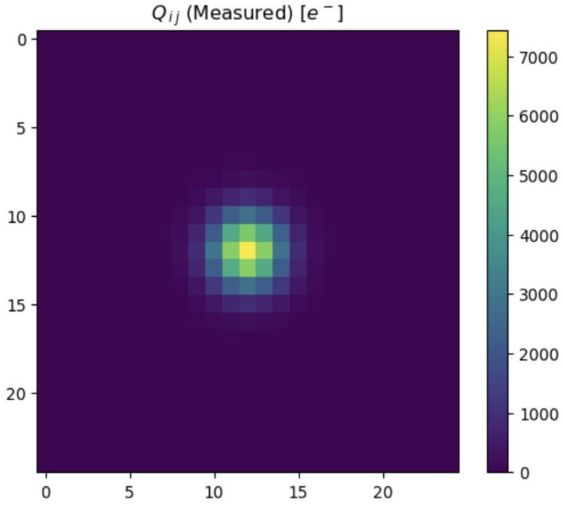


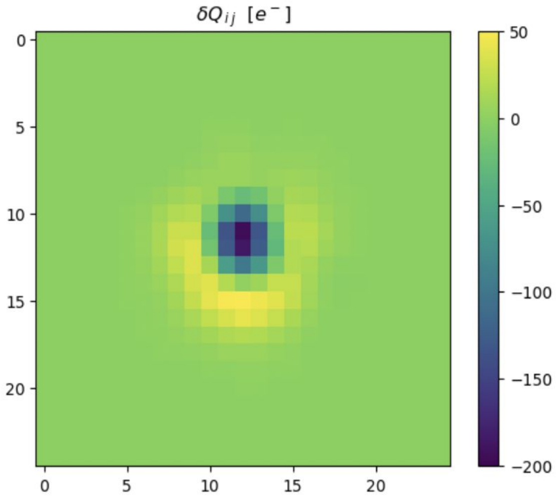
More than 50% of charge displacement happens beyond 4 pixels away!

Broughton et al. (2023)

The Brighter-Fatter Effect (BFE)

The BFE makes bright sources appear larger.
e.g. Calibration stars, brightest cluster galaxies (BCGs), type Ia SNe etc.





These higher-order effects make up 30% of the total effect near sensor saturation

At <u>low</u> signal levels, the pixel-to-pixel effects are approximated well by a constant fractional area change “matrix”

At <u>high</u> signal levels, the pixel-to-pixel effects are non-trivial and need to be measured empirically.

The Correction

Calculate Covariances → Derive a 2D kernel from covariances → Apply to Image

Based on
Coulton et al. 2018
Astier et al. 2019
Broughton et al. 2023

The Correction

Calculate Covariances → **Derive a 2D kernel from covariances** → **Apply to Image**

Pixel-pixel covariances derived from PTC

$$C_{ij}(\mu) = \frac{\mu}{g}\left[\overbrace{\delta_{i0}\delta_{j0}}^{\text{Original Poisson term}} + \overbrace{a_{ij}\mu g}^{\text{Modified by change in area}} + \overbrace{\frac{2}{3}[\mathbf{a}\otimes\mathbf{a}+\mathbf{ab}]_{ij}(\mu g)^2}^{\text{Higher-order BFEs}} + \frac{1}{6}[2\mathbf{a}\otimes\mathbf{a}\otimes\mathbf{a}+5\mathbf{a}\otimes\mathbf{ab}]_{ij}(\mu g)^3 + \cdots\right] + n_{ij}/g^2$$

Based on
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Astier et al. 2019
Broughton et al. 2023

The Correction

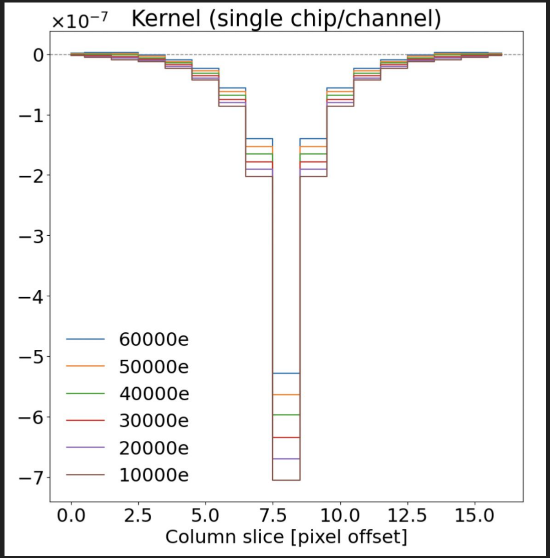
Calculate Covariances → **Derive a 2D kernel from covariances** → **Apply to Image**

Pixel-pixel covariances derived from PTC

$$C(\mathbf{x}-\mathbf{x}') = -\mu^2 \frac{\partial}{\partial x} \cdot \frac{\partial}{\partial x} K$$

Original Poisson term — Modified by change in area — Higher-order BFEs

$$C_{ij}(\mu) = \frac{\mu}{g}\left[\delta_{i0}\delta_{j0} + a_{ij}\mu g + \frac{2}{3}[\mathbf{a}\otimes\mathbf{a} + \mathbf{ab}]_{ij}(\mu g)^2 + \frac{1}{6}[2\mathbf{a}\otimes\mathbf{a}\otimes\mathbf{a} + 5\mathbf{a}\otimes\mathbf{ab}]_{ij}(\mu g)^3 + \cdots\right] + n_{ij}/g^2$$



