Astrometry with the WFIRST WFI

Robyn Sanderson
for the WFIRST Astrometry Working Group

WFIRST is an exquisite astrometric instrument

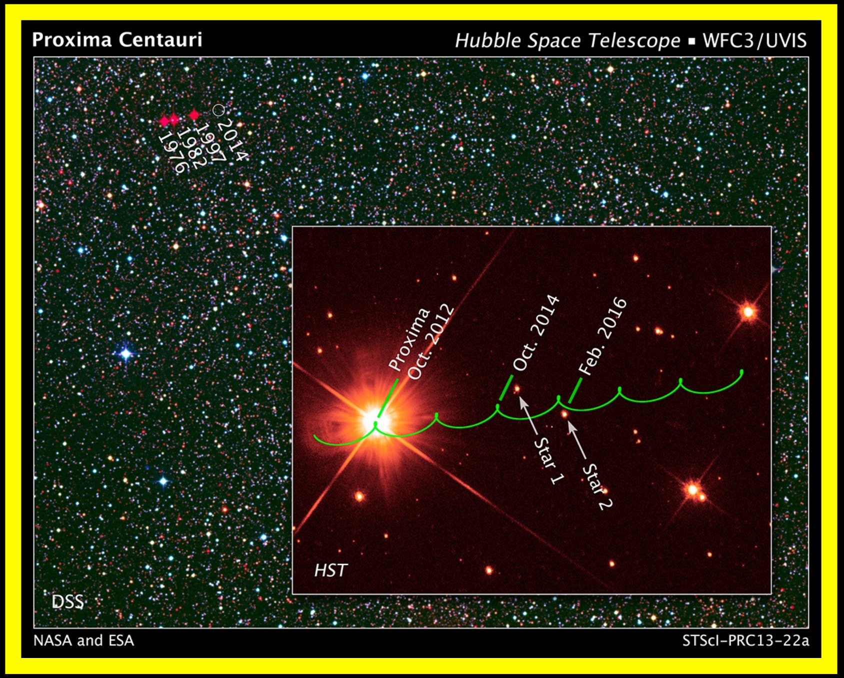
- Same **mirror size** as Hubble, **space-based** resolution
- **100x larger FOV** —> many more astrometric anchors per field
- Goes far **deeper** than Gaia will
- **Infrared**: Galactic plane and bulge are accessible
- **Quieter** thermal environment than HST
- HLS and microlensing survey - astrometry for “**free**”

WFIRST Astrometry Working Group

- Robyn Sanderson [Caltech/Columbia] - FSWG Co-Chair
- Andrea Bellini [STScI] - Science Center Co-Chair
- Sangeeta Malhotra [GSFC/ASU] - Project Liaison
- Jessica Lu [Berkeley] - Milky Way GO SIT liaison
- Jay Anderson [STScI] - MicroSIT team member
- David Bennett [NASA/GSFC] - FSWG, MicroSIT Deputy PI
- Jason Rhodes [JPL]
- Scott Gaudi [OSU] - FSWG, MicroSIT PI
- Raja GuhaThakurta [UCSC, UCO/Lick Obs]
- Michael Fall [STScI] - STScI AWG liaison
- Peter Melchior [Princeton]
- Stefano Casertano [STScI]
- Mike Shao [JPL]
- Ed Nelan [STScI]

Ways to do astrometry with the WFIRST WFI

- Direct reference
  - Assume 0.5 mas localization, 5 yr time baseline, good S/N
  - HLS fields: ~25-50 μas/yr
  - Bulge fields: ~0.05 μas/yr (systematics?)
  - Pointed obs can go deeper
  - Longer time baselines cross-platform (HST, Gaia, JWST)



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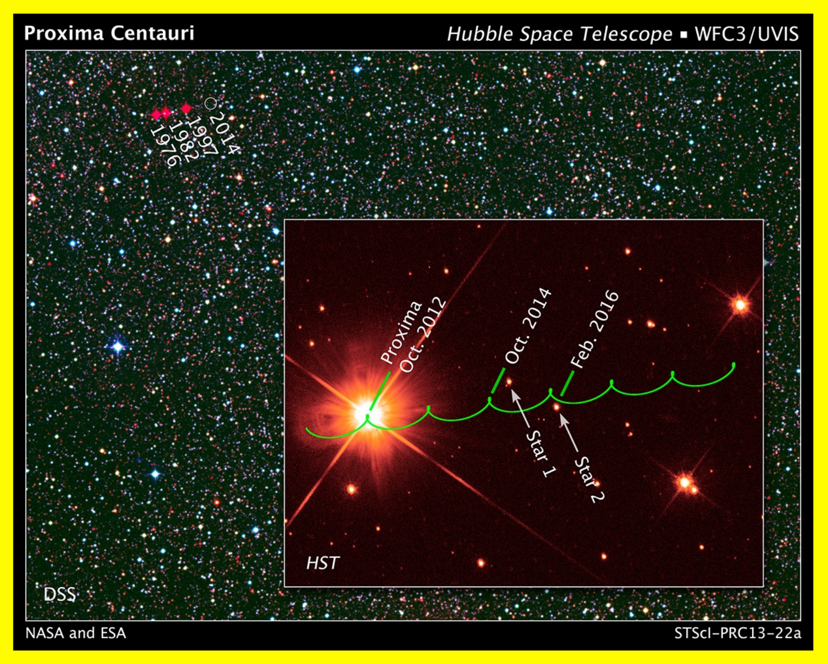
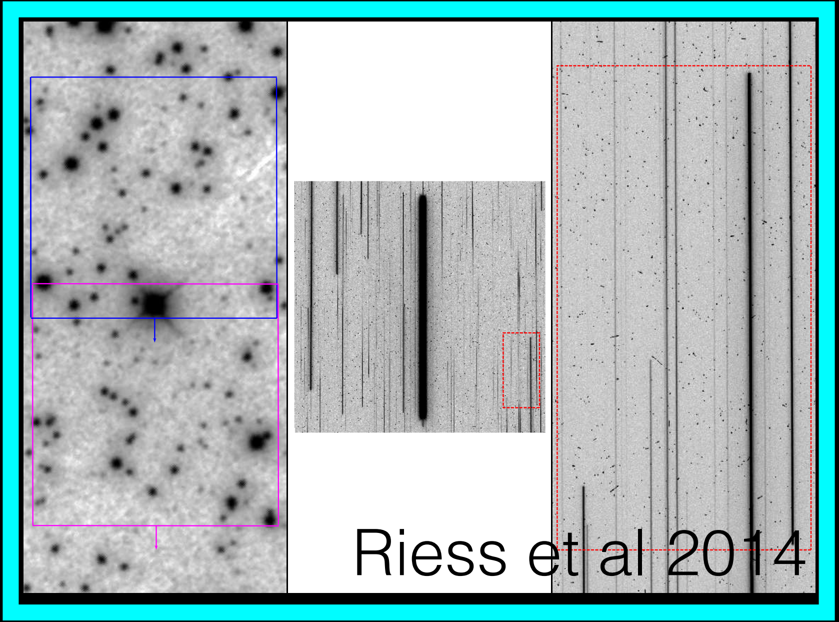
- Spatial scanning
  - good for fairly bright stars
  - 10 μas or better precision





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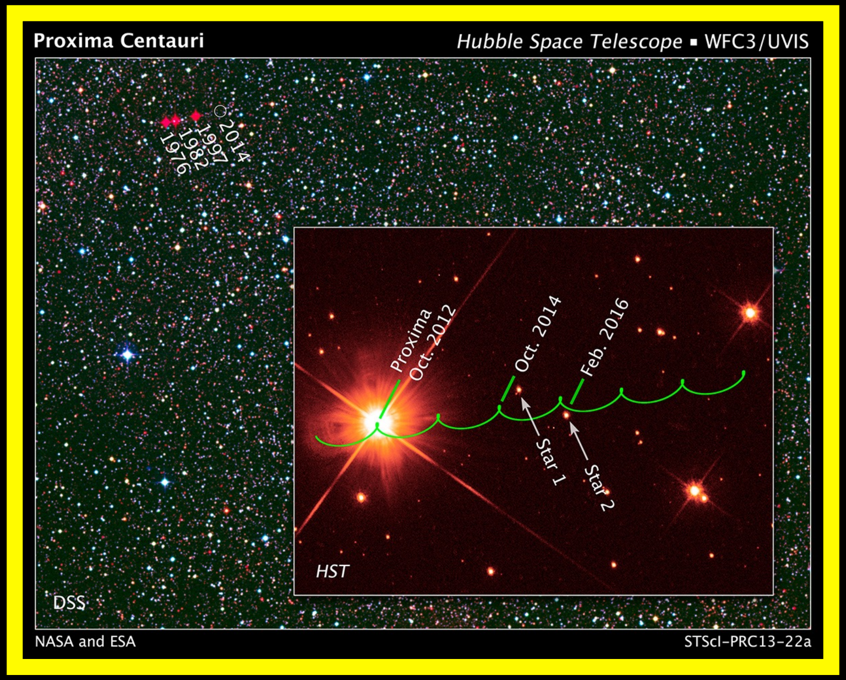

