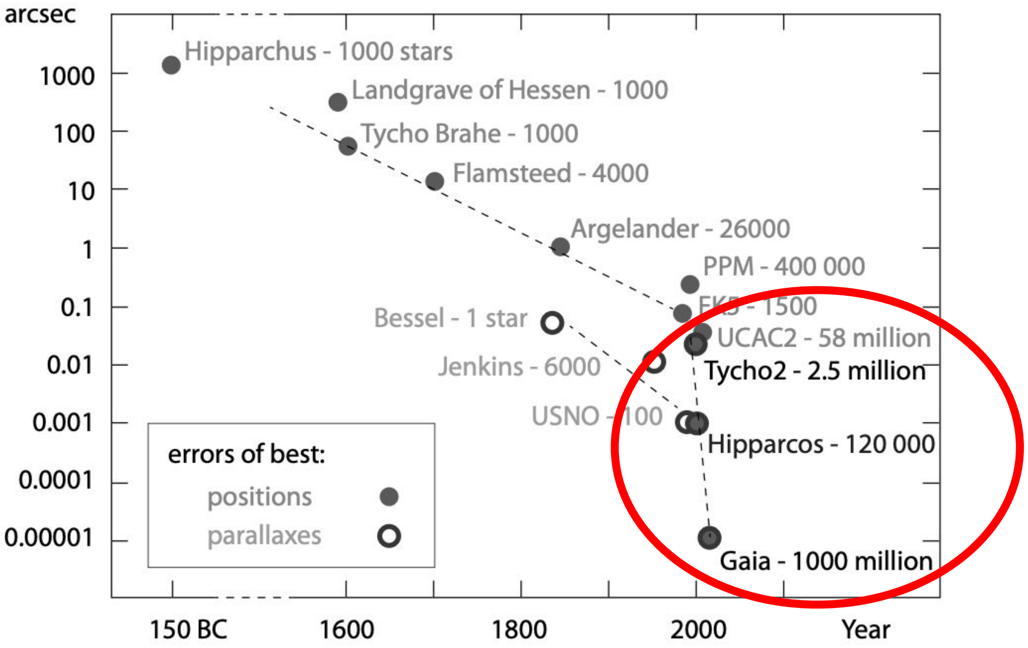
Improving ground-based astrometry via turbulence reduction

Daniel C. H. Gomes
& Gary M. Bernstein
University of Pennsylvania

Motivation



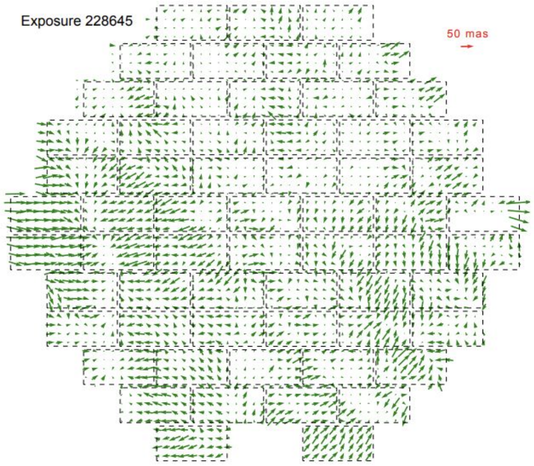
Perryman, 2012, *The History of Astrometry*.

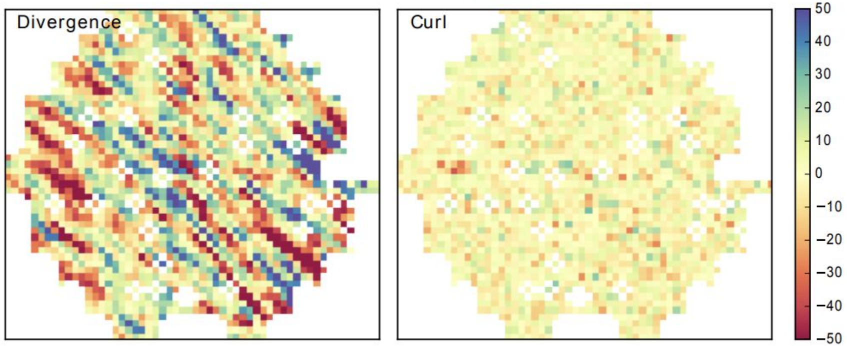
Can we use space-based stellar solutions to get ground-based solutions for fainter objects (DES, LSST)?

