Towards precision Astromety & photometry from the ground

Eran Ofek
Weizmann Institute of Science

With: N. Segev, O. Springer, D. Polishook, B. Zackay, J. Lu, A. Goobar, E. Waxman, I. Arcavi



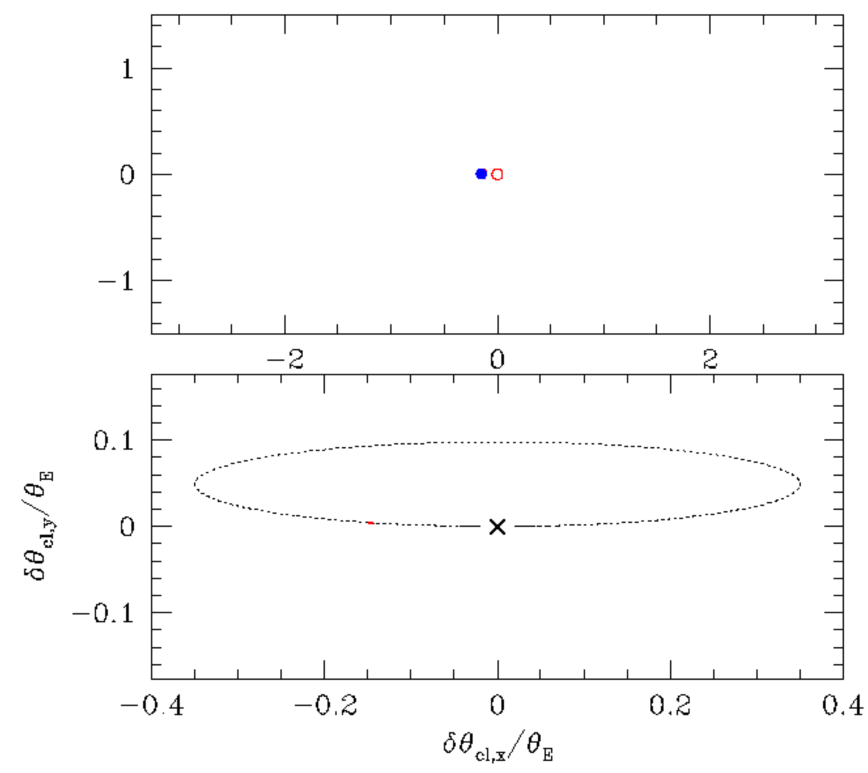





Outline

- Motivation for astrometry & photometry
  - Search for isolated stellar-mass BH
  - Binary asteroids
  - Lensed quasars and time delay
  - GW170817 jet
  - exoplanets
- Ground based astrometry
  - Limitations
  - Progress
- Ground based photometry
  - Limitations
  - Progress

Astrometric microlensing



Credit: S. Gaudi

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{d_{ls}}{d_s d_l}}$$

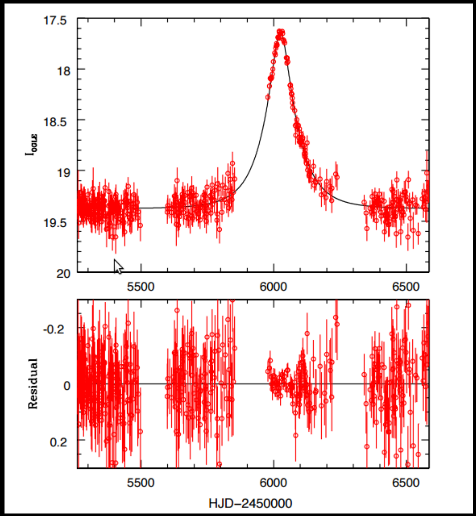
Search for compact objects

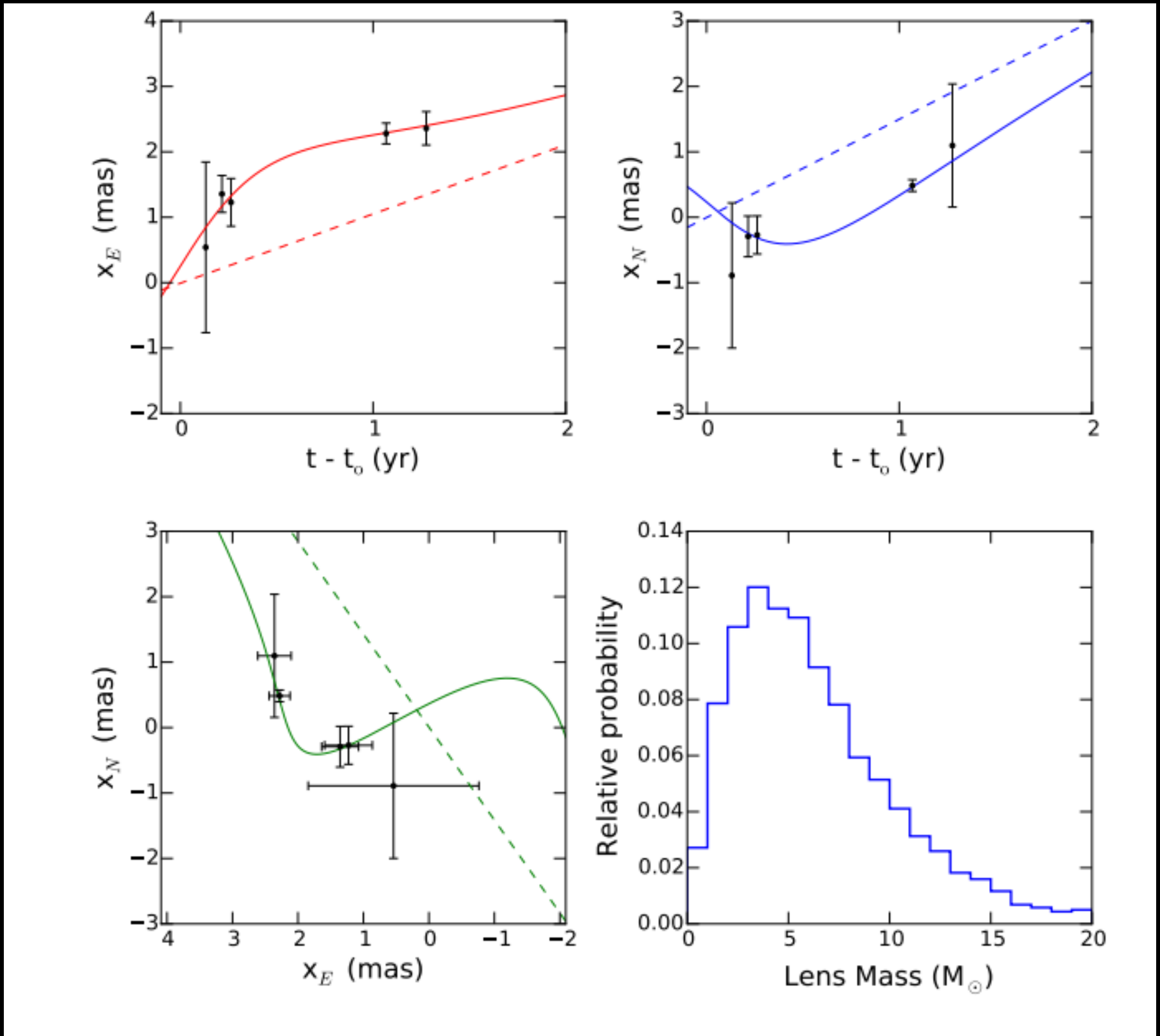
- Stellar-mass isolated BH/NS: product of stellar evolution
- Counting, and mass-function -> stellar death, GW,...