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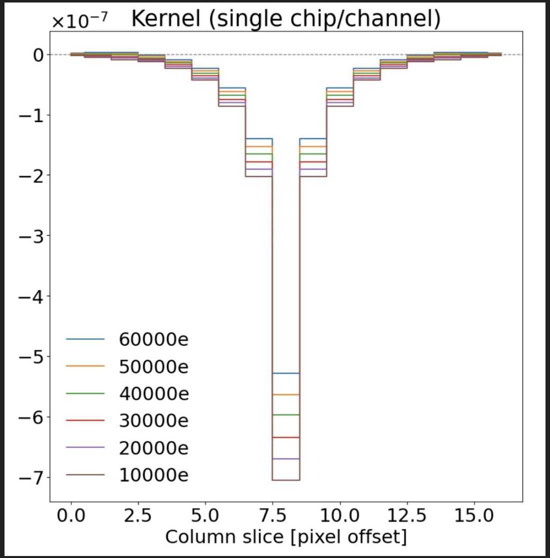


Step 1: $\Phi = F * K$

Step 2: $V = F\nabla\Phi$

Step 3: $\delta F = \frac{1}{2}\nabla \cdot V$

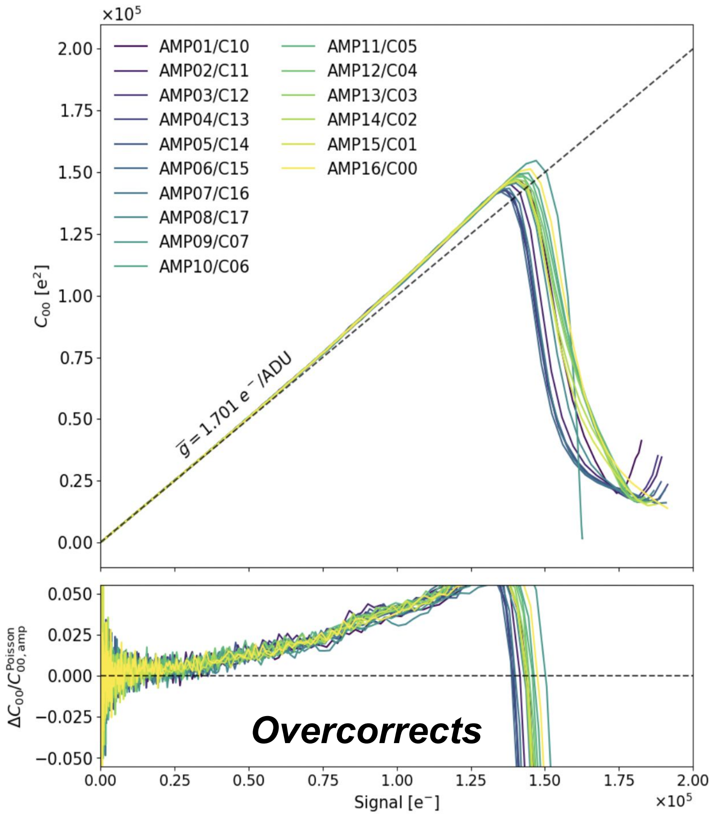
$$\hat{F} = F + \delta F$$

Based on
Coulton et al. 2018
Astier et al. 2019
Broughton et al. 2023

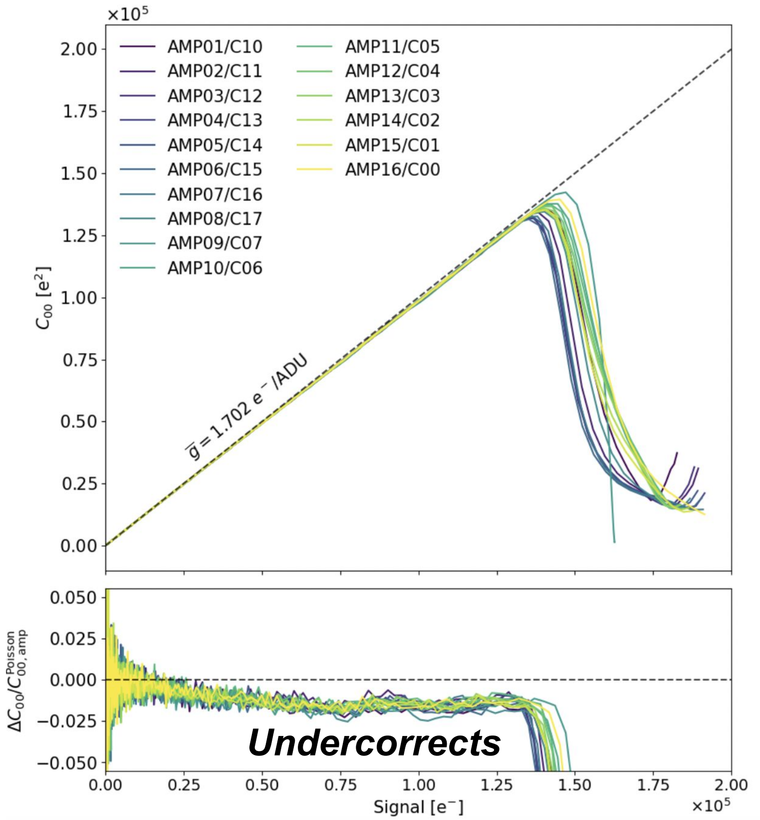
The correction is derived from measured pixel correlations at some arbitrary signal level.

Can this correction reconstruct the expected variance in flat fields?