Dominant sources of error

Dark Energy Survey astrometric solution (Bernstein et al 2017)

- Shot noise (unavoidable for fainter sources)
- Stochastic wander due to atmospheric turbulence
  - ~10-30 mas for a 30s exposure
  - 5-10 arcmin coherence length
- Unmodelled variations in the DECam astrometric solution (2-4 mas)
- Static detector effects (up to 2-4mas)



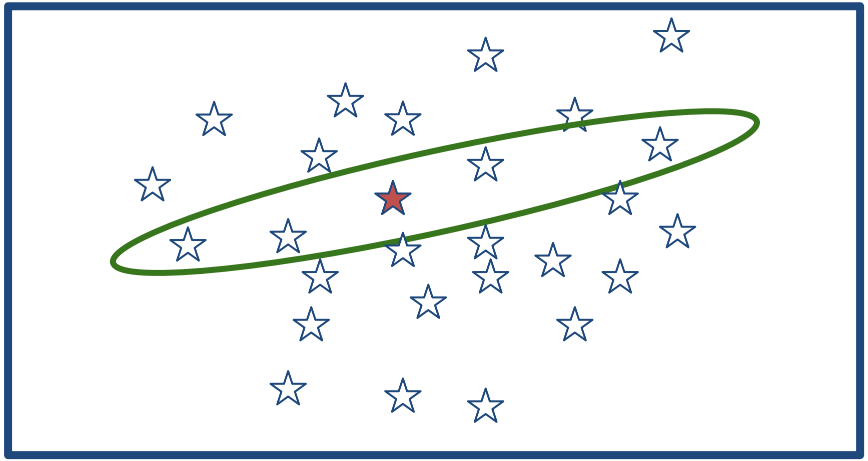


Bernstein et al 2017, Astrometric Calibration and Performance of the Dark Energy Camera

Using reference stars

- Gaia catalog grid with ~ 1 star per arcmin^2 at high galactic latitude.
  - Measure displacement of sources wrt. the Gaia solution, and treat them as a model for turbulence.
- A few 2021 solutions
  - Lubow et al. 2021 (PanSTARRS1):
    - Subtract the median shift of the nearest 33 reference stars.
    - Variance reduced by a factor of 2
  - Fortino et al 2021 (DES):
    - Gaussian Process Regression (GPR) to interpolate the displacement fields
    - Optimization routine for the GPR kernel (time-consuming)
    - Variance reduced by a factor of 12
  - Leget et al 2021 (Hyper Suprime-Cam):
    - GPR, no optimization (parametrized kernel)

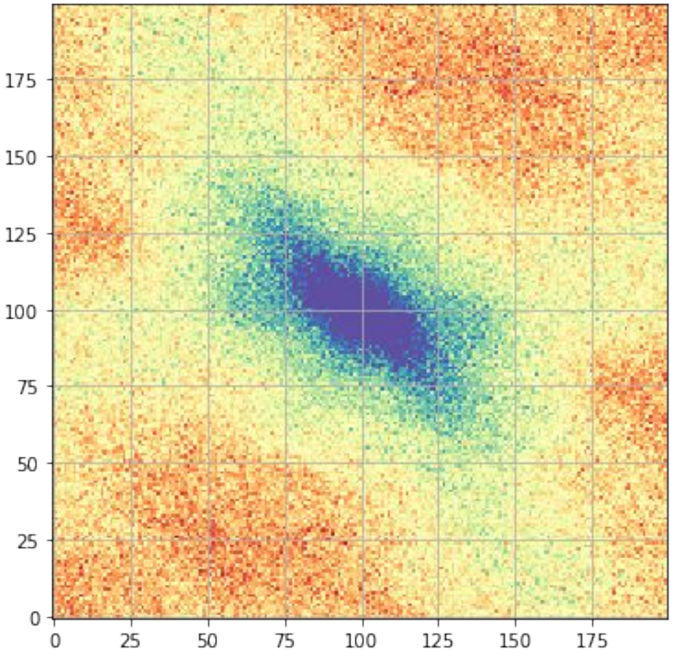
The correlation function (kernel)



The GP kernel, as a descriptor of the similarity between the turbulence displacement field in two different points, determines which combination of reference stars is used for field estimation in each target location, and how they should be weighted.