- Targets:
  - ML surveys (w/ long duration) i.e., Lu et al. (2016)
  - GAIA predictions (e.g., Bramich+2018, Ofek 2018)
  - High gal. lat blind surveys (e.g., ZTF)

A search (with: J. Lu+)

- OB120169
- Best fit:
- First 5 yr

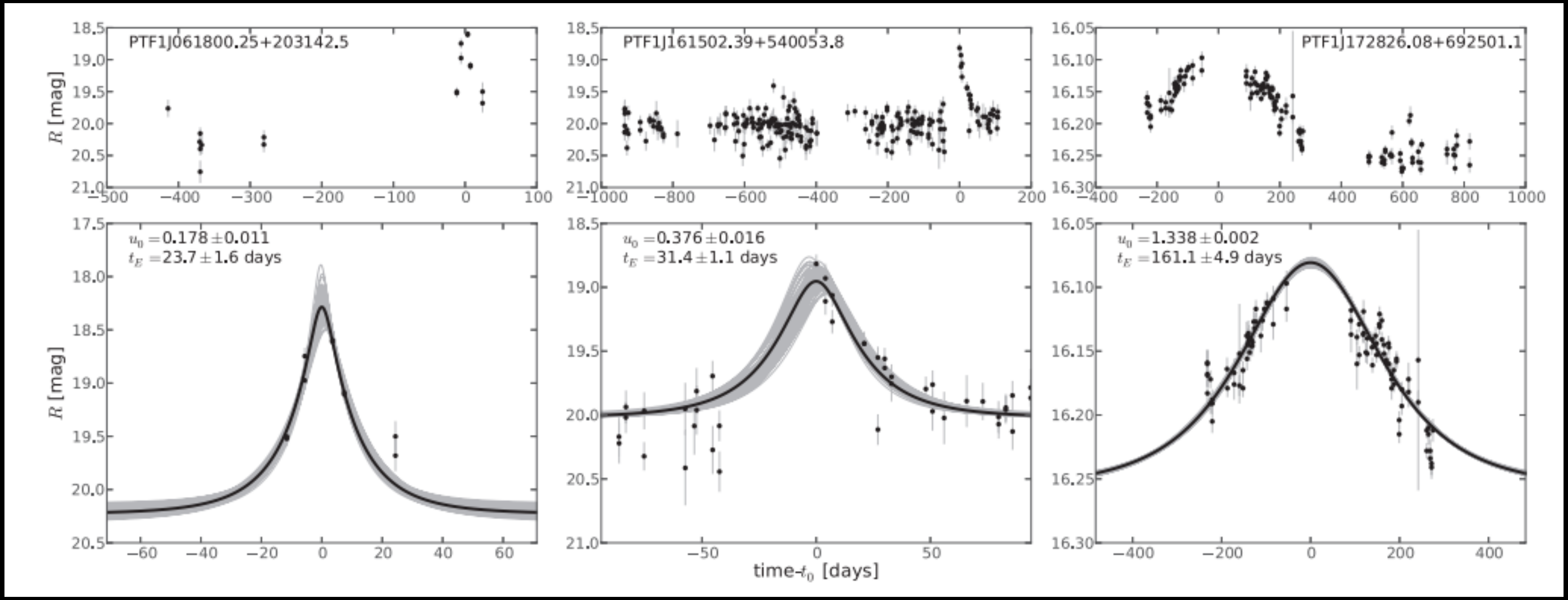




Lu et al. 2016 ApJ 830, 41

Relative Astrometry with ZTF

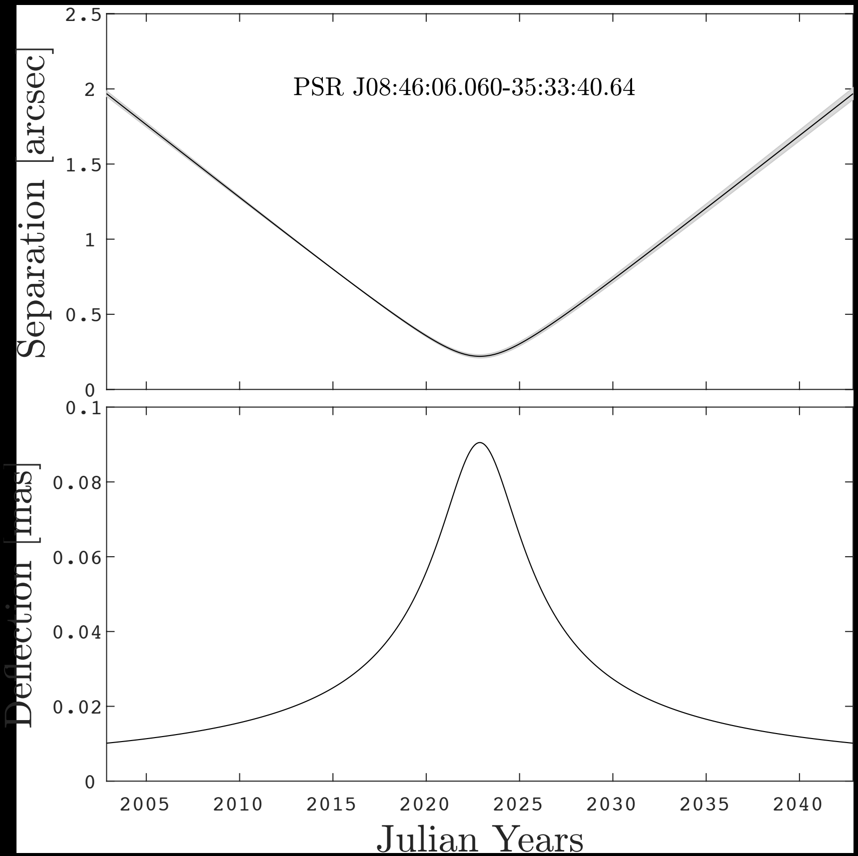
- ZTF can find (very rare) high Galactic latitude ML events (nearby->large θ_E)
- Candidates from PTF:



Price-Whelan et al. 2014

Lensing by pulsars

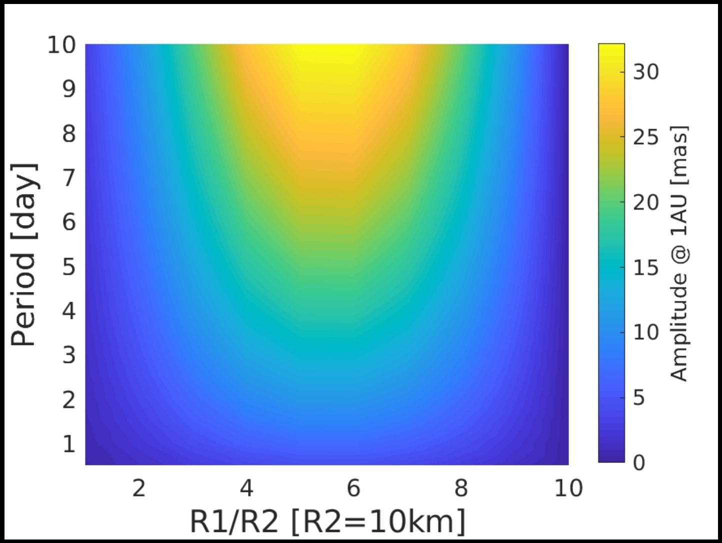
- Another possibility: detecting astrometric lensing of known pulsars on background stars



Ofek 2018, ApJ

Binary asteroids

- Characterizing binary asteroids is important for understanding the YORP effect
- Methods: radar, light curves, imaging,…