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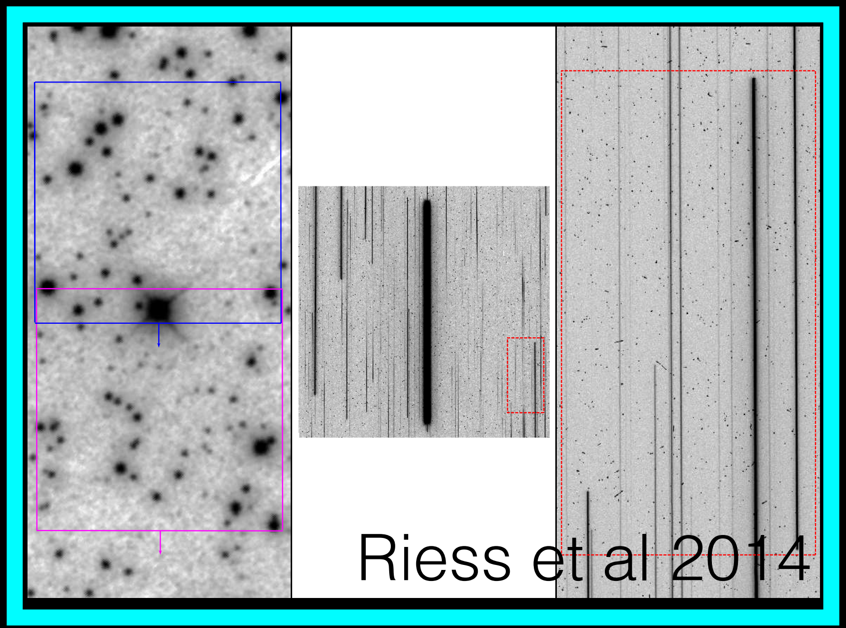
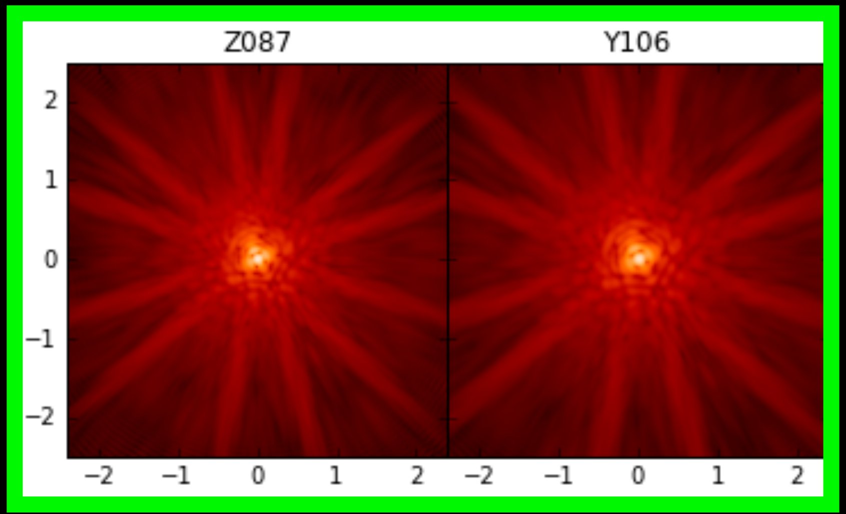


- Modeling of diffraction spikes
  - Can reach ~3–10 μas for bright stars



WFIRST can use Gaia stars as guide stars and astrometric anchors

For G<15.5:

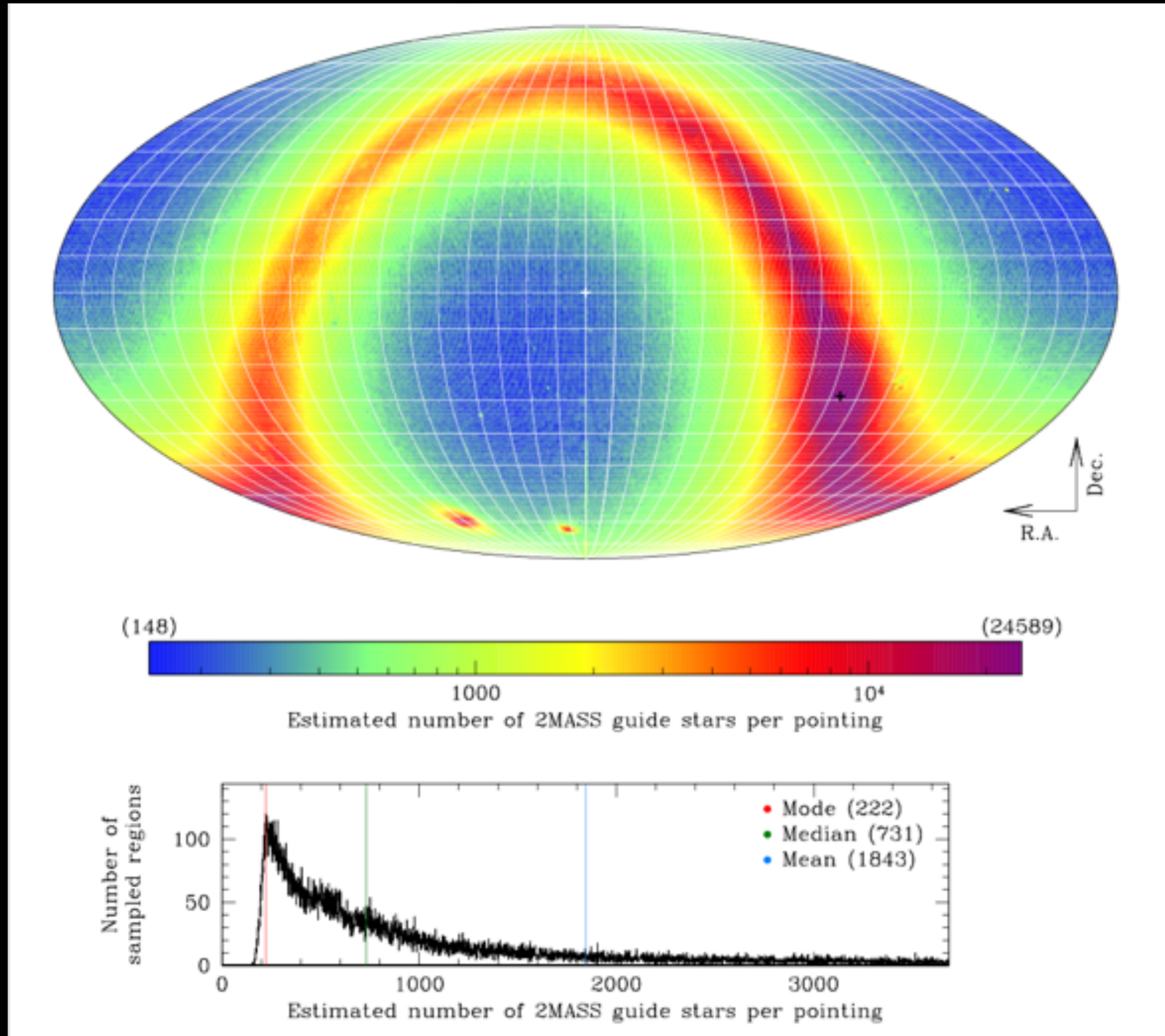
Gaia parallax errors are $5<\sigma_\pi<40$ μas

$\sigma_\mu \sim 0.5\sigma_\pi$ μas/yr

(end of mission)

Minimum **150** stars per WFIRST field

$15.5 > H_{2MASS} > 9.5$, no bright neighbors within 5"



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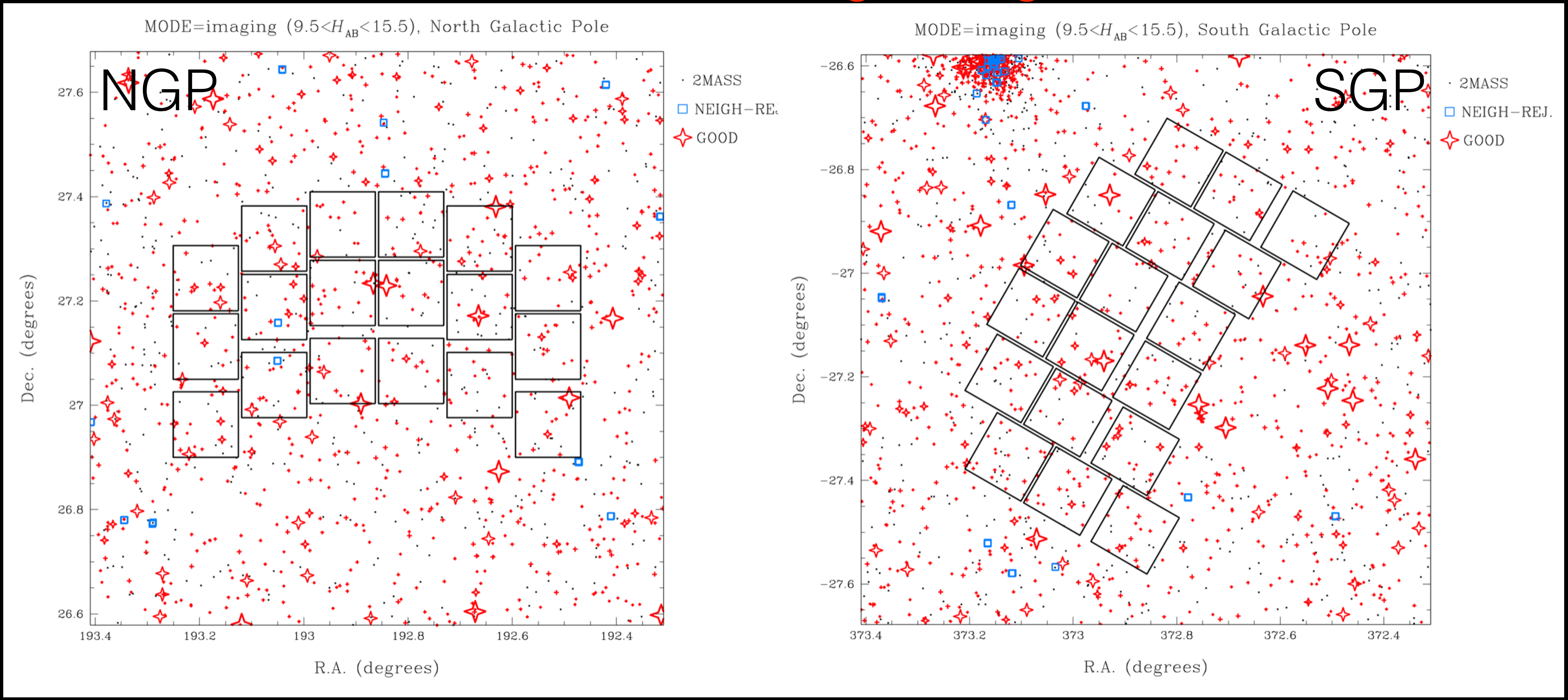
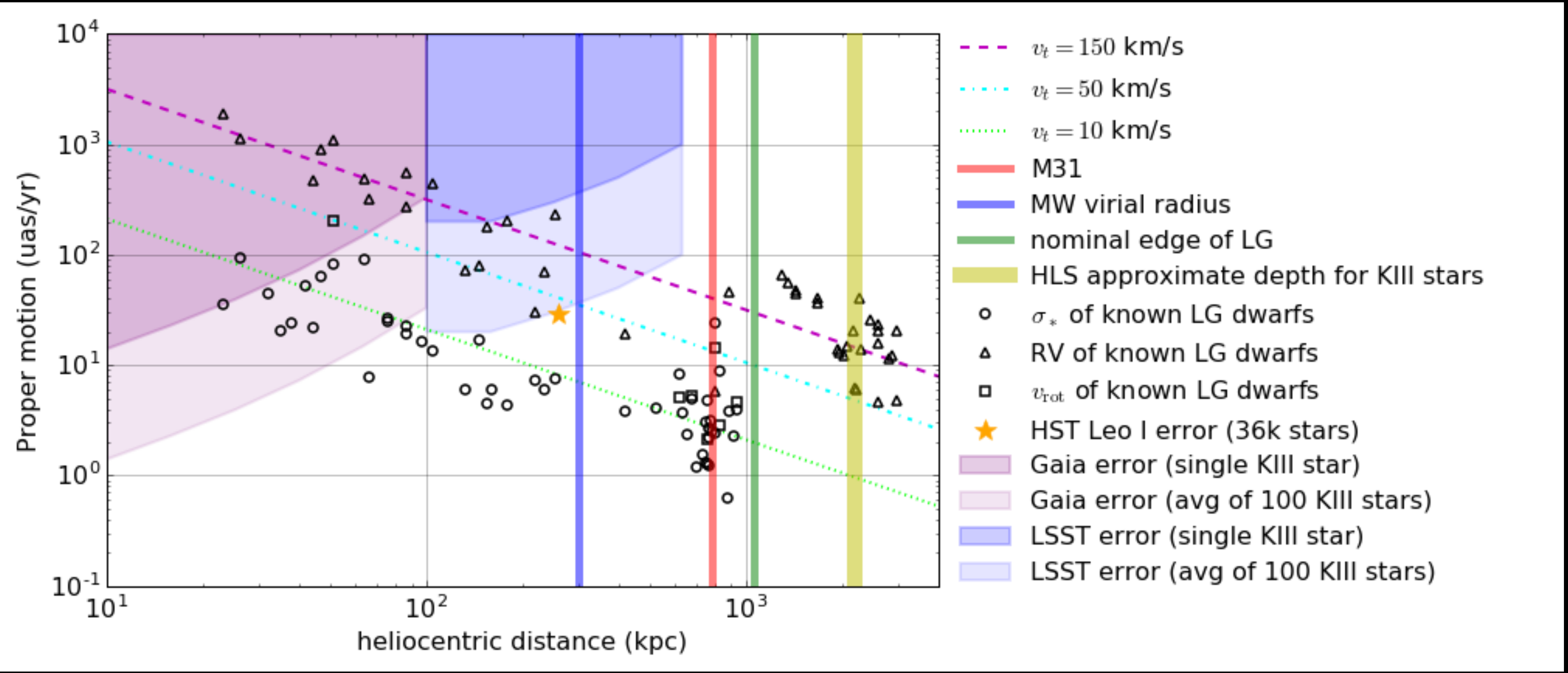