GPR with empirical kernels

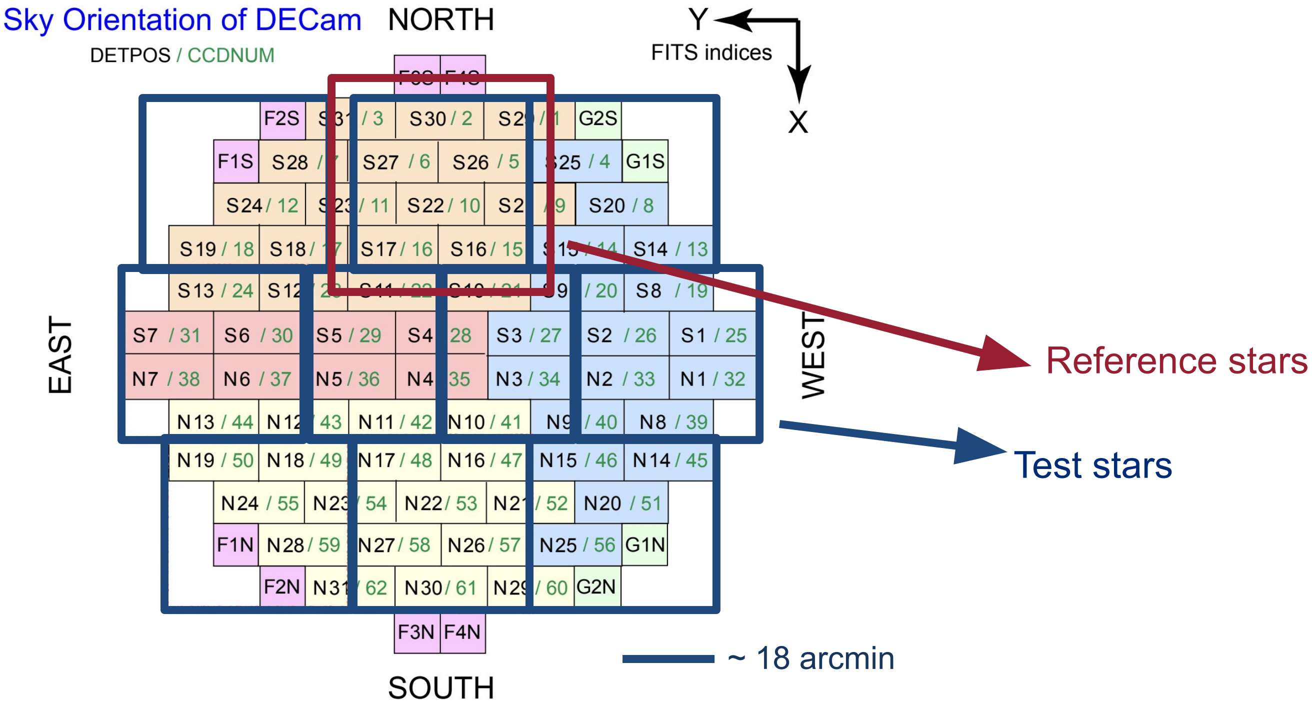
- Covariance matrix needs to be positive definite. Kernel model must ensure this
- Empirical kernels might present an advantage where turbulence patterns are more complex than the model
- Our solution: Use the empirical kernel with smoothing
  - Apodization
  - Fourier transform, keep only positive Fourier components that are above a certain S/N threshold