- Detection using the Center of light motion (Segev et al., in prep.)



Lensed quasars / time delays

- Time delay measurements of lensed quasars offers an independent method for measuring H_0.
- Hindered by: model dependent and systematics – requires large sample.
- Expensive!
- Springer+ in prep. – using Astrometry…

Why not GAIA?

- Cadence is too sparse for some applications
- Missing some objects (e.g., GW170817)

Precision photometry motivation

- Search for transiting exoplanets
- Debris around WDs
- Role of massive spectroscopy: radial velocities

Sub mas astrometry from the ground?

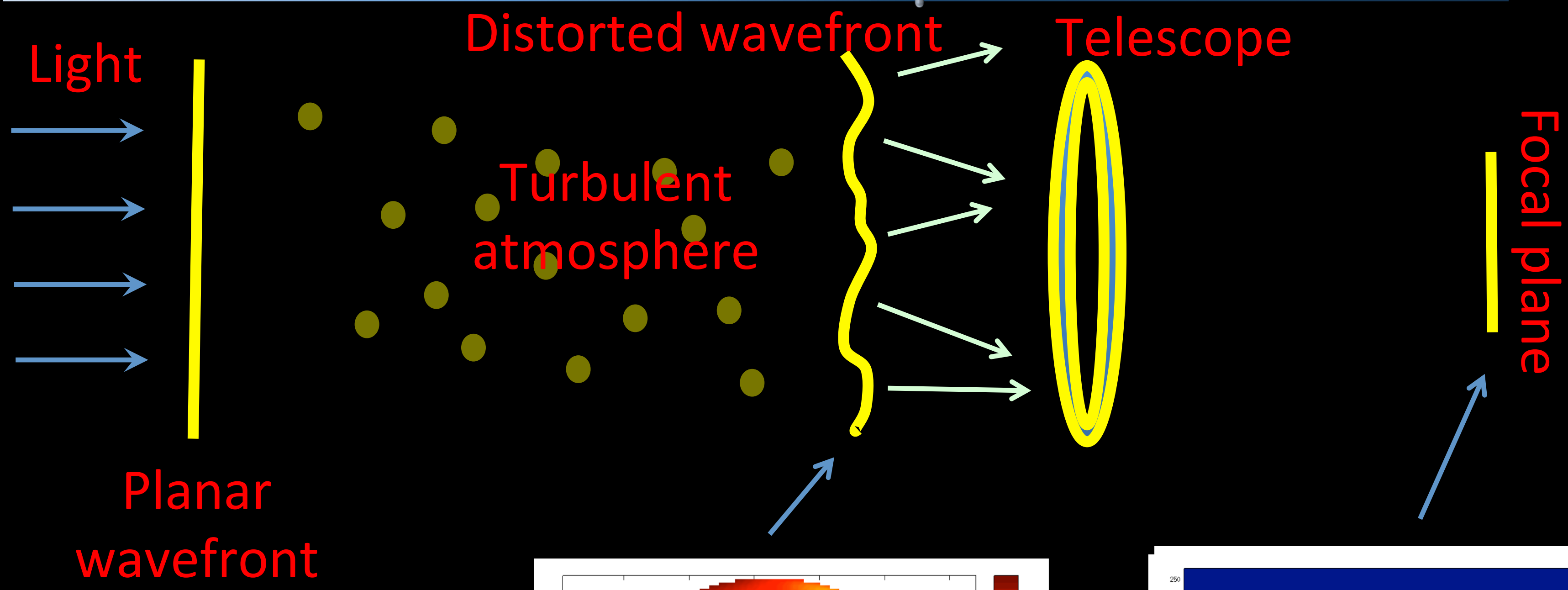
- With AO 100-200 μas is possible
- With GRAVITY ~tens μas is doable
- For seeing limited Monet (1983) claimed 1 mas parallax accuracy, but...
- All methods are likely limited by systematics(!)