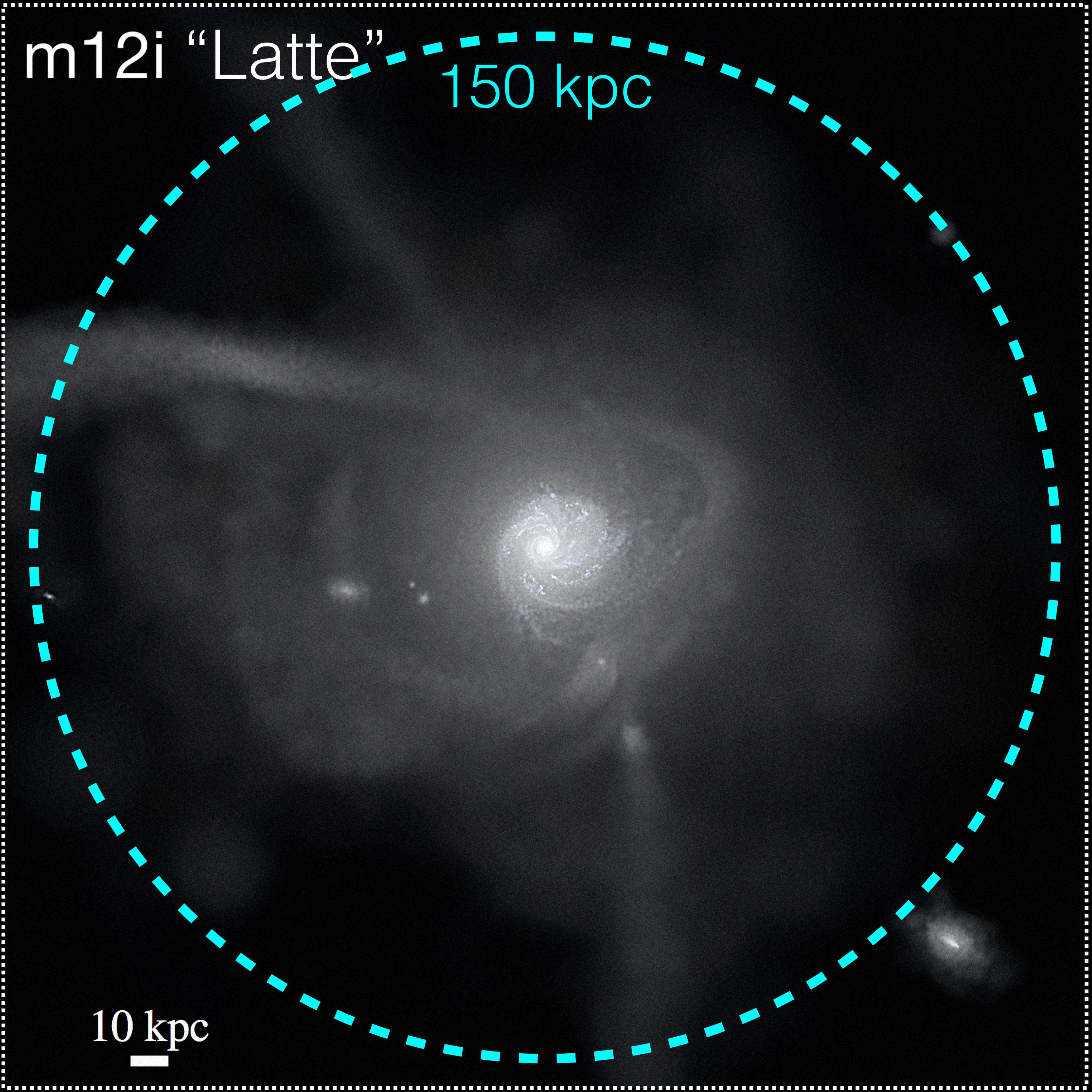
WFIRST will go deeper than Gaia or LSST

Typical proper motions in the Milky Way/Local Group



Structure in the Galactic halo

Bound and disrupted satellites extend to the MW's virial radius



Wetzel et al. 2016

- Tracers of the MW's dark halo
- Tests of LCDM through:
  - accretion history
  - mass and shape of DM halo
  - mass and orbit distribution of satellites
- bound structures good GO targets
- unbound structures require wide area —> HLS

300 kpc
(Rvir?)

Orbits & dynamics of MW satellites

HST-WFIRST joint observations are powerful!
This scaling does not account for WFIRST's larger FOV

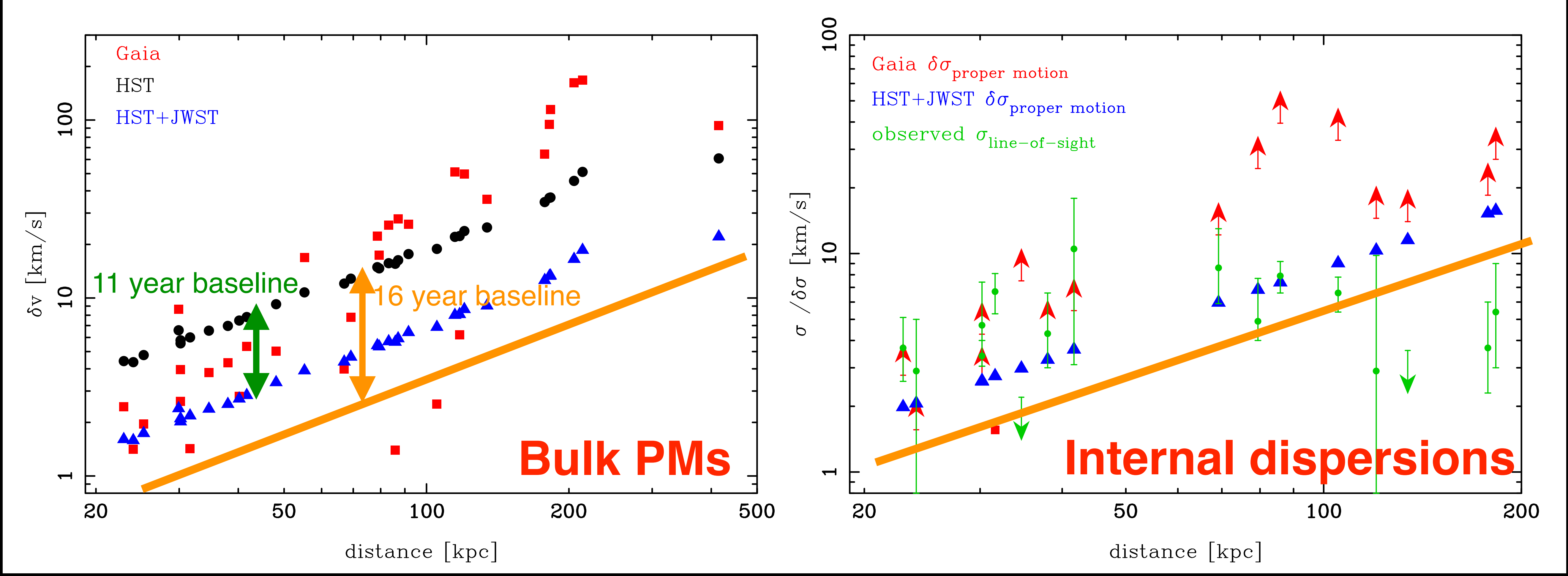
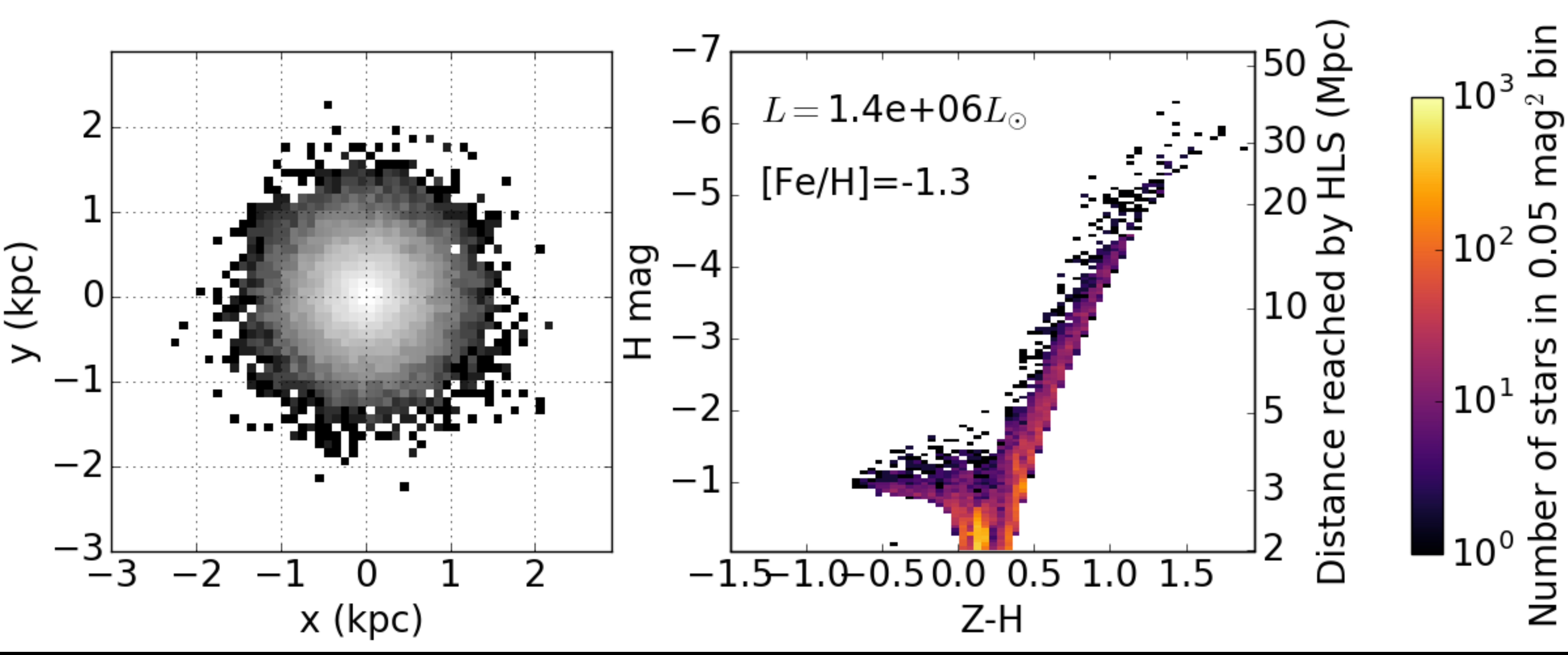