Measured correlation function (v direction), 20’’/pixel

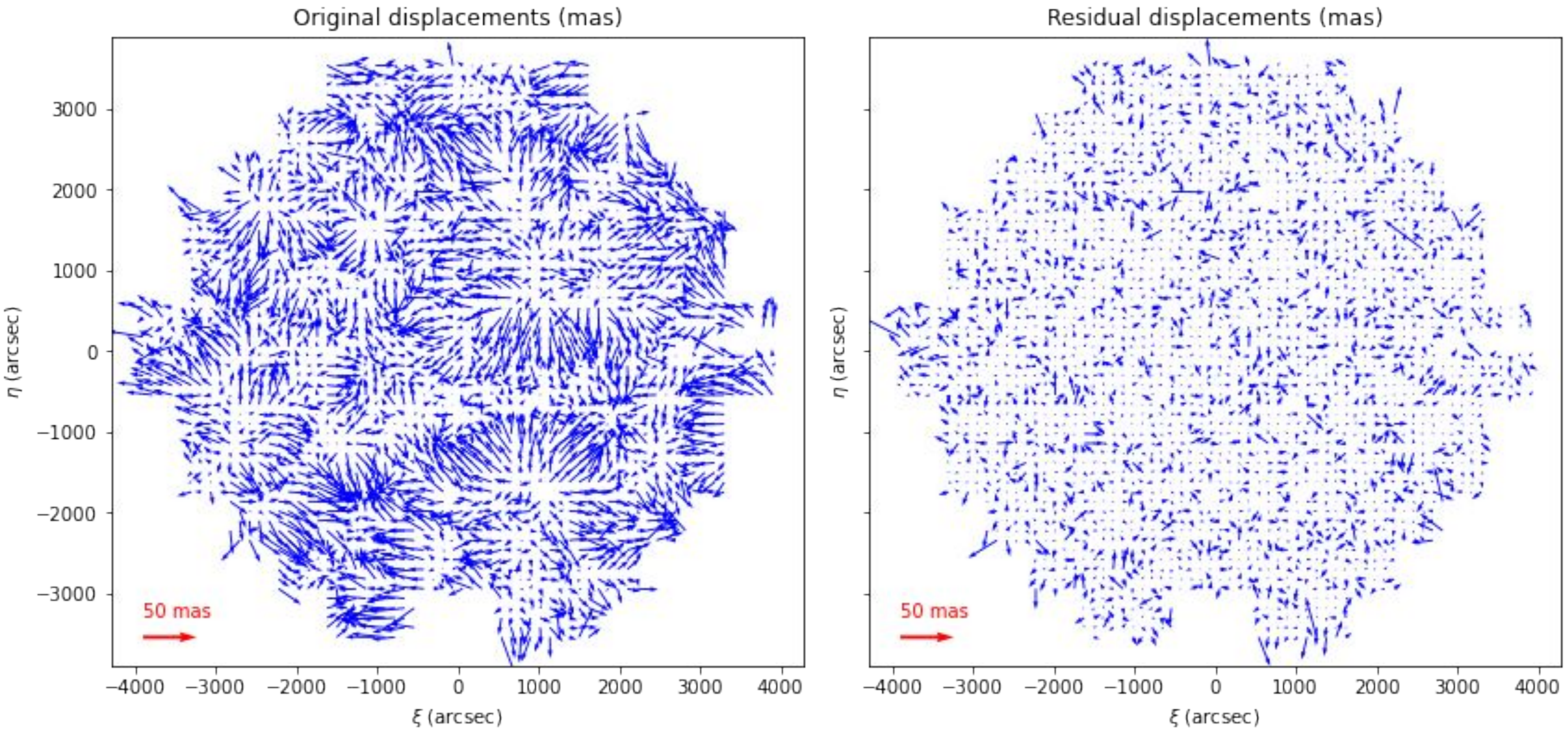
Patching of the focal plane (Testing with DES)

- Perform GPR in patches
  - $O(N^3) + O(N^2M)$ for N reference stars and M targets
  - No advantage in doing the entire exposure at once