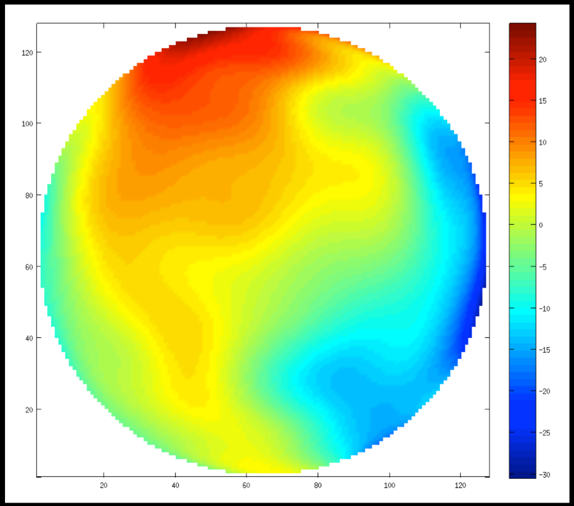
Astrometry – limiting factors

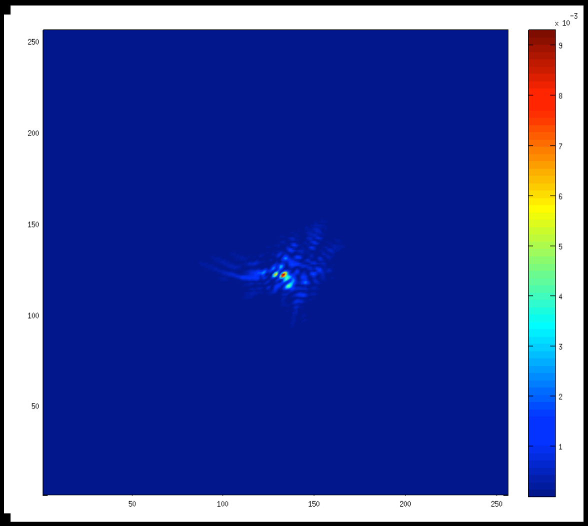
- Poisson noise: FWHM/$\sqrt{N_{ph}}$~1 mas
- Optical distortions: ~1"/deg
- Atmospheric refraction: ~2"/deg
- Color refraction: ~a few mas
- Aberration of light: 0.5"/deg
- Grav. Deflection: ~0.1 mas/deg
- At. scintillation: FWHM/(Exp/τ_{sc})~20mas
- Systematics:
  - My leading suspect – non uniformities in detectors – a few milipixel(?)