figure courtesy A. Wetzel, from funded HST Cycle 24 proposal

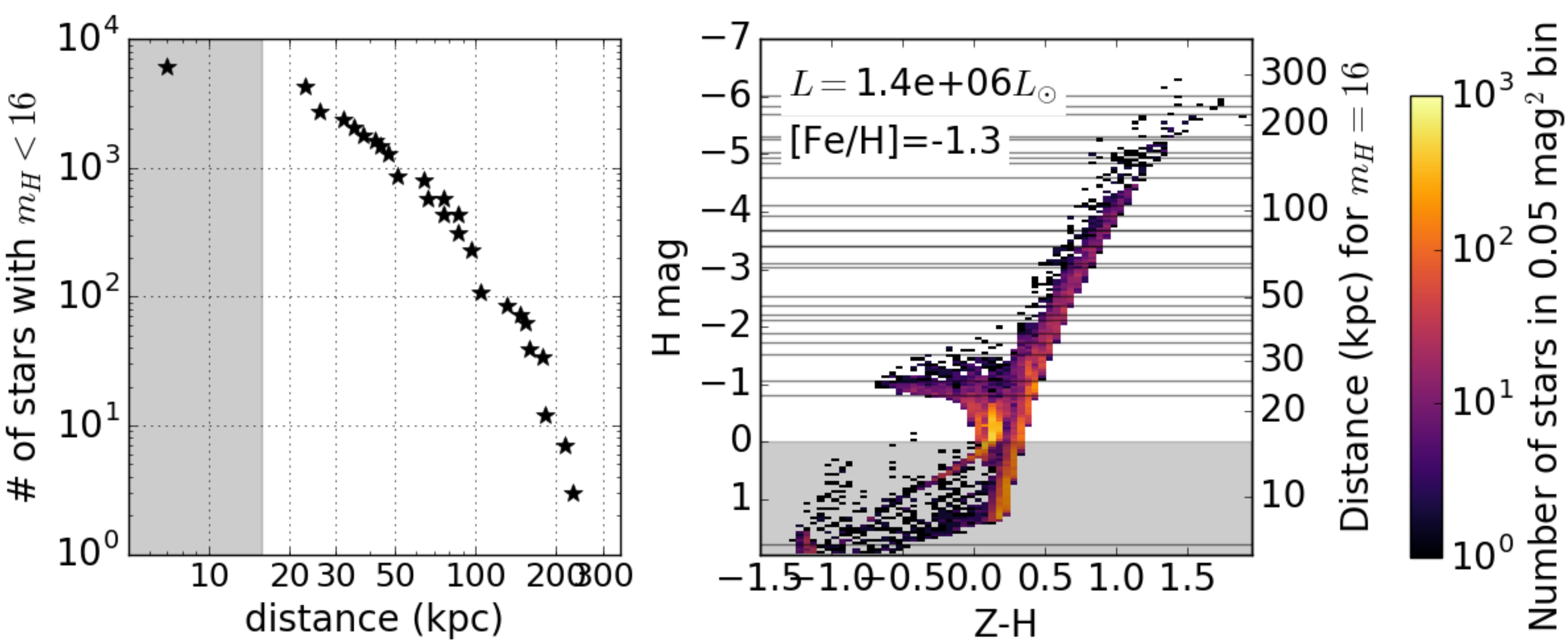
Orbits & dynamics of MW satellites and beyond?



using dwarf galaxy model from Bullock & Johnston 2005 + IR isochrones from L. Girardi
inspired by Antoja et al. 2015

Orbits & dynamics of MW satellites

Internal dynamics of nearby dwarfs
are potentially accessible to spatial scans



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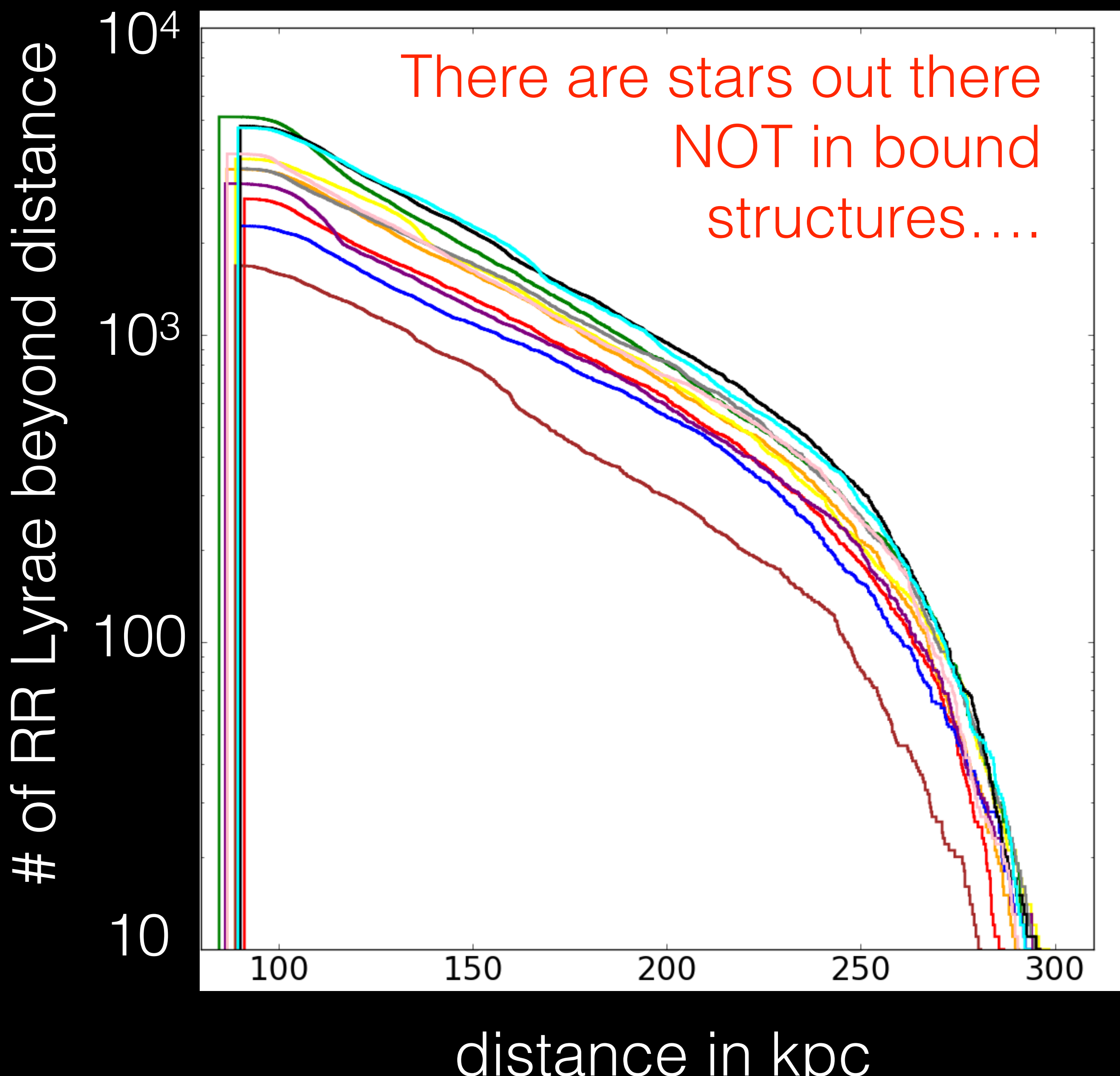
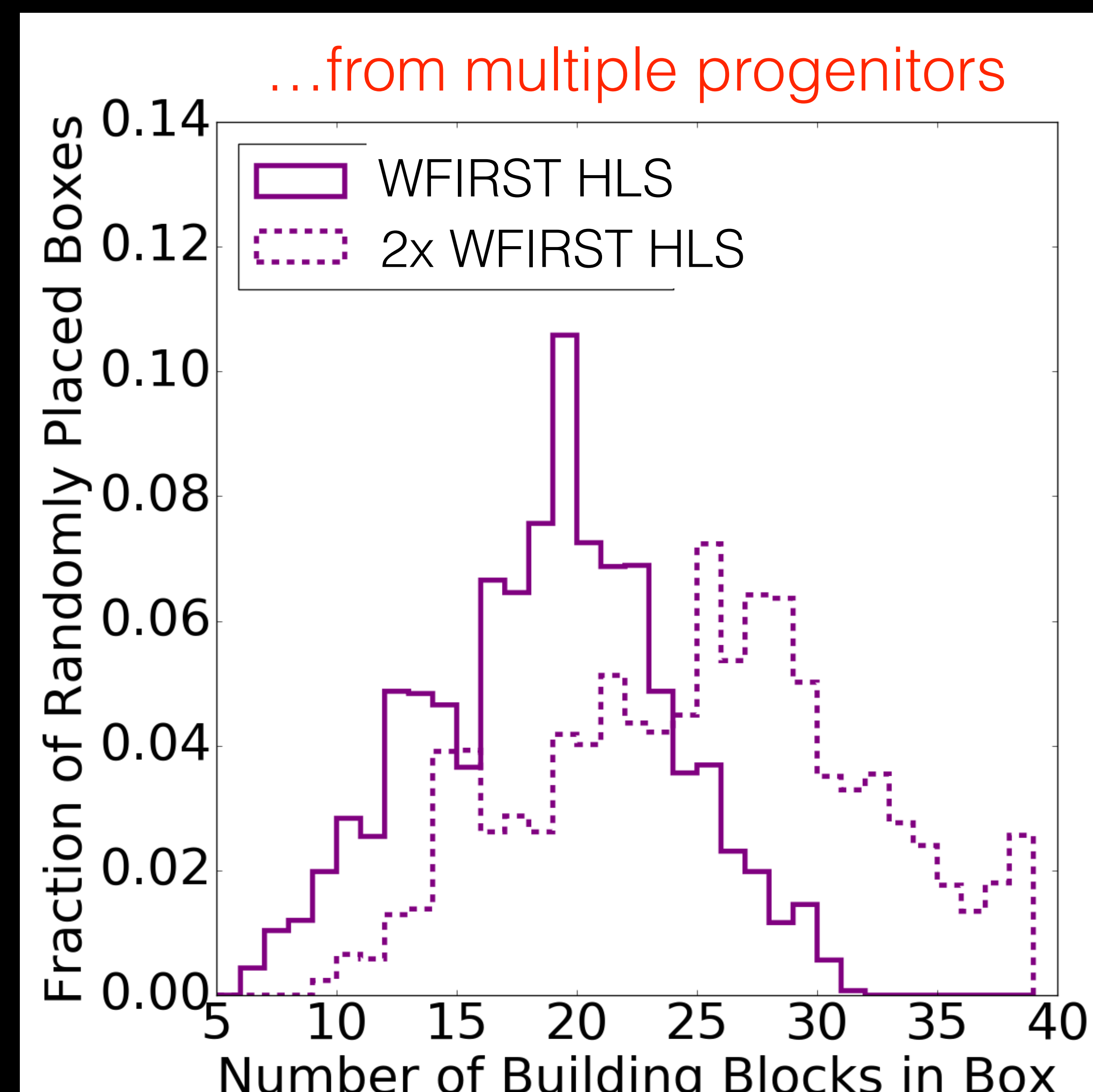
Tidal structures in the Galactic halo with the HLS