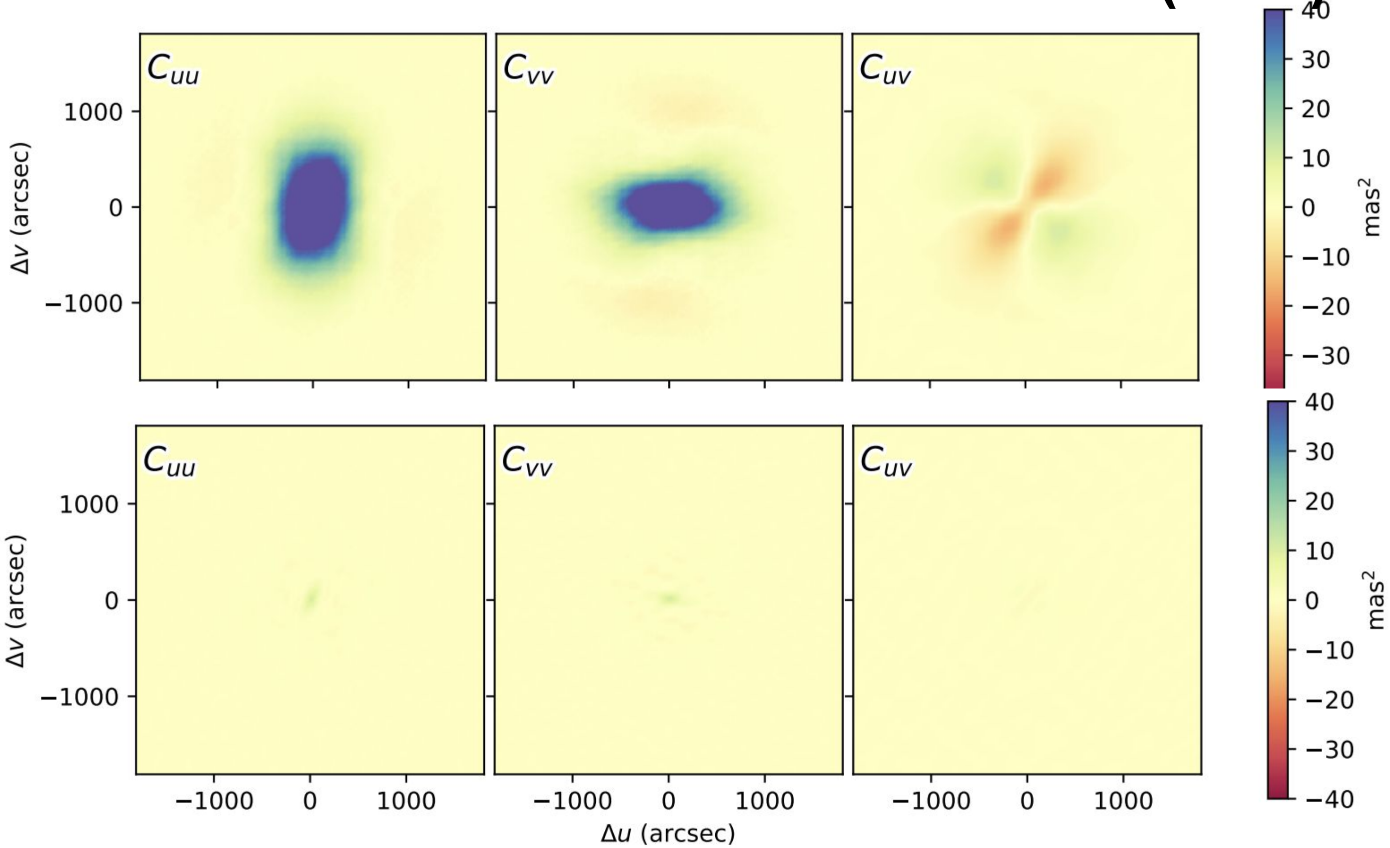


Statistics

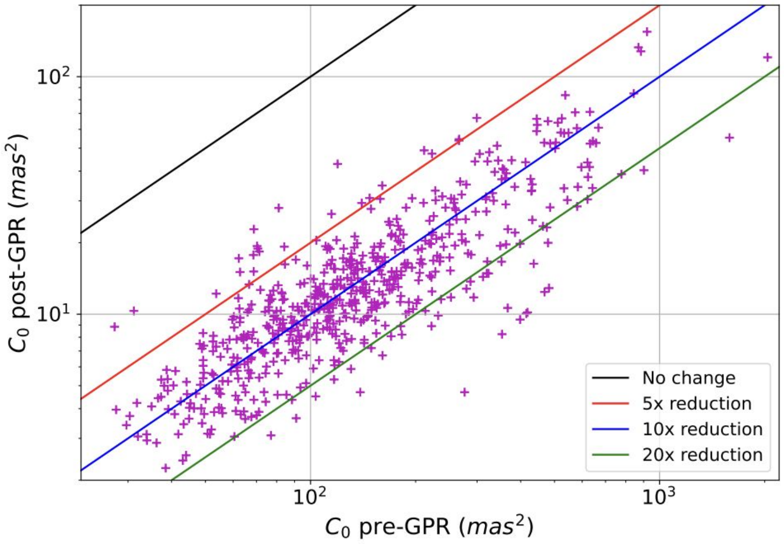
- Perform GPR 5 times in each patch, reserving 20% of the gaia stars on each run
- Get statistics from the residuals wrt. the reserved set
  - Estimate the variance of the turbulence displacements by averaging the correlation function for displacements < 1'. Value chosen as a compromise between two problems:
    - Correlation functions C(r) are decreasing with r, so the larger r is chosen, the more the true variance will be underestimated
    - The smaller we choose r, the fewer pairs of reserved stars are available, and the noisier our estimate of the variance becomes.
  - RMS per axis computed from this variance estimate


Original displacements (mas)
Residual displacements (mas)
η (arcsec)
ξ (arcsec)
50 mas
3000
2000
1000
0
−1000
−2000
−3000
−4000
4000