Have model

The turbulent atmosphere & the PSF

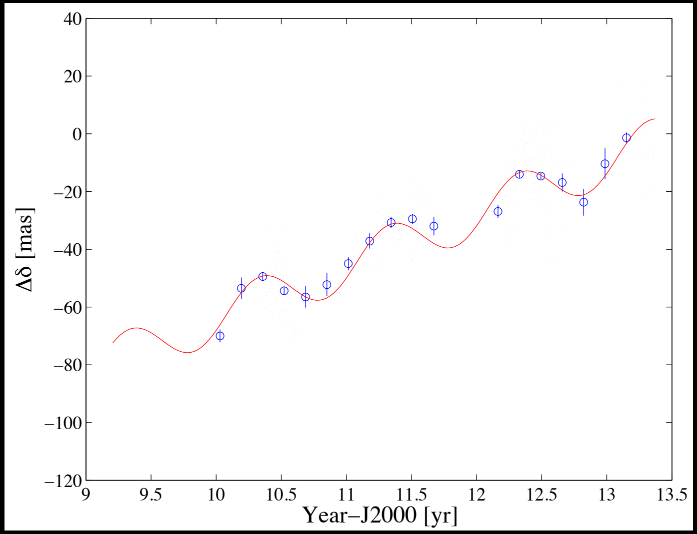


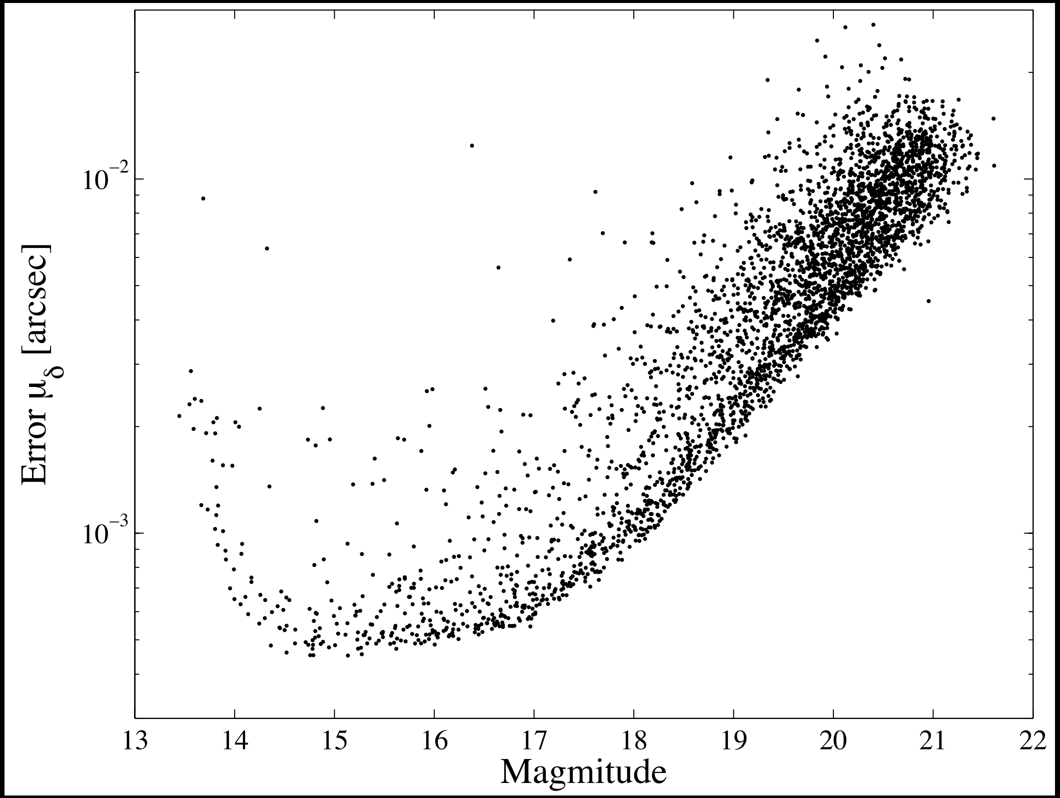




Before GAIA...

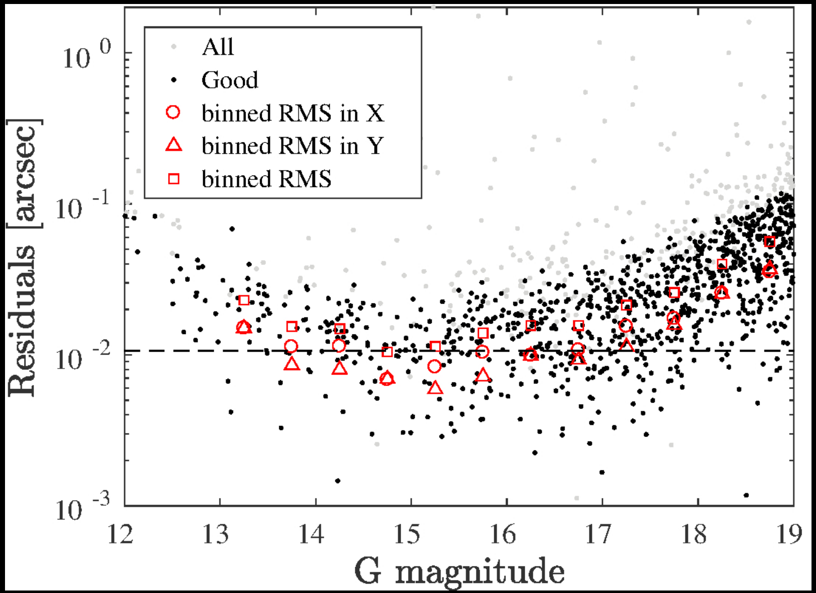
- Relative astrometry w/PTF
- Problem: difficult to estimate if the results are biased





Astrometry relative to GAIA

- New astrometry code – performances:
- Failure rate ~<1 in 50,000
- Typical rms w/PTF: 14 mas (2 axes comb.)
- ~2-3 times better than ZTF pipeline