Discovering & connecting tidal structures beyond 100 kpc





Sanderson, Secunda,
Johnston, & Bochanski 2017

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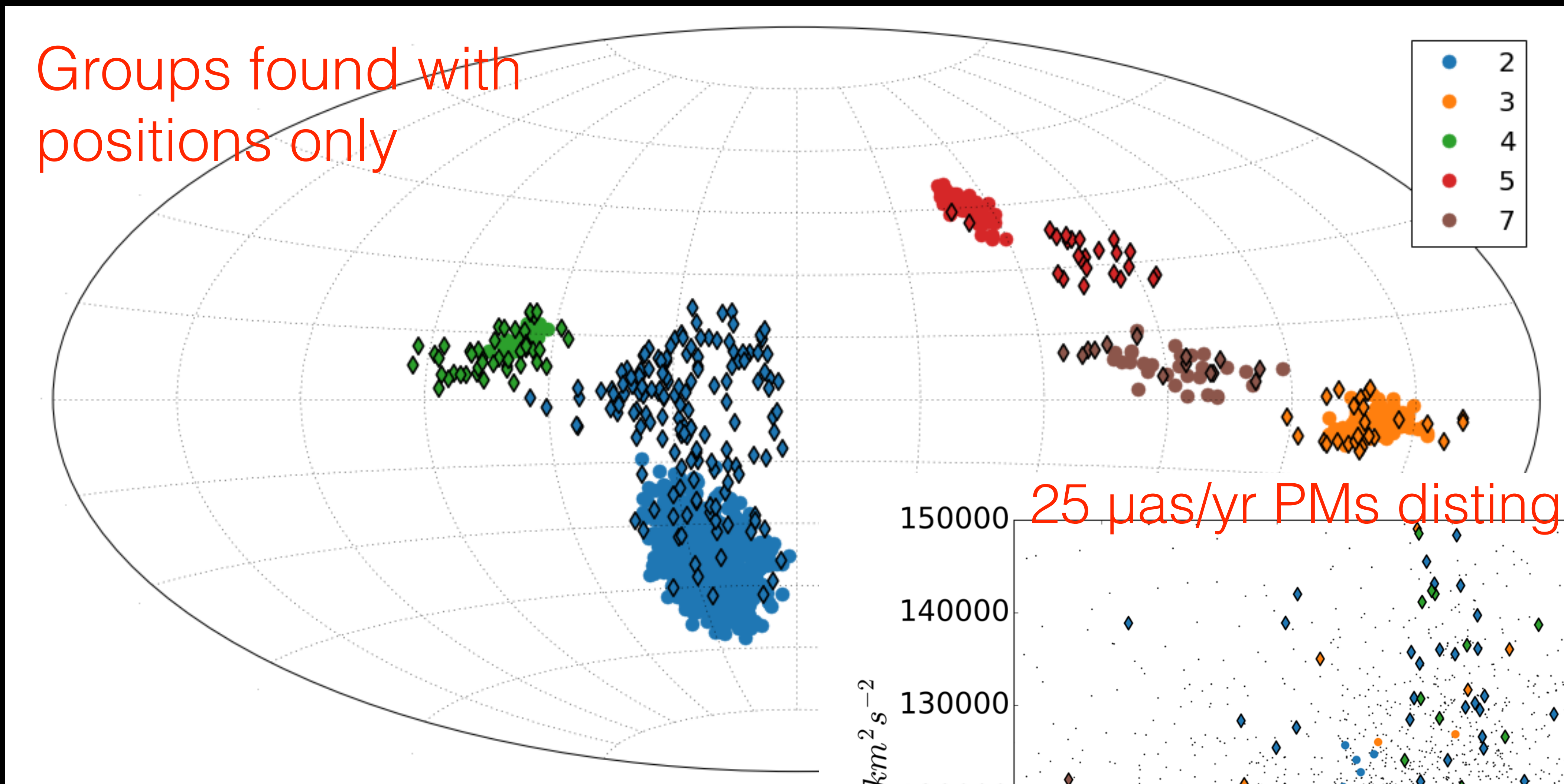
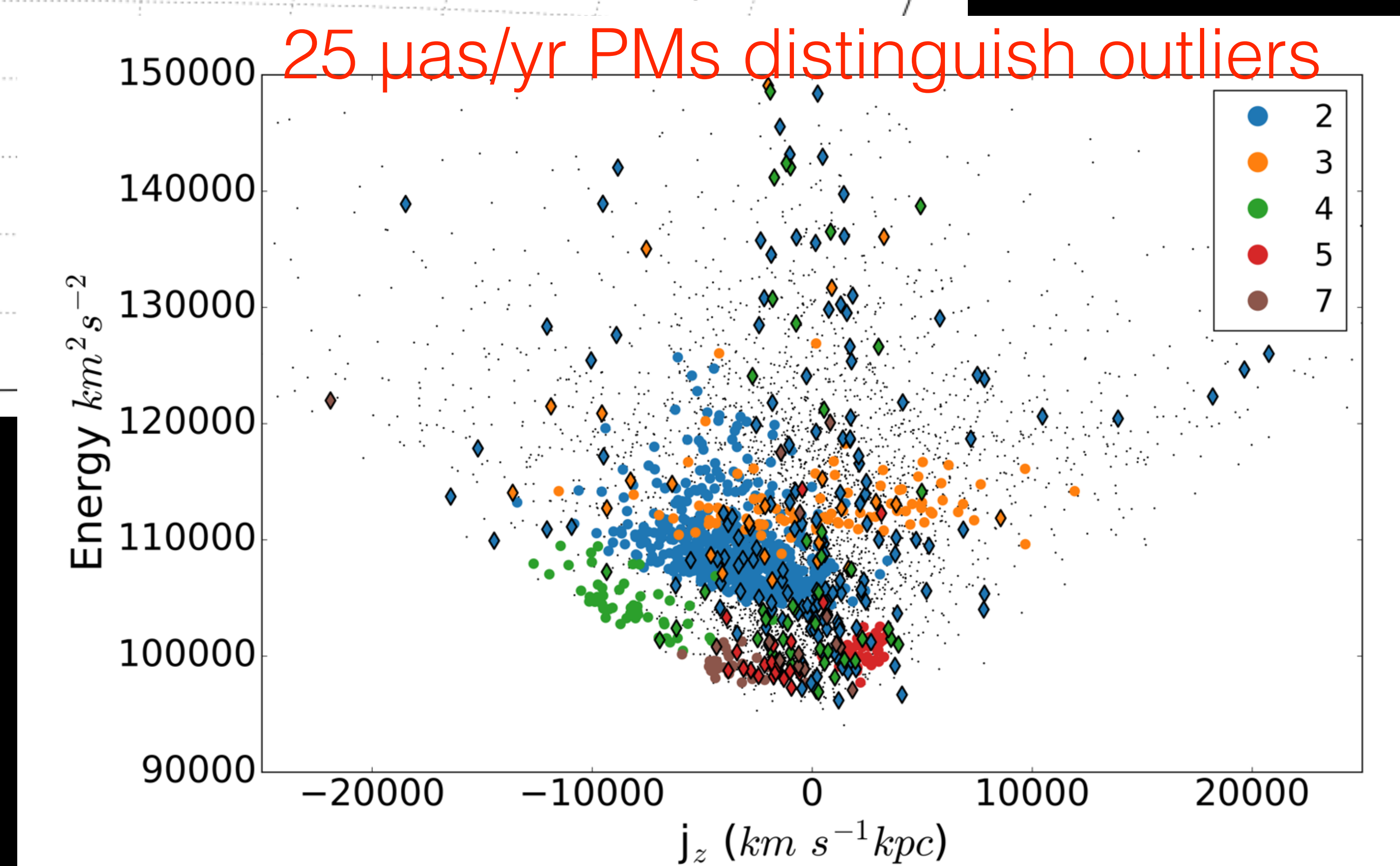