10k electrons



60k electrons



1st improvement to ISR:

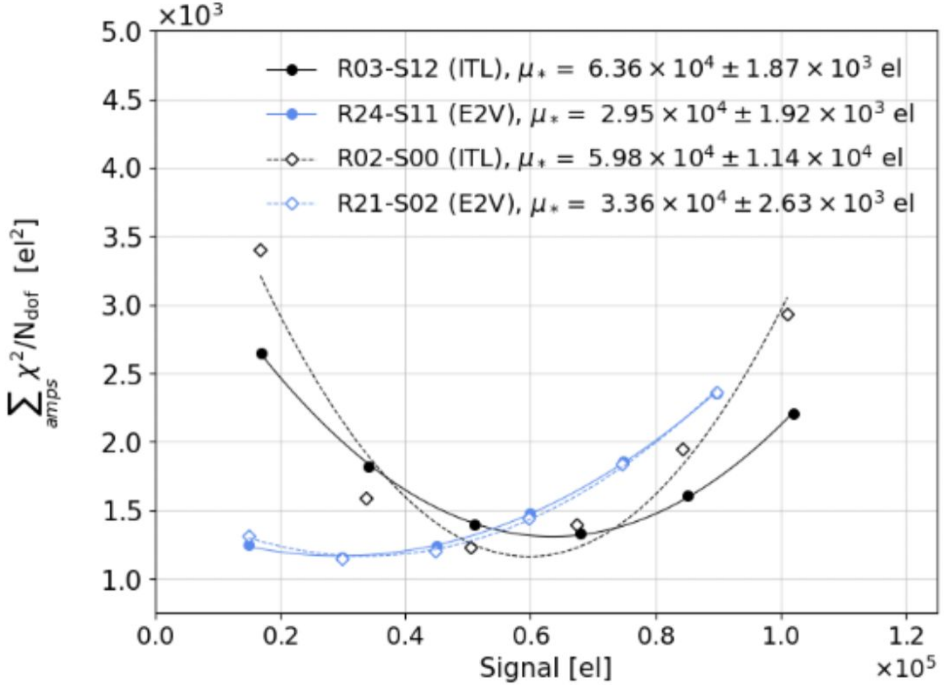
"Flux-sampling"

DM-41952

Let's pick the "sweet spot" signal level that best reconstructs the Poisson form of the PTC.

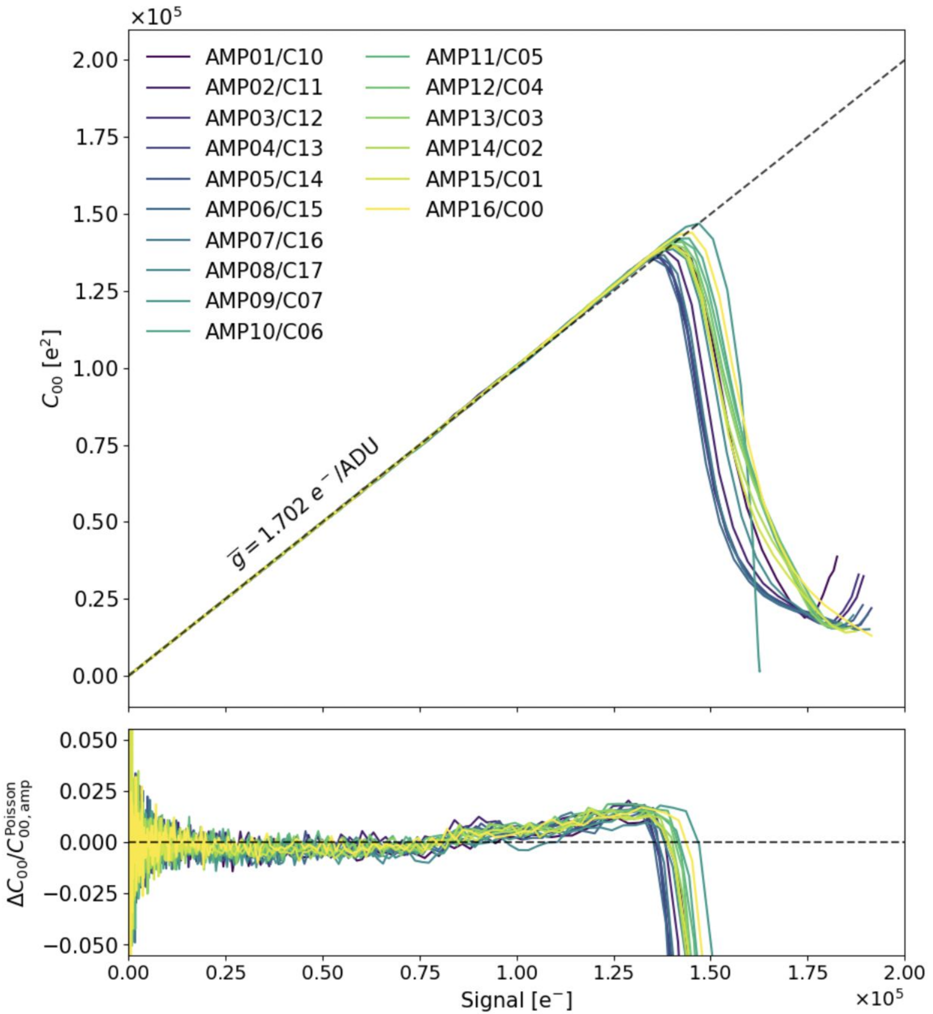
Test kernels at multiple signal levels, and find the one that minimizes the chi^2

$$\chi^2 = \sum_{\mu} (C_{00} - C_{00}^{Poisson})^2 w_{\mu}$$



×10³
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
R03-S12 (ITL), μ* = 6.36 × 10⁴ ± 1.87 × 10³ el
R24-S11 (E2V), μ* = 2.95 × 10⁴ ± 1.92 × 10³ el
R02-S00 (ITL), μ* = 5.98 × 10⁴ ± 1.14 × 10⁴ el
R21-S02 (E2V), μ* = 3.36 × 10⁴ ± 2.63 × 10³ el
∑amps χ²/Ndof [el²]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Signal [el]
×10⁵