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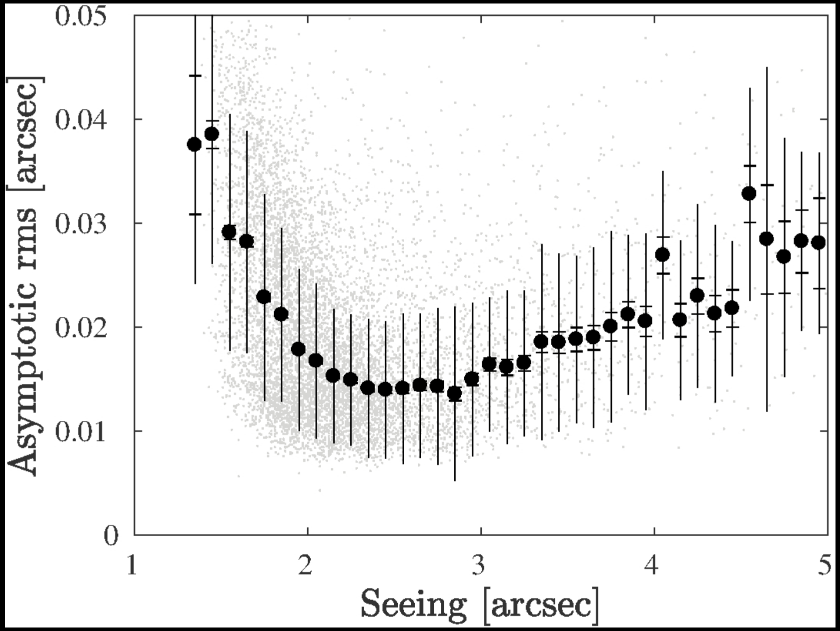
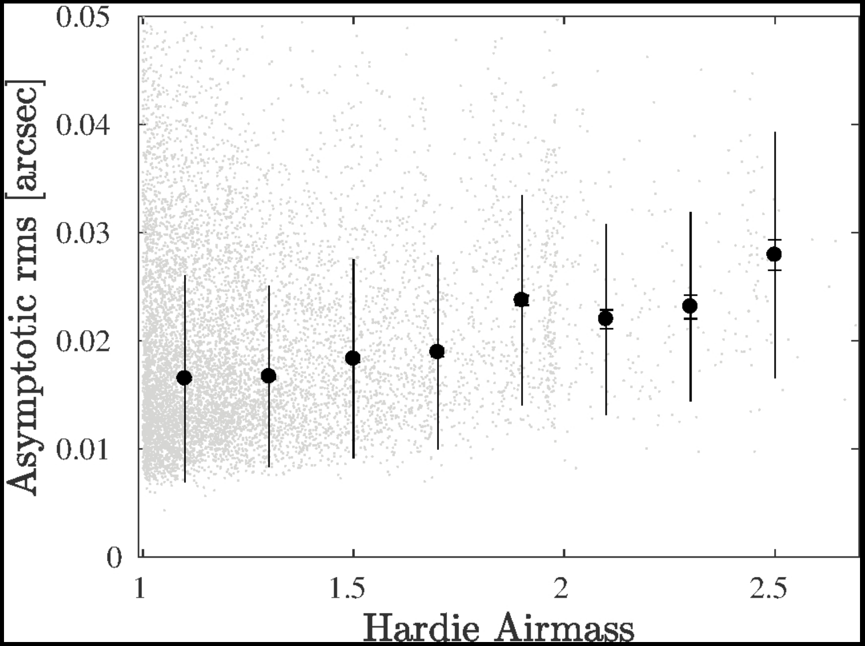
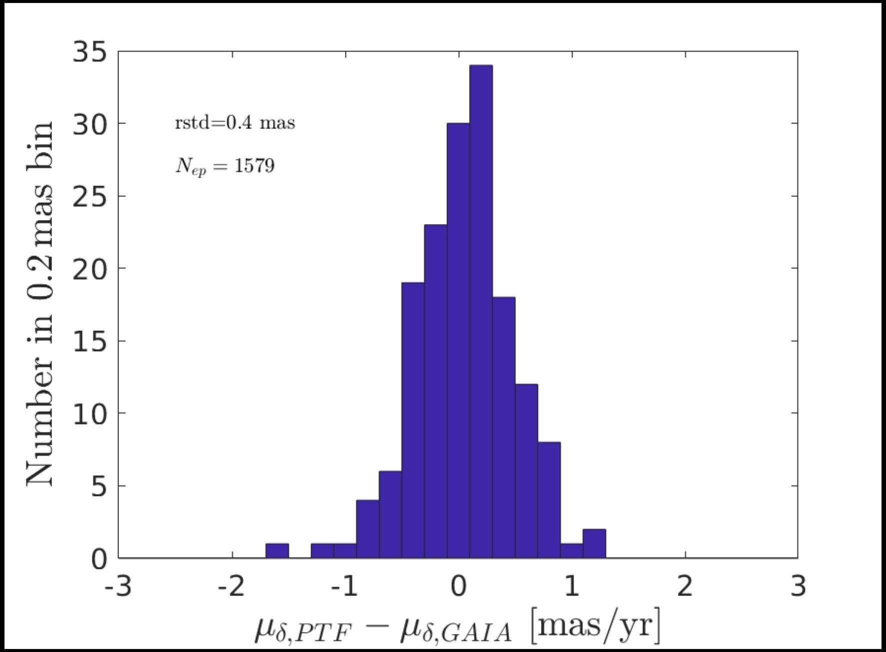
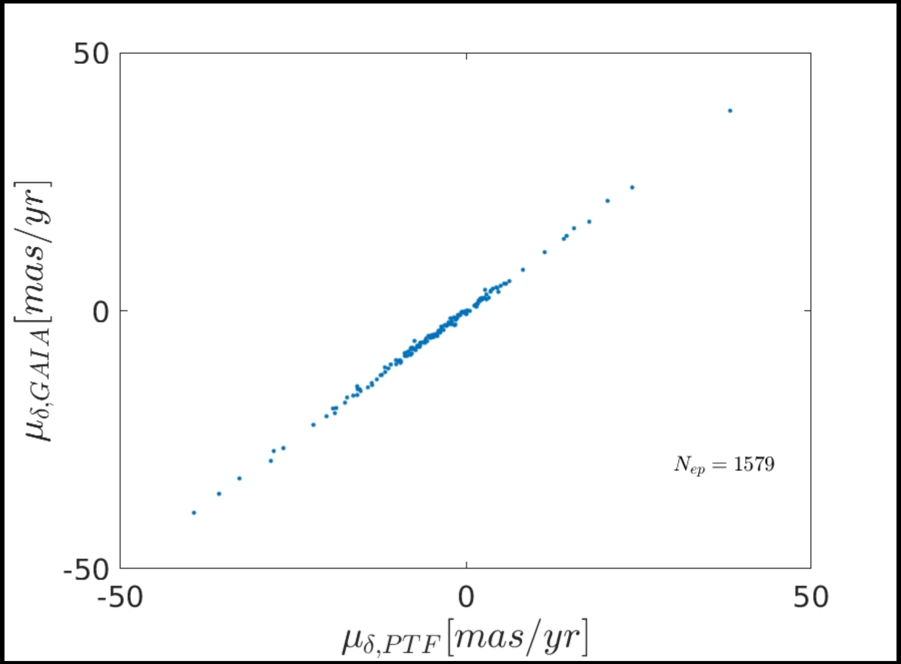