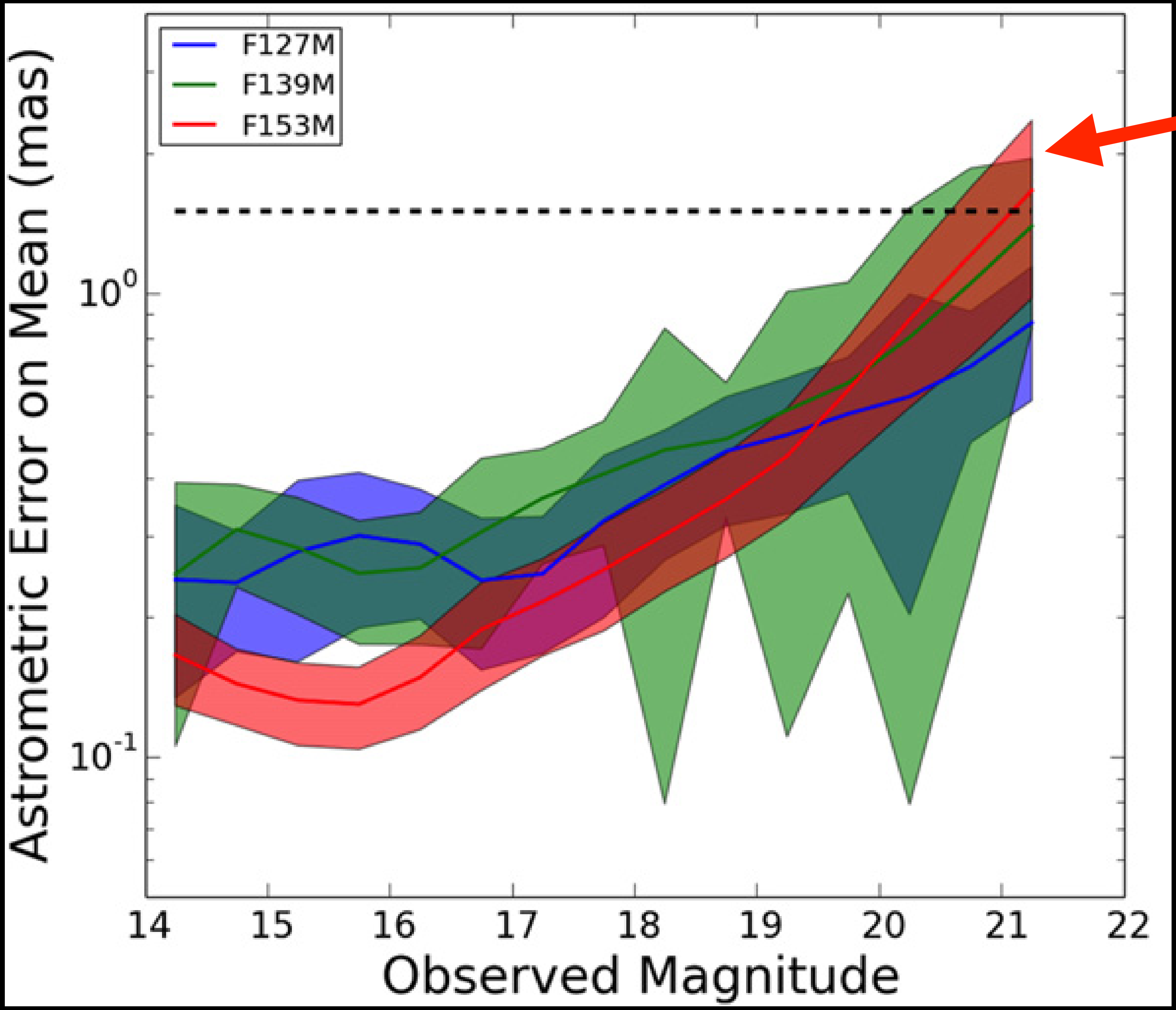
see poster by A. Secunda

Isolated Stellar-Mass Compact Objects

- Black holes/neutron stars formed via stellar collapse
- Mass Function of BHs/NSs constrains:
  - BH/NS formation mechanism
  - supernova physics
  - nuclear equation of state
  - predictions for gravitational-wave detectors
- 10^8 to 10^9 BHs predicted in Galaxy
- **No** confirmed detections of isolated stellar-mass BHs to date

Isolated Stellar-Mass Compact Objects

Astrometry using HST's WFC3-IR in bulge fields
is already being done successfully



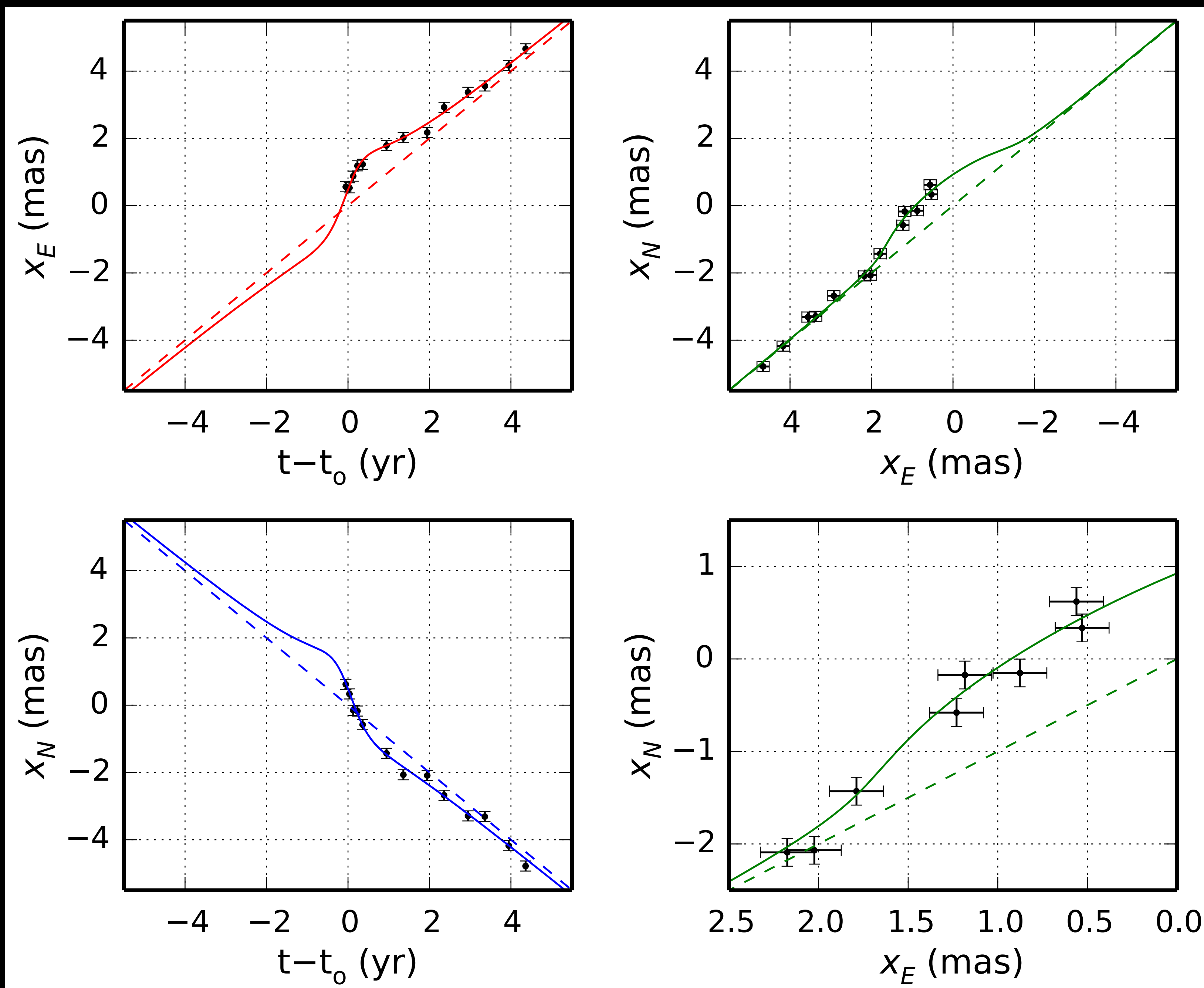
Red: data chosen for cleanest astrometry

Stars from Arches (cluster near GC)

Hosek et al. 2015
see also Kains et al 2017

Isolated Stellar-Mass Compact Objects

Astrometric shift constrains masses of microlensing events detected by the bulge survey