Corrects 94%
of the effect
in Flat Fields



Corrects 90%
of the anisotropy
between x/y

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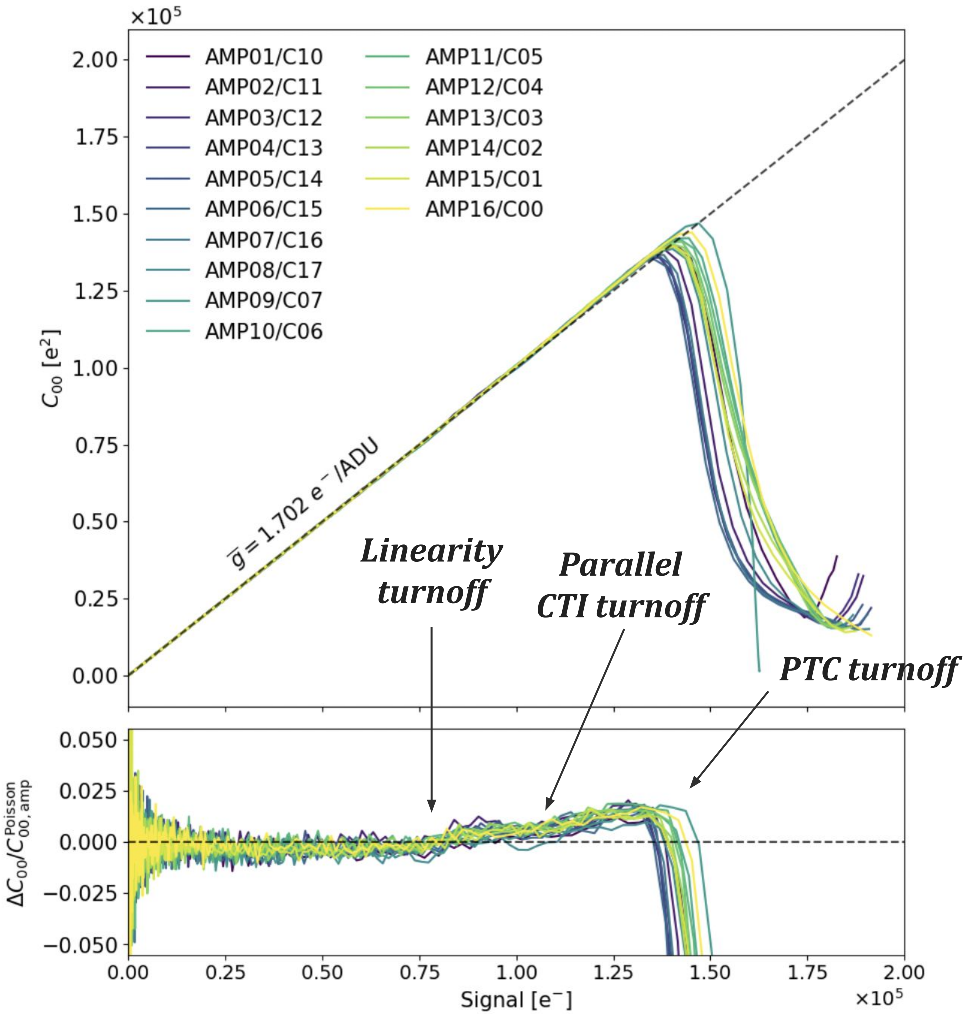
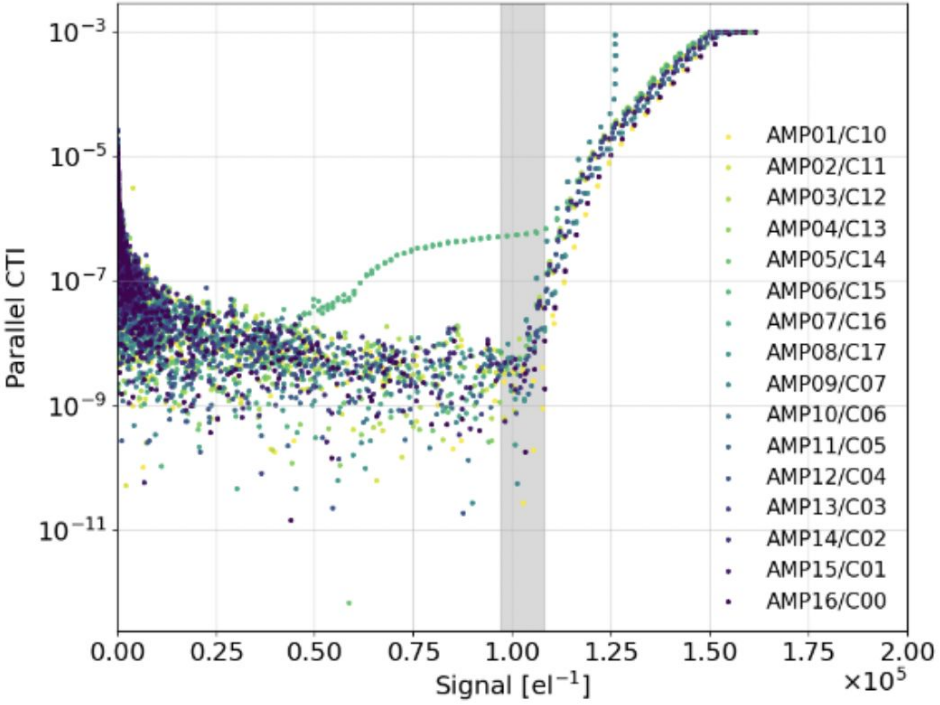


2nd improvement to ISR:

"Parallel CTI turnoff"