Comparison w/GAIA

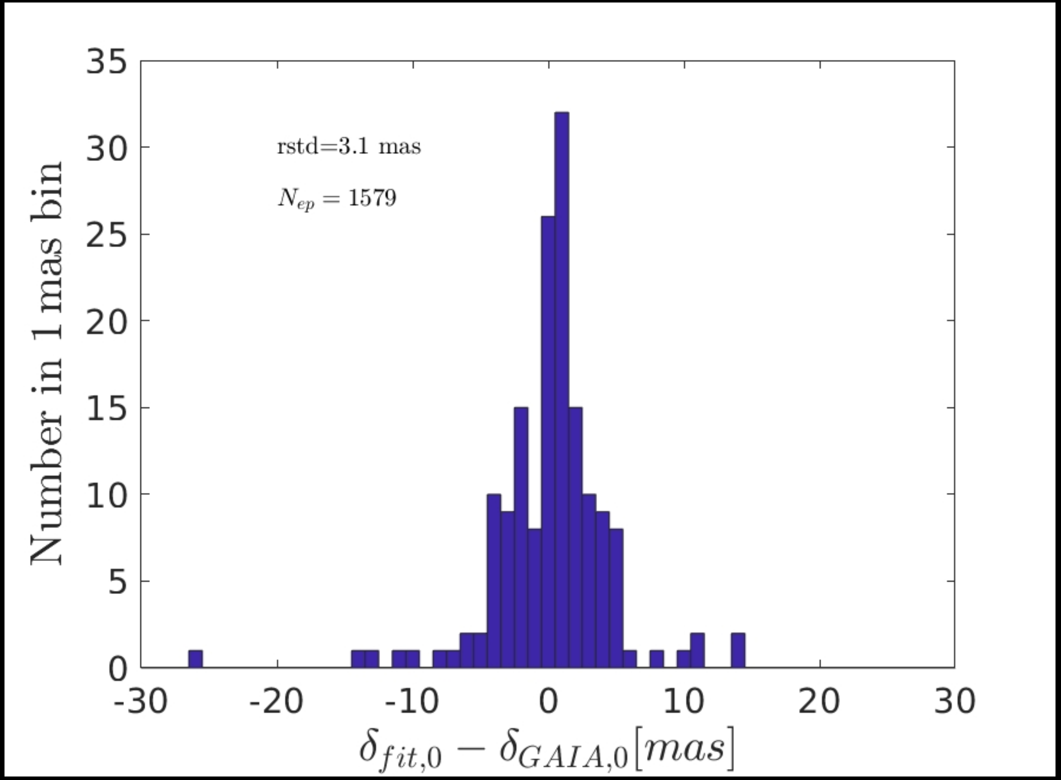
- Use GAIA to verify results
- ~0.4 mas/yr in PM over 7 years





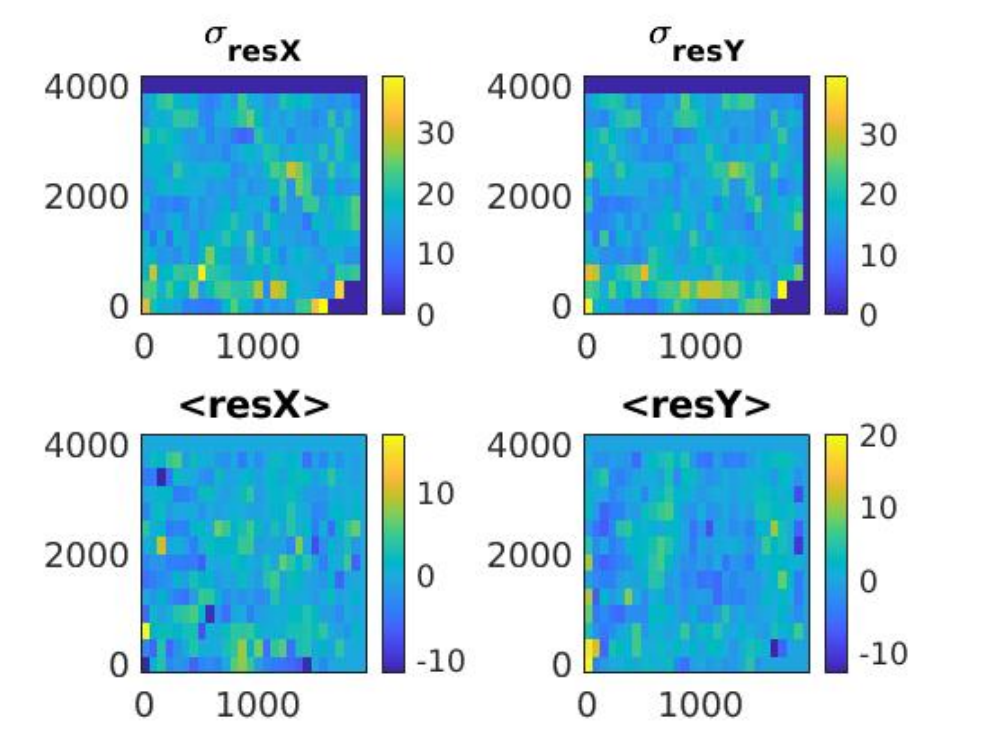
Comparison w/GAIA

- but ~3mas error in positions (w/1500 images)
- Predicted Poisson noise: 14/sqrt(1500)~0.4 mas
- Systematics!