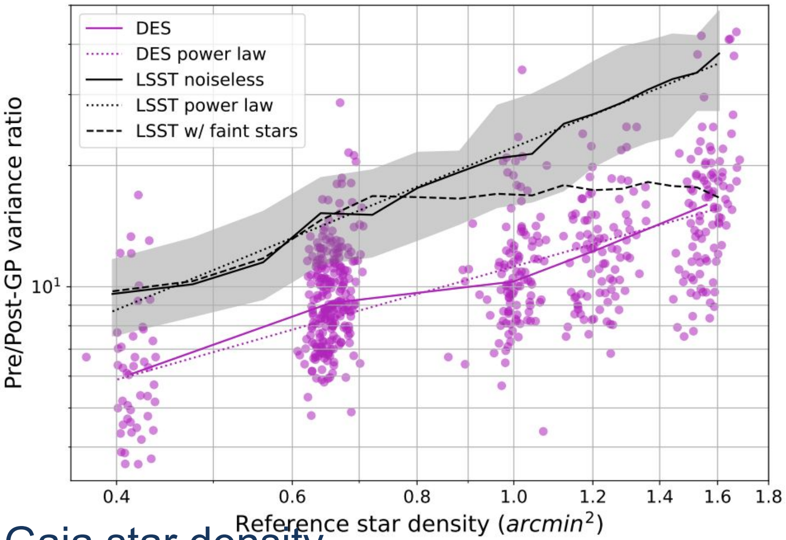
Correlation functions before and after GPR (DES)