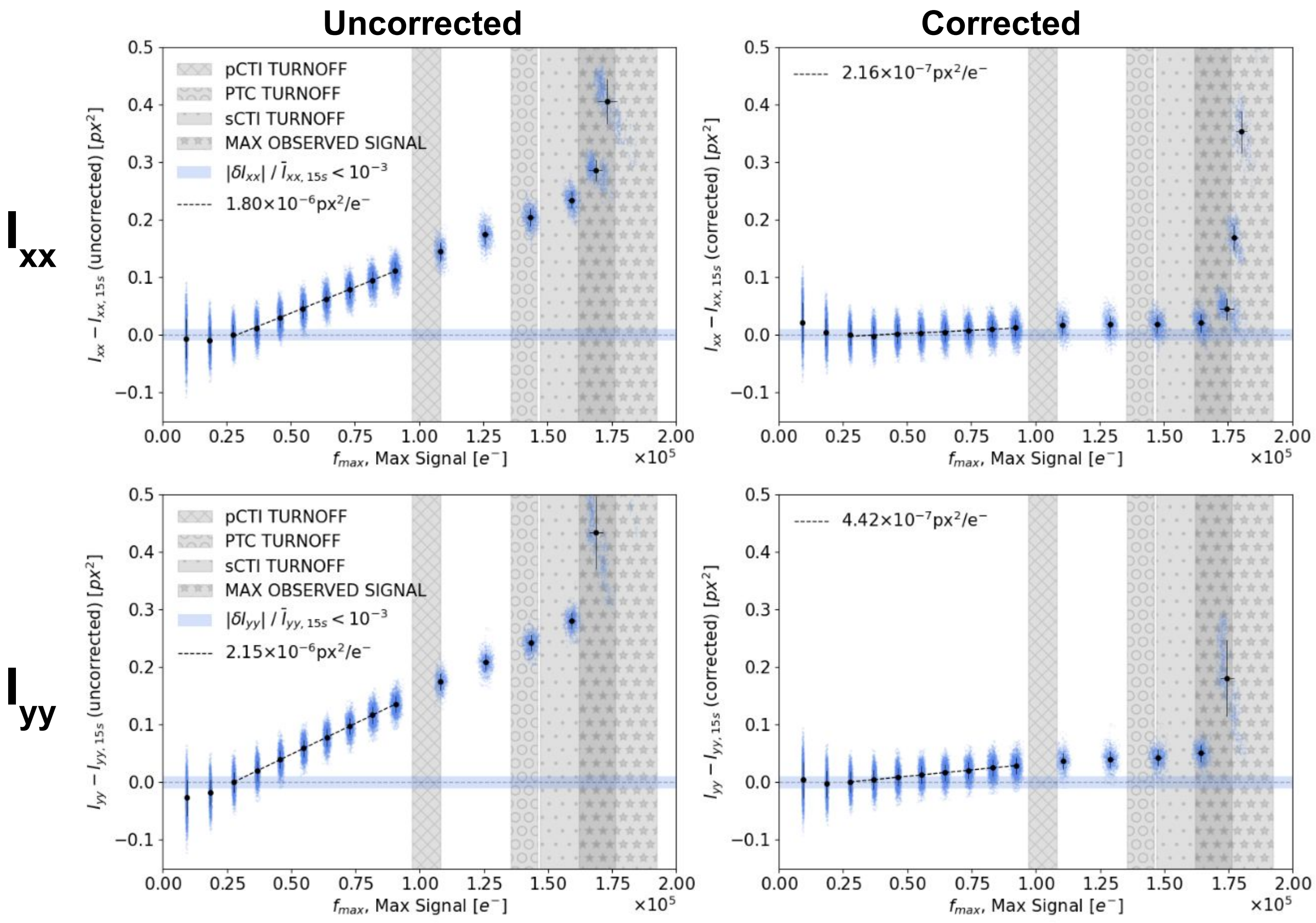
DM-38989

Defined by point with n# of consecutive increases in parallel CTI above thresholds in x and y



Corrects 90% of the effect in stars

Corrects 77% of the anisotropy between x/y

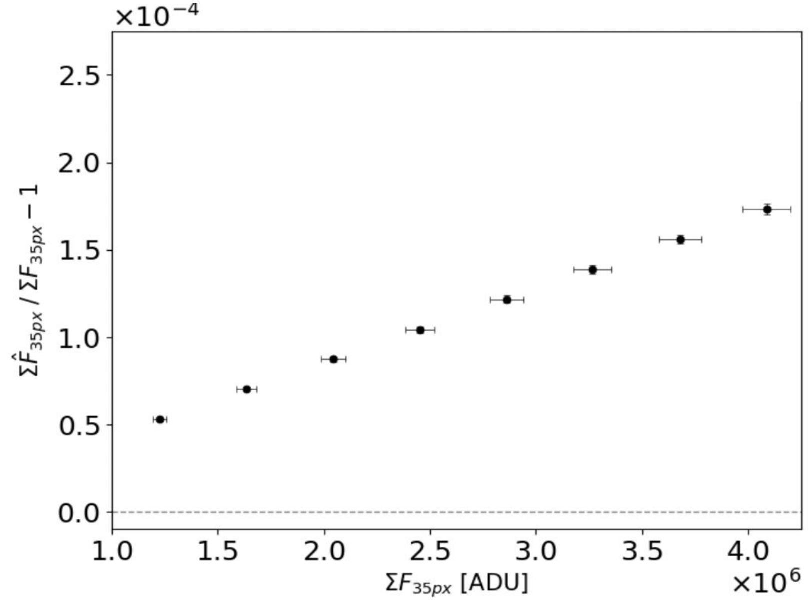


Broughton et al. (2023)

Why is the overall correction better in flat fields than in stars?