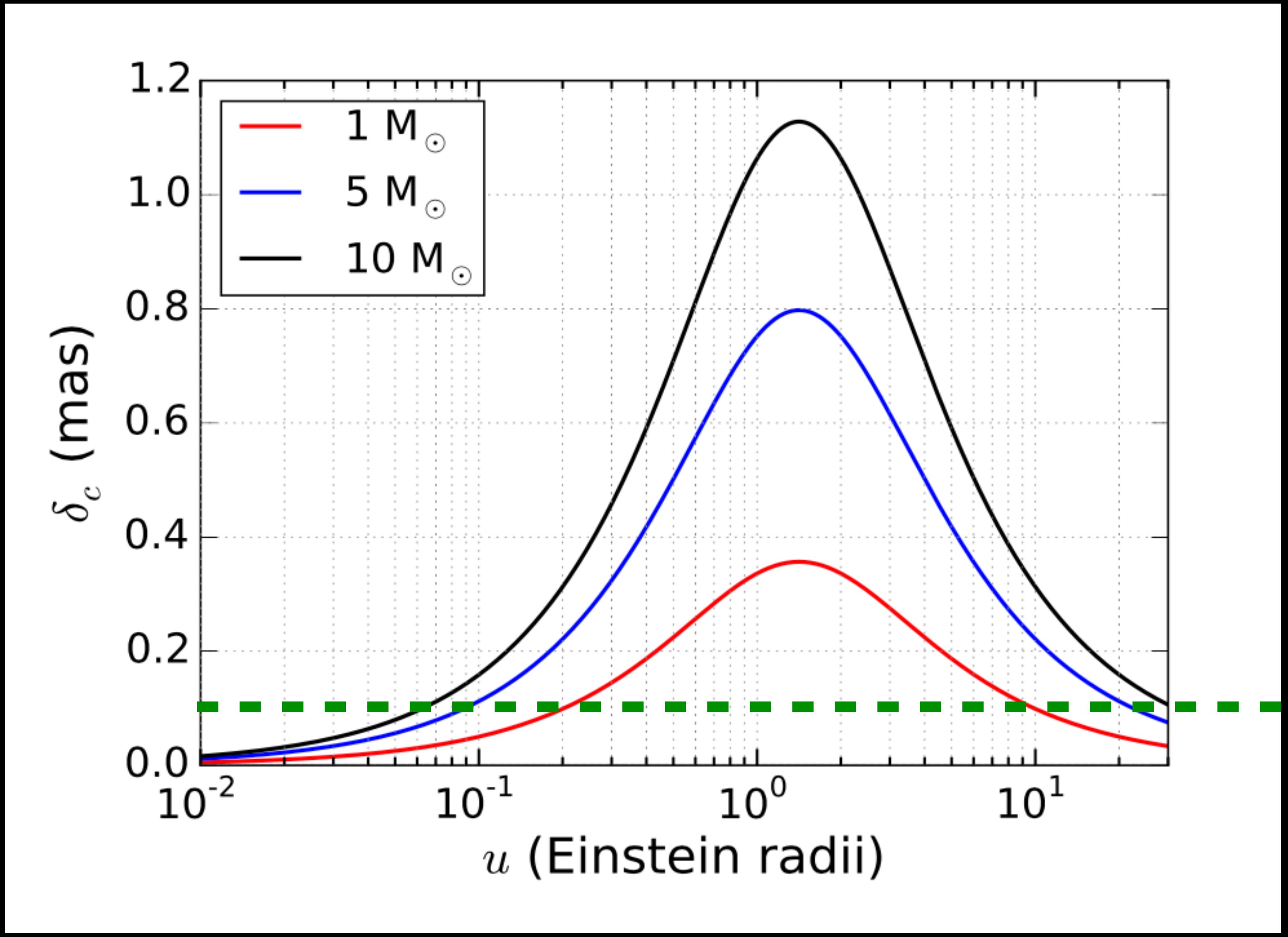


- Simulated event
- $10 M_\odot$ BH at 4kpc
- lensing source in bulge (8kpc)
- requires 150 μas astrometric errors
- dashed line = unlensed model

Lu et al. 2016

Isolated Stellar-Mass Compact Objects

WFIRST Bulge Microlensing Survey is naturally good for this:
N=thousands, N_{yrs} = 6, millions of targets



Approx. WFIRST precision

$$\delta_c \sim \frac{0.5 \text{ mas}}{\sqrt{N}}$$

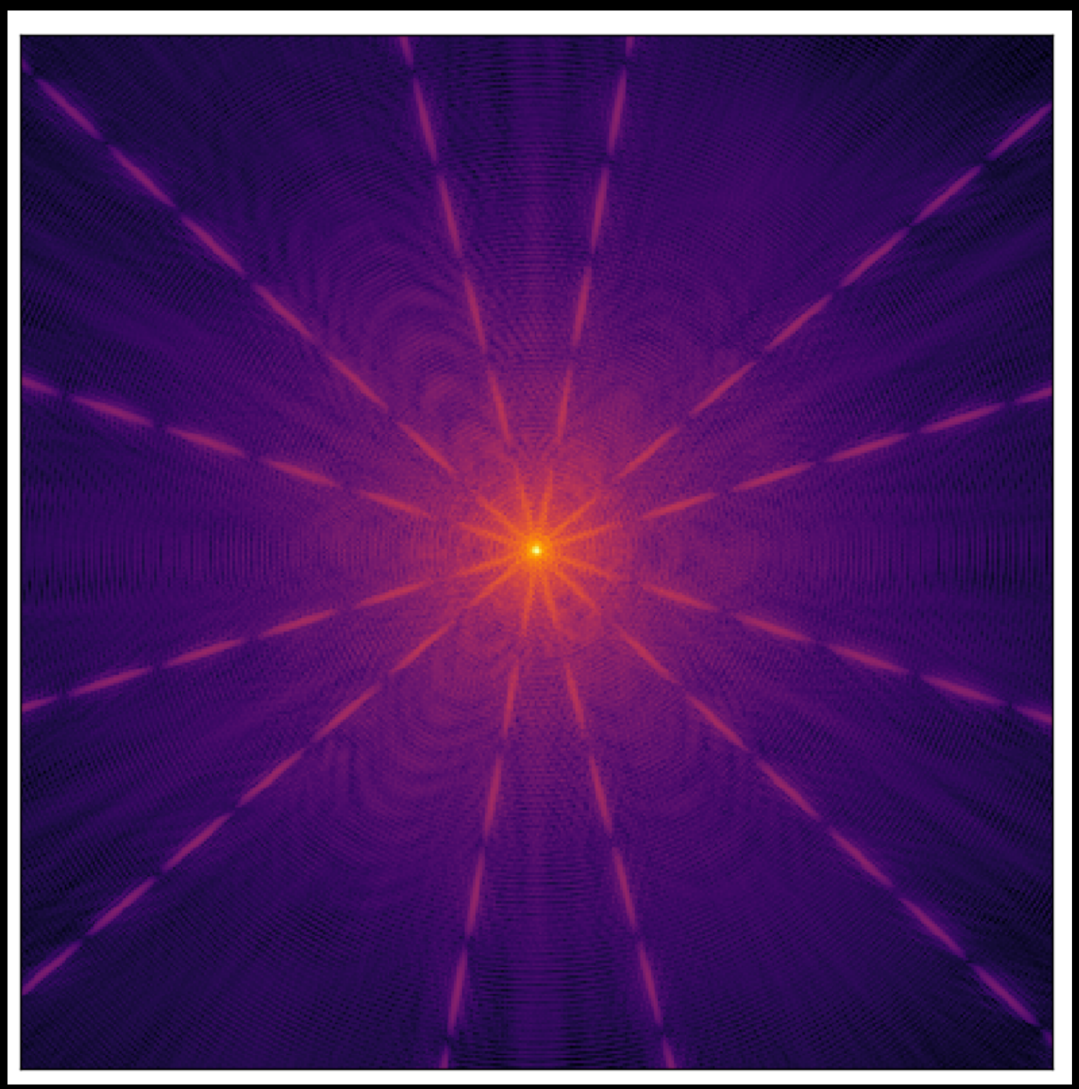
for N~25

Lu et al. 2016

WFIRST's wide FOV will allow microlensing searches outside the bulge fields too (e.g. LMC?)