Results w/ ~600 DECam exposures

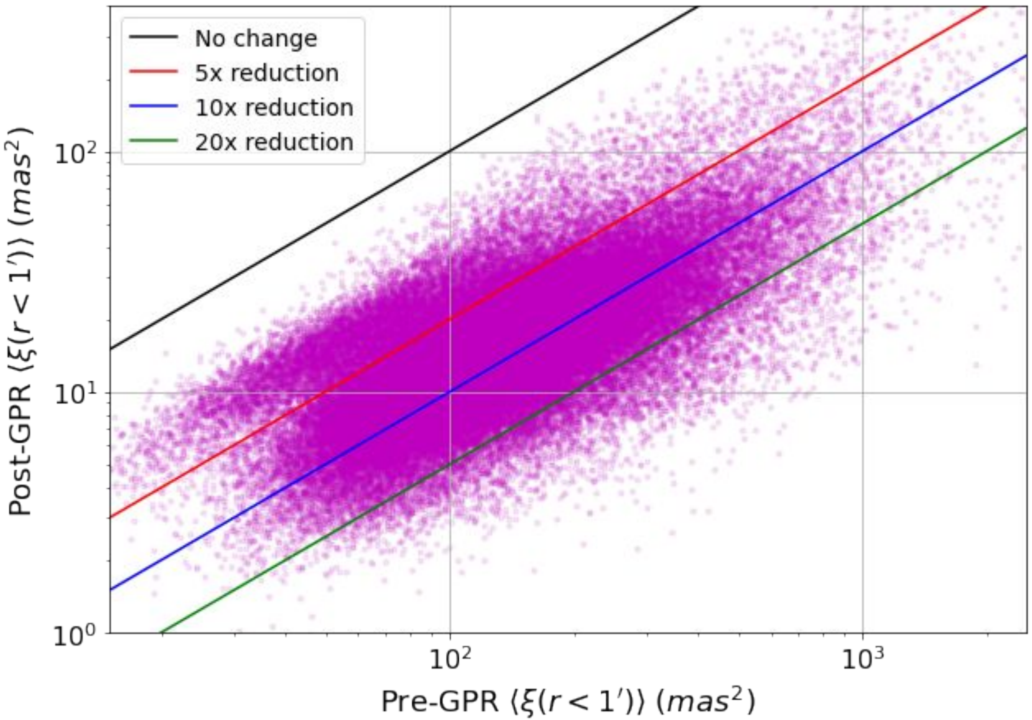


Average 12x reduction, typical 2-3 mas residuals



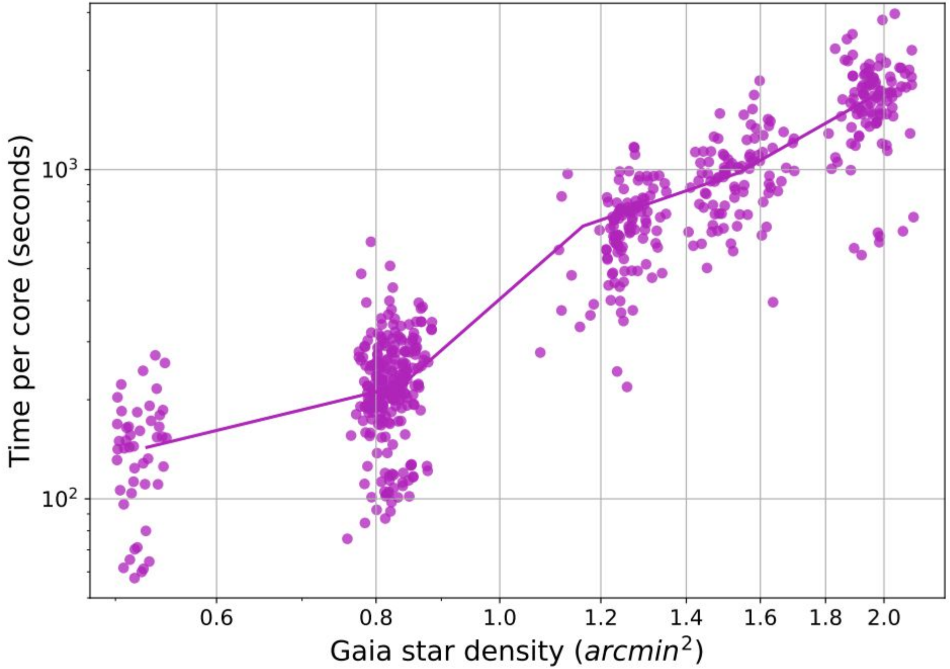
Scaling with Gaia star density
(DES / LSST simulated fields)

Results with the entire DES Y6 catalog



Computational cost

DES test exposures



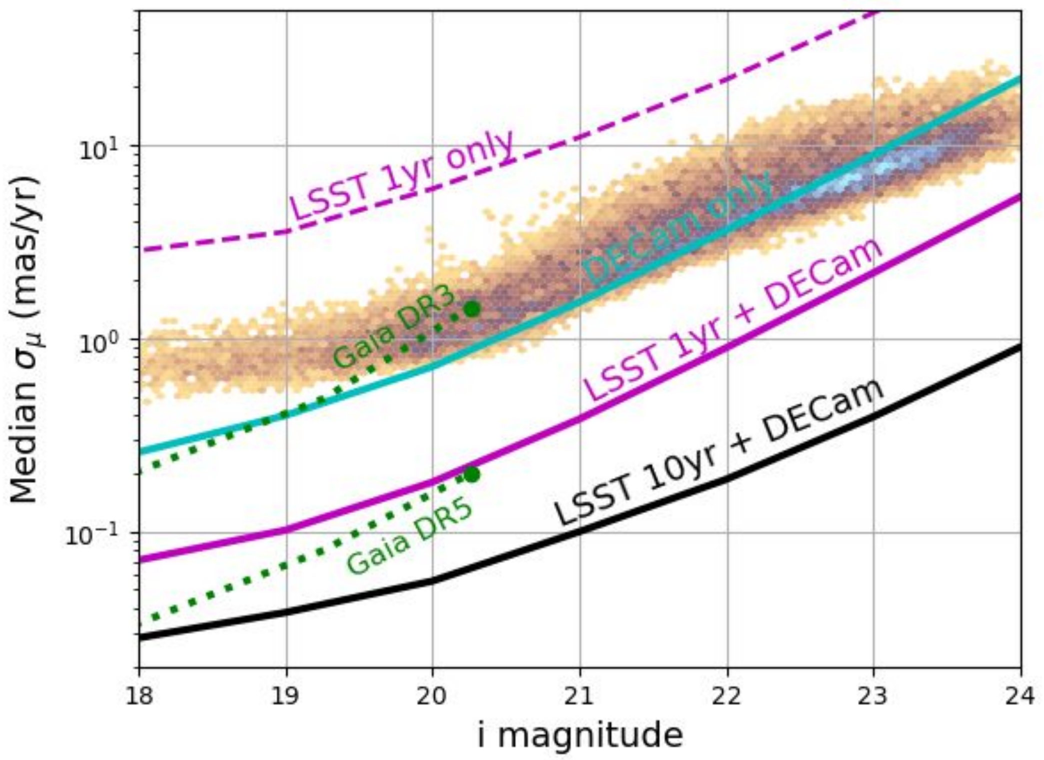
Bottleneck is generally due to the number of targets - $O(N^2M)$

LSST estimate:
~500 core-seconds for DECam field
x 2.5 (10 → 25 patches)
x ~1000 exposures/night
/2000 cores

Total ~10 minutes/night

[Pierre-Francois Leget currently working to ensure turbulence correction is optimally applied in LSST.]