1. *Most of the correction is dominated by K_{00}, but realistically most of the BFE is contributed by correlations > 4px away.*

2. *The application of the correction deviates from Gauss's Law on small scales, resulting in loss of charge conservation in stars (!)*



More flux is gained by the central pixels than is taken from the neighboring pixels

Flux is conserved, but only in the continuous limit

$$\langle \delta F \rangle = 0$$

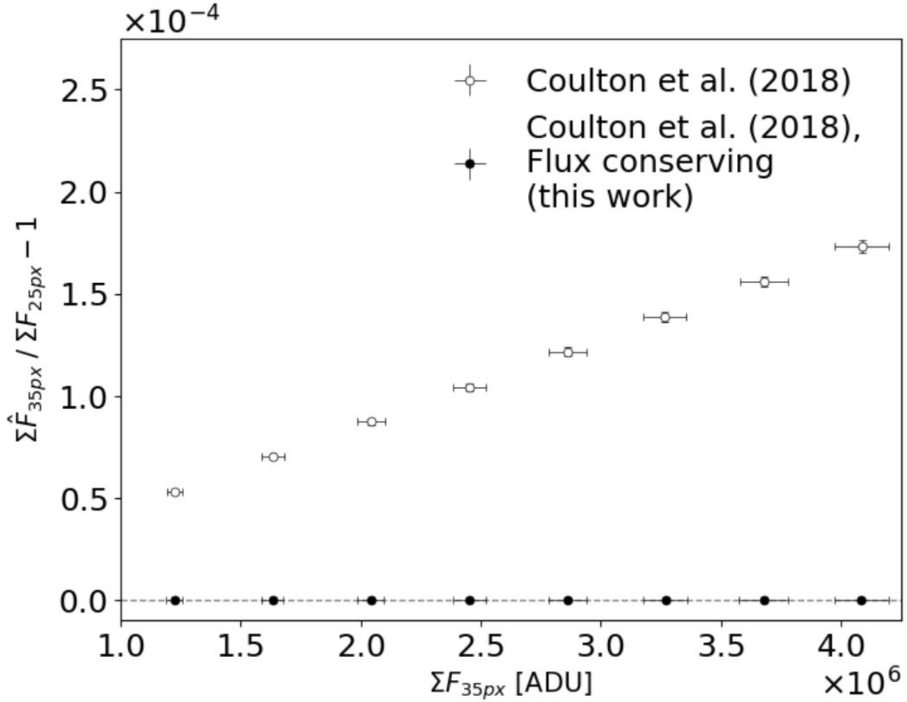
Poor modeling of local charge transport=worse overall correction

Broughton et al. (2023)

3rd improvement to ISR:

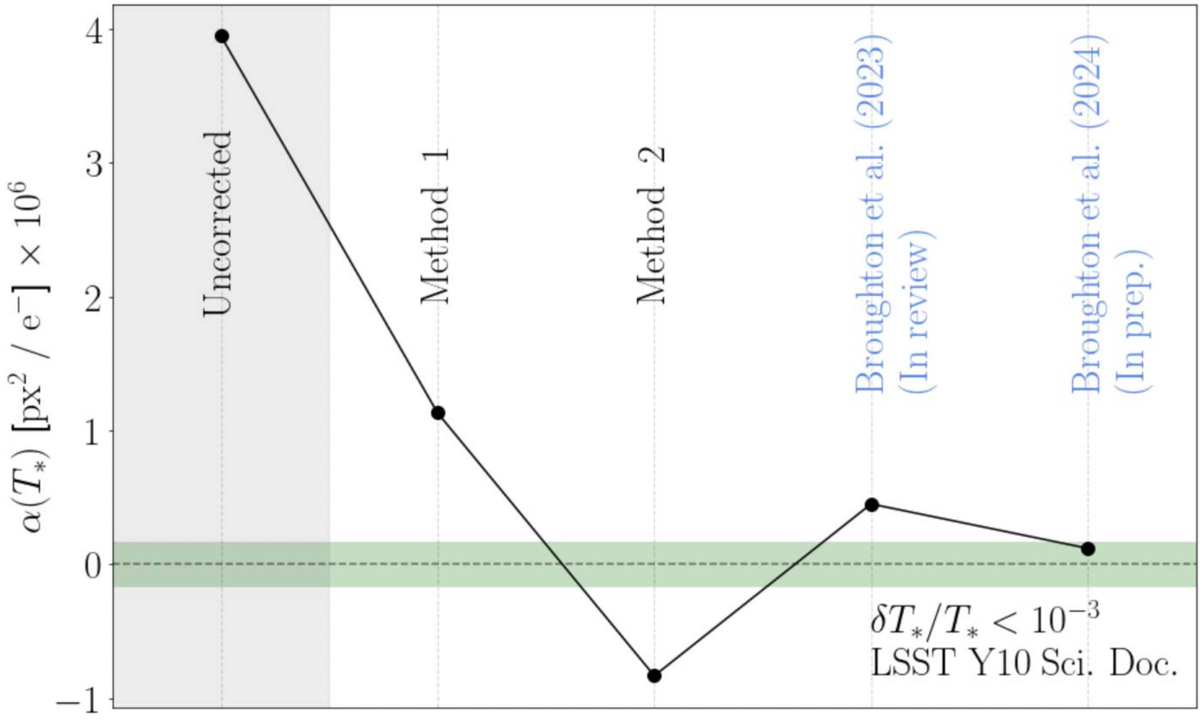
"Flux conserving corrections"

DM-38555



Improvements can reconstruct true star size $T_* = \langle I_{xx} + I_{yy} \rangle$

Residual BF strength after correcting stars



Method 1: Using kernel derived from high signal

Method 2: Using kernel derived from low signal

Method 3: Using kernel at the level that best reconstructs Poisson noise in flat fields.

Method 4: Method 3 + flux-conserving corrections (in prep.)

Why is the anisotropy correction better in flat fields than in stars?