Searching for systematics

- Pixel size variations?
- Requires simultaneous solution



Conclusion / Astrometry

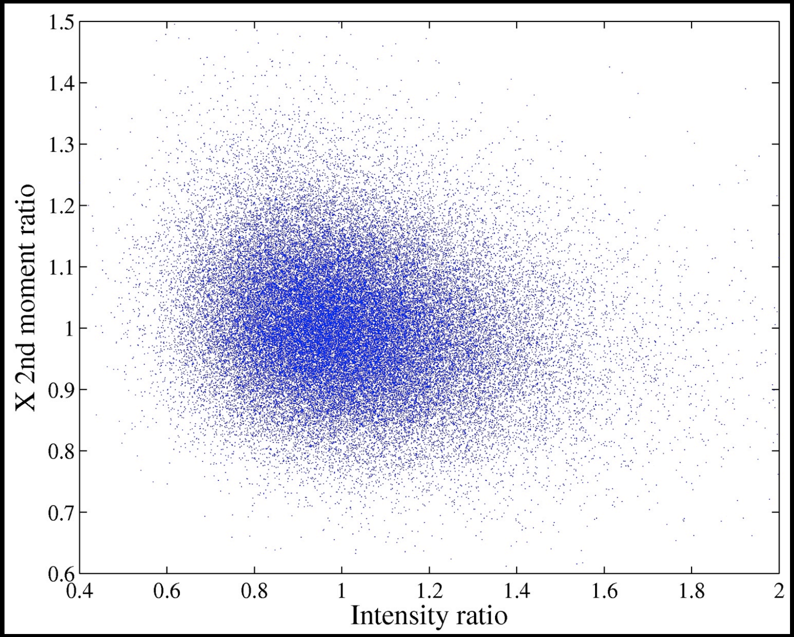
- Ground based seeing limited astrometry is useful
- We currently able to measure stellar positions to accuracy of about 3mas
- We are limited by systematic noise
- Next: trying to beat the systematics

Precision photometry / Limitations

- Flat fielding errors
  - Separate scattered light
  - Color dependency
- Scintillations
  - Intensity scintillations
  - Phase scintillations
- Transparency
  - Correlated noise

Precision photometry / Mitigation

- Flat fielding errors
  - TDI
  - Out of focus / small pixels
  - Keep star on the same pixel (hard)
- Scintillations
  - ML?
  - Aperture corrections
  - Fast imaging!
- Transparency [progress]
  - Model and filtering
  - Fast imaging!



End

Optimal Image coaddition

Transparency

Image

Noise

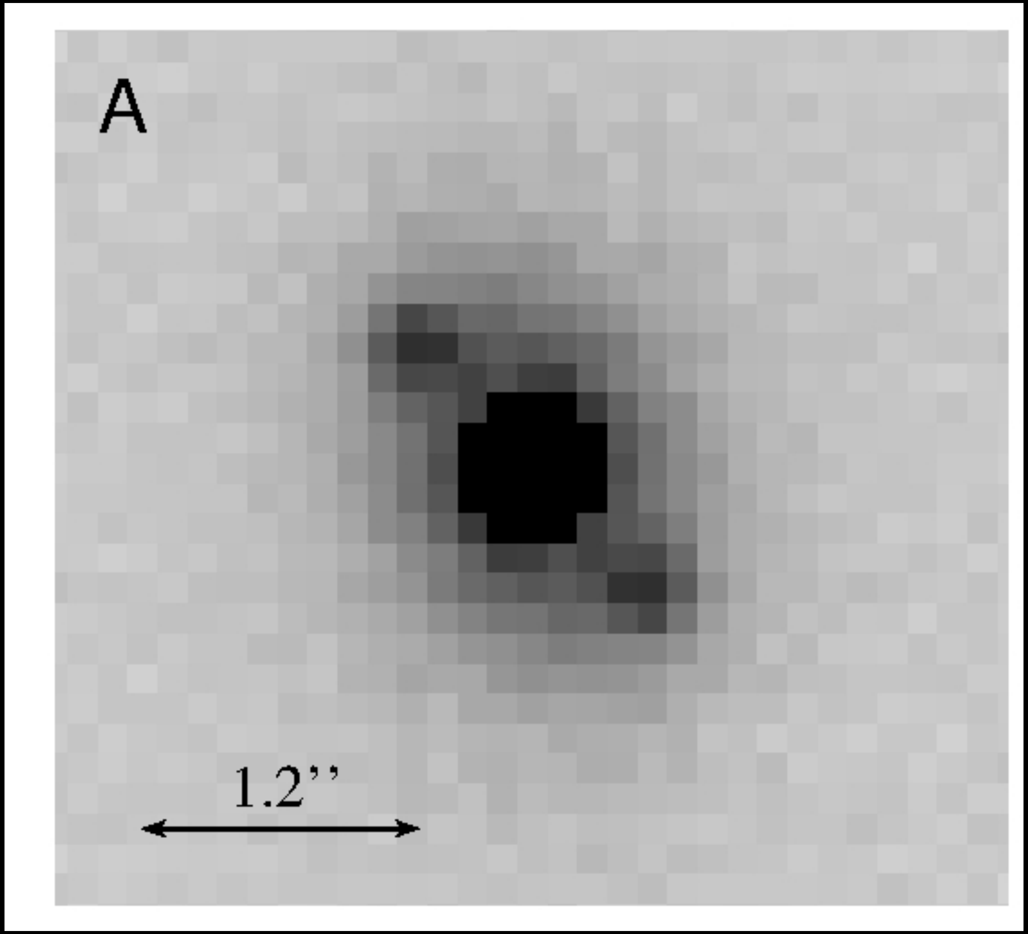
PSF of M_j

$$\hat{R} = \frac{\sum \frac{F_j}{\sigma_j^2} \hat{M}_j \bar{\hat{P}}_j}{\sqrt{\sum \frac{F_j^2}{\sigma_j^2} \left|\hat{P}_j\right|^2}}$$

$$\hat{P}_R = \sqrt{\sum \frac{F_j^2}{\sigma_j^2} \left|\hat{P}_j\right|^2}$$

Zackay & EO 15a; 15b

Coaddition: Tests on real images



Zackay & Ofek 2015b