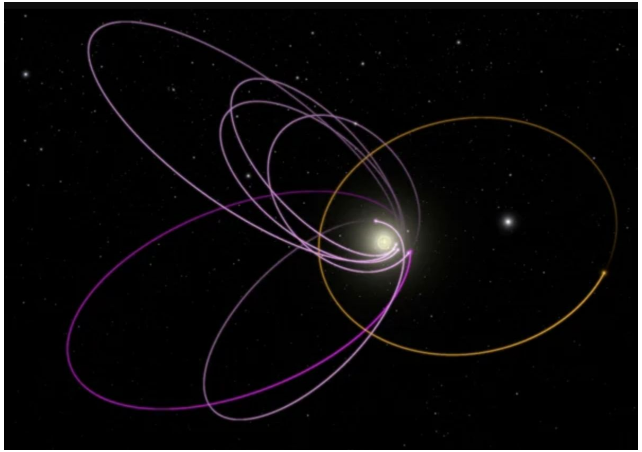
Applications: Proper motions



- LSST (w/ reduced astrometric floor) + DECam outperforms Gaia DR5 in proper motion uncertainties
- Identify Milky Way satellite members (Vernon Wetzell)

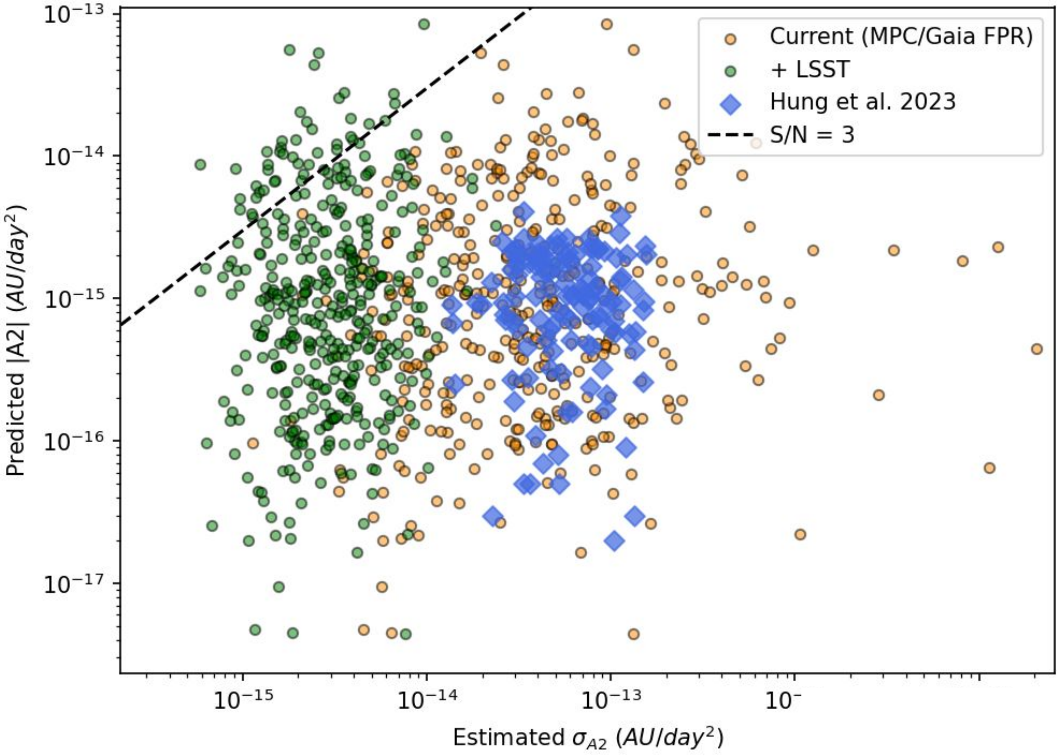
Applications: Solar system orbits with LSST

- Astrometric floor moved from 10 mas → 3 mas
- Smaller positional uncertainties translate into higher sensitivity to perturbations
- Improve solar system dynamical model, detect unseen mass
  - PBHs, Planet X, etc.
- Improve initial predictions for stellar occultations by small solar system bodies



Applications: Solar system orbits with LSST

- Non-gravitational accelerations (ex: detecting Yarkovsky effect on Main Belt Asteroids)



Thank you!