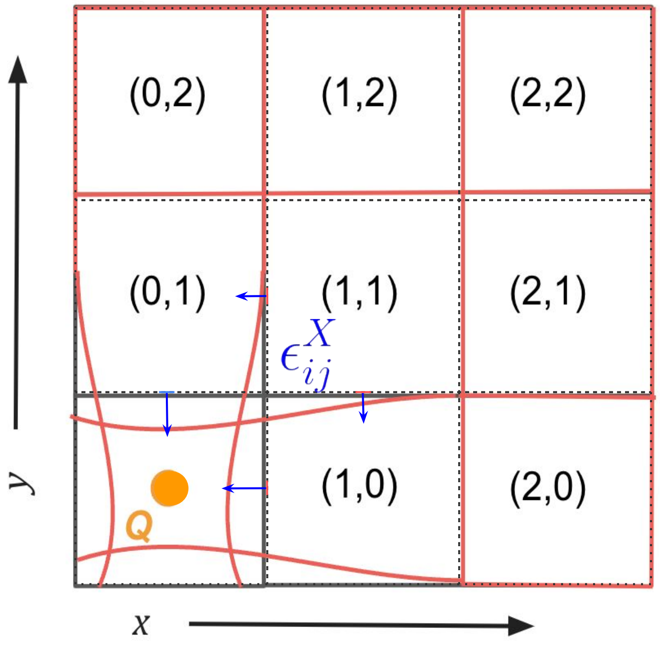
Poor local modeling of sub-pixel charge transport also due to the assumption that the curl of the displacement field created by the accumulated charges is zero.

The kernel is only defined by the divergence:

$$\boldsymbol{\epsilon} \propto \boldsymbol{\nabla}_{\boldsymbol{x}} \boldsymbol{K}$$

… which assumes:

$$\boldsymbol{\nabla}_{\boldsymbol{x}} \times \boldsymbol{\epsilon} = 0$$



<u>4th improvement to ISR:</u>

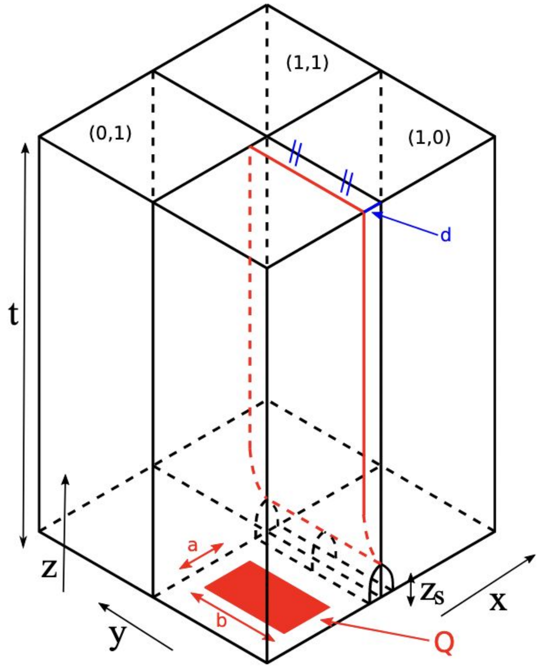
“Adds Astier+23 correction”