(Super-)Earths & Neptunes around bright stars

Diffraction spikes average
over many pixels



Melchior, Spergel & Lanz, in prep

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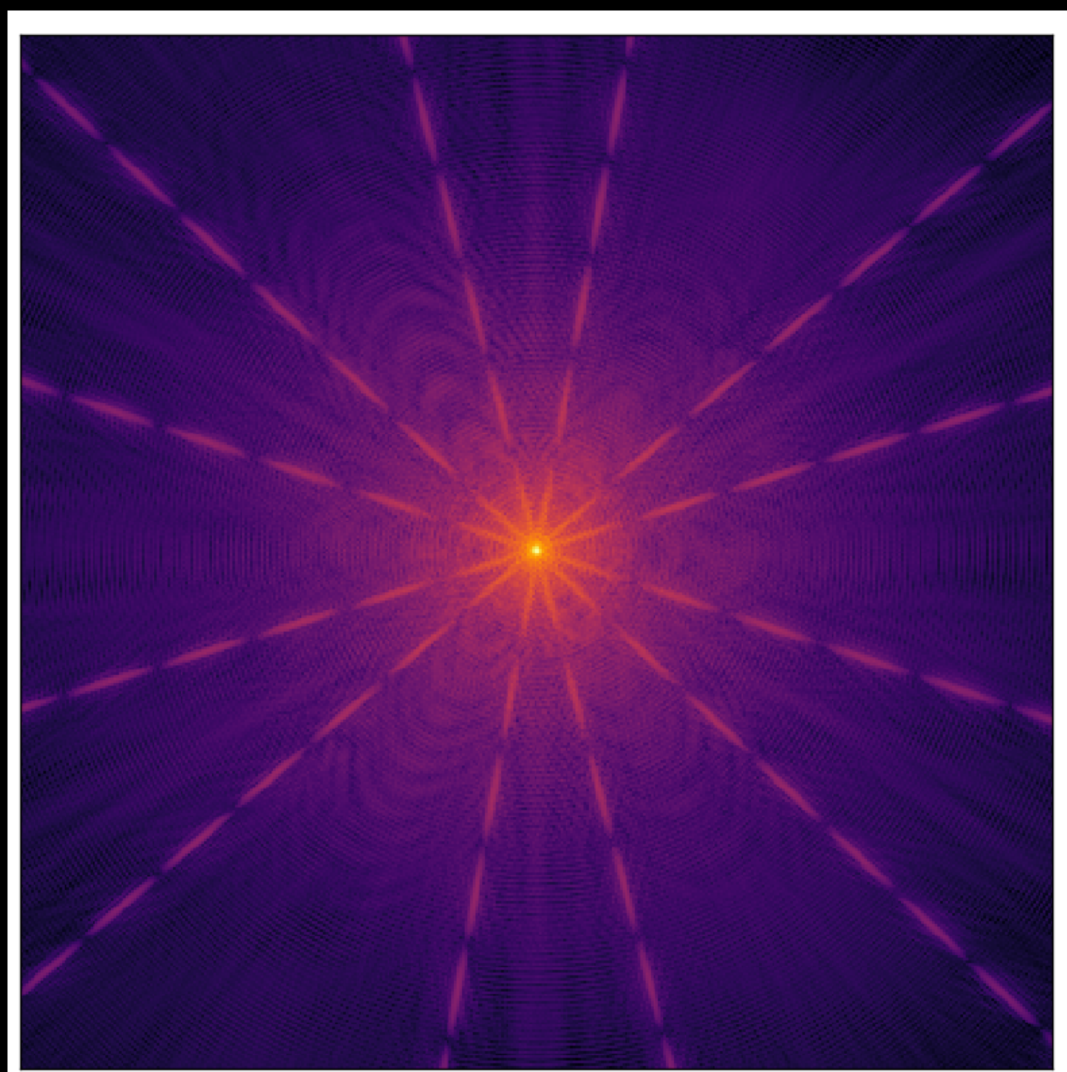
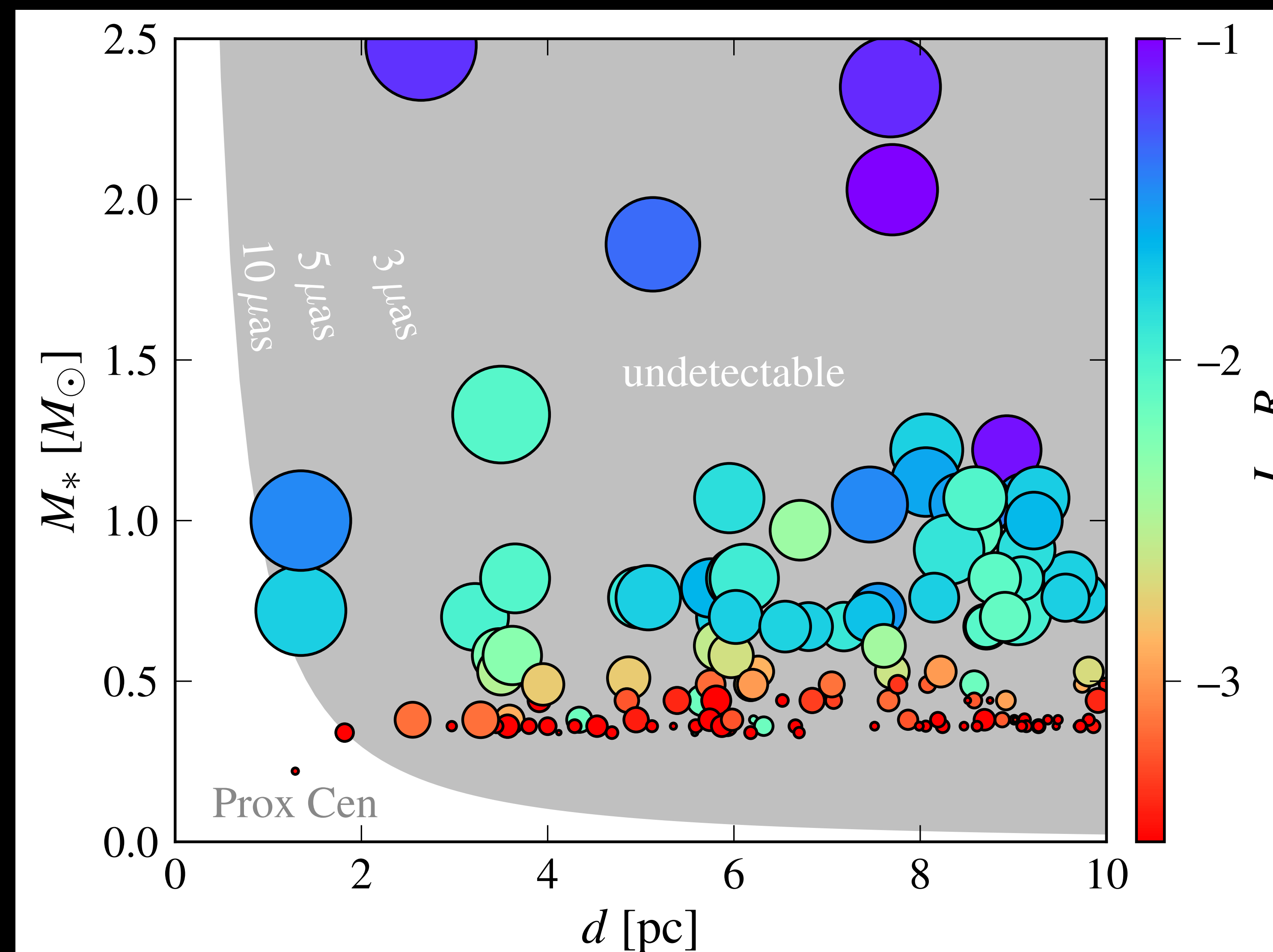


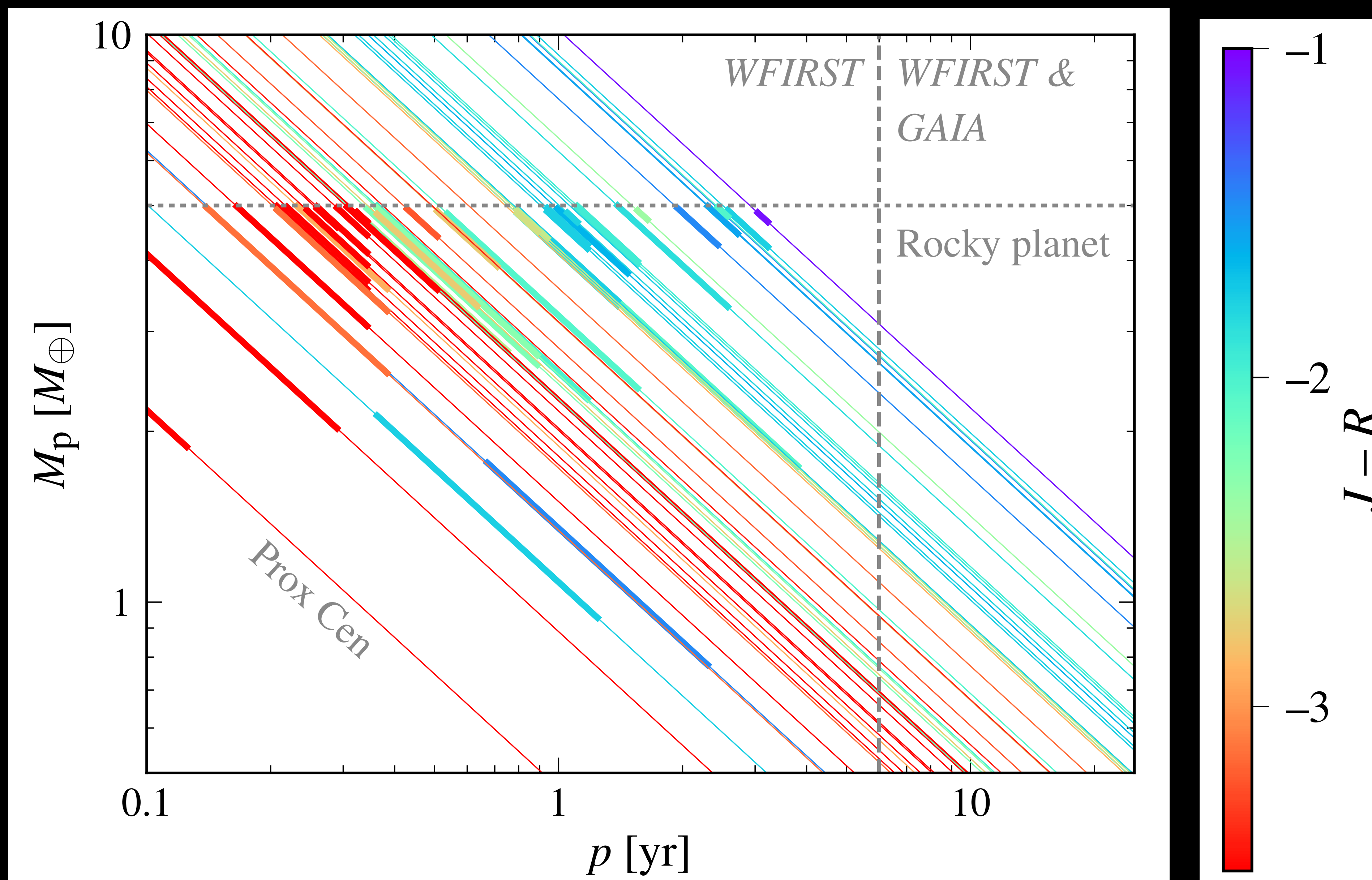
WFIRST can **astrometrically** detect a $3M_e$ planet with a 1-year period around 10s of the nearest stars



Melchior, Spergel & Lanz, in prep

(Super-)Earths & Neptunes around bright stars

WFIRST will extend
Gaia's detection space



…and possibly complement coronagraph

Melchior, Spergel & Lanz, in prep

Other science with WFIRST astrometry

- Detection and dynamics of young star clusters and star-forming regions in the Galactic disk
- Three-dimensional stellar dynamics in the inner bulge
- ISM tomography (3D map) toward the bulge/in the plane
- 3D orbits of high-velocity stars
- BH/NS “kicks” & multiplicity
- Globular cluster internal kinematics of faint MS stars (multiple populations, H-burning limit, tidal-field exploration, etc.)
- Internal motion of stellar populations in M31, LMC, SMC

Astrometry in the 2020s will be part of a cross-instrumental renaissance

- **Gaia** sets astrometric frame
- **HST** sets 25-40 year time baselines for local dwarf galaxies, GCs
- **LSST** finds standard candles & new targets over wide FOV @ matched depth
- **Ground-based** spectroscopy completes/extends stellar phase space distribution to MW Rvir
- **WFIRST** adds PMs over HLS field, precise astrometry in bulge fields, pointed obs of e.g. dwarf galaxies, exoplanets

Maximizing Astrometry Output for WFIRST

- An **excellent understanding of the PSF and detector is critical** for astrometry as well (work ongoing):
  - Understanding subpixel sensitivity is very important (ongoing)
  - investigate time-dependence (radiation-dependence) of sub pixel detector fluctuations (esp intrapixel QE) - is this an issue?
  - So is calibration of the distortion solution
- Some attention when **scheduling** can make a big difference:
  - allow for multi-year GO proposals to optimize PM baselines
  - maximize time between field revisits when possible, esp for large sky areas (HLS, WINGS, …)
- consider a **GO spatial scanning** mode (subgroup active)
- allow **archival searching for all observations of a given field (level 2 pixel data,** GO and programmed) for GI astrometry

Geometric-Distortion simulations

Motivation

Create a “somewhat realistic Bulge field” as seen by the WFIRST WFI to:

- Test the feasibility of solving for the WFI GD using Gaia stars;
- Test the impact of:
  jitter RMS (i.e., PSF time-dependent variations),
  IPCs (i.e., static PSF variations),
  persistence,
  read-out amplifier hysteresis,
  intra-pixel sensitivity variations,
  etc…

on the achievable GD-solution accuracy.

Implementation (initial tests)

Reference frame based on a typical MicroSIT pointing