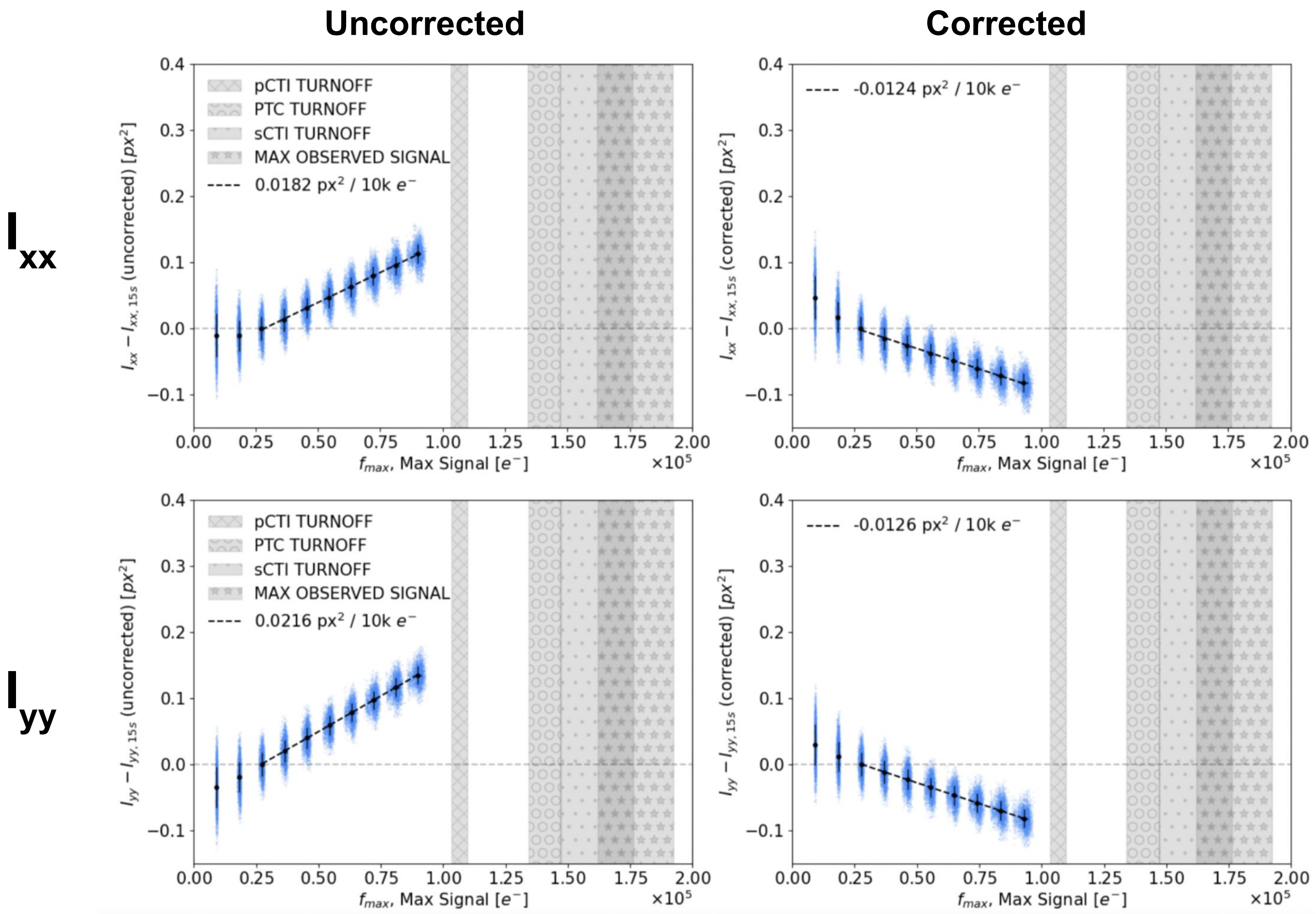
DM-39515

Takes in the <u>scalar a-matrix</u> (1 number/pixel) and fits the electrostatic solution for the boundary shifts given a charge +Q in a potential well to derive the <u>vector a-matrix</u> (4 numbers/pixel)

$$a_{ij} \xrightarrow{\text{e-model fit}} \vec{a}_{ij} = \begin{pmatrix} a^N_{ij} \\ a^E_{ij} \\ a^S_{ij} \\ a^W_{ij} \end{pmatrix}$$

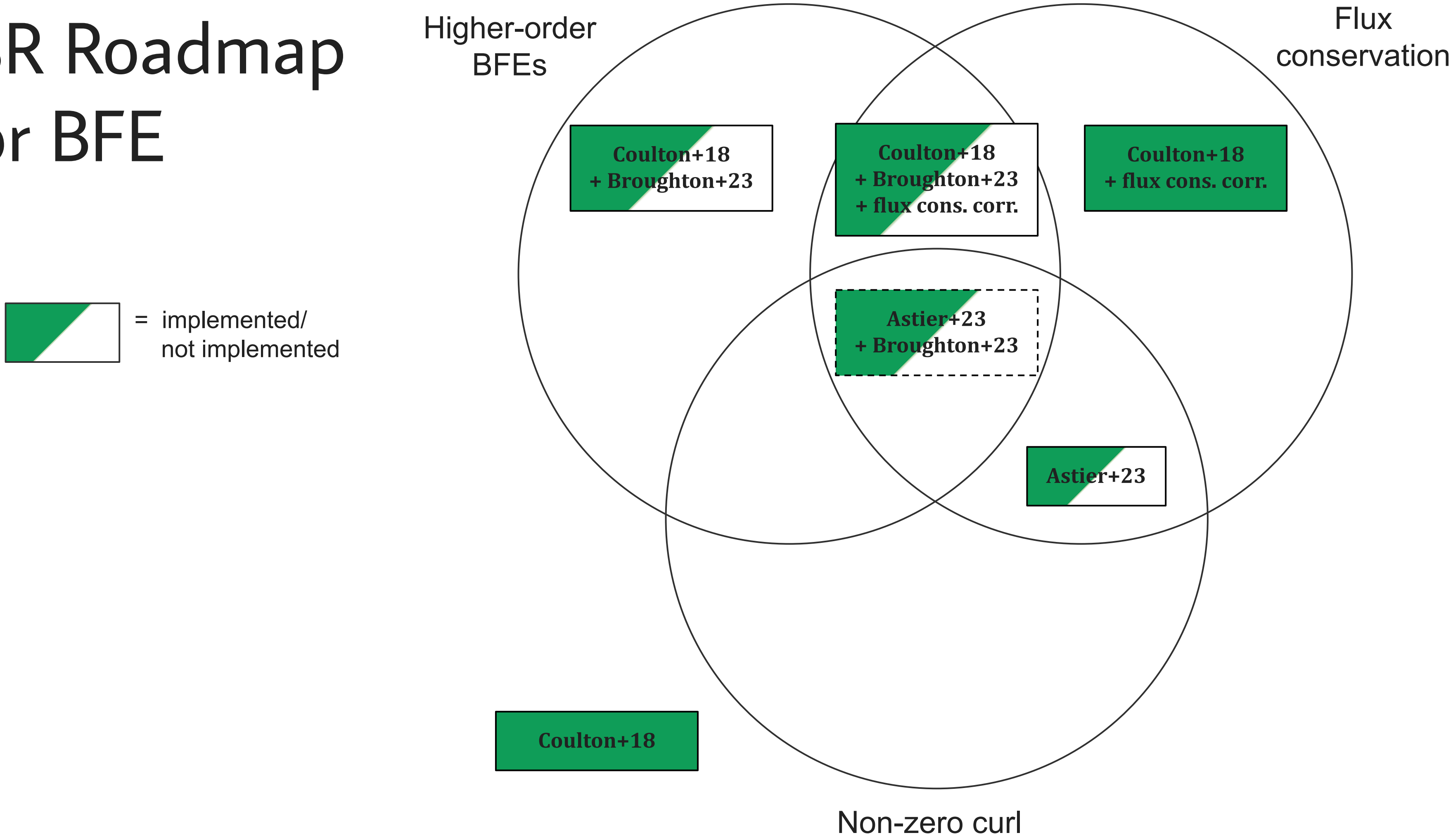
$$\delta F^X_{ij} = 1/2 \sum_{kl} a^X_{k,l} F_{i-k,j-l}$$





Corrects >95% of the anisotropy between x/y

ISR Roadmap for BFE



ISR Roadmap for BFE

- Add flux sampling method from Broughton+23
- Add `elec_fit` from Astier+23 (found here: https://gitlab.in2p3.fr/astier/bfptc)
- Add parallel CTI turnoff calculation and store as curated dictionary
- Add option to PhotonTransferCurveSolveTask to set maxSignalAdu to:
  - Parallel CTI turnoff? Or x.x% of PTC turnoff?
- Add optional higher-order shape statistics on sources (up to 4th order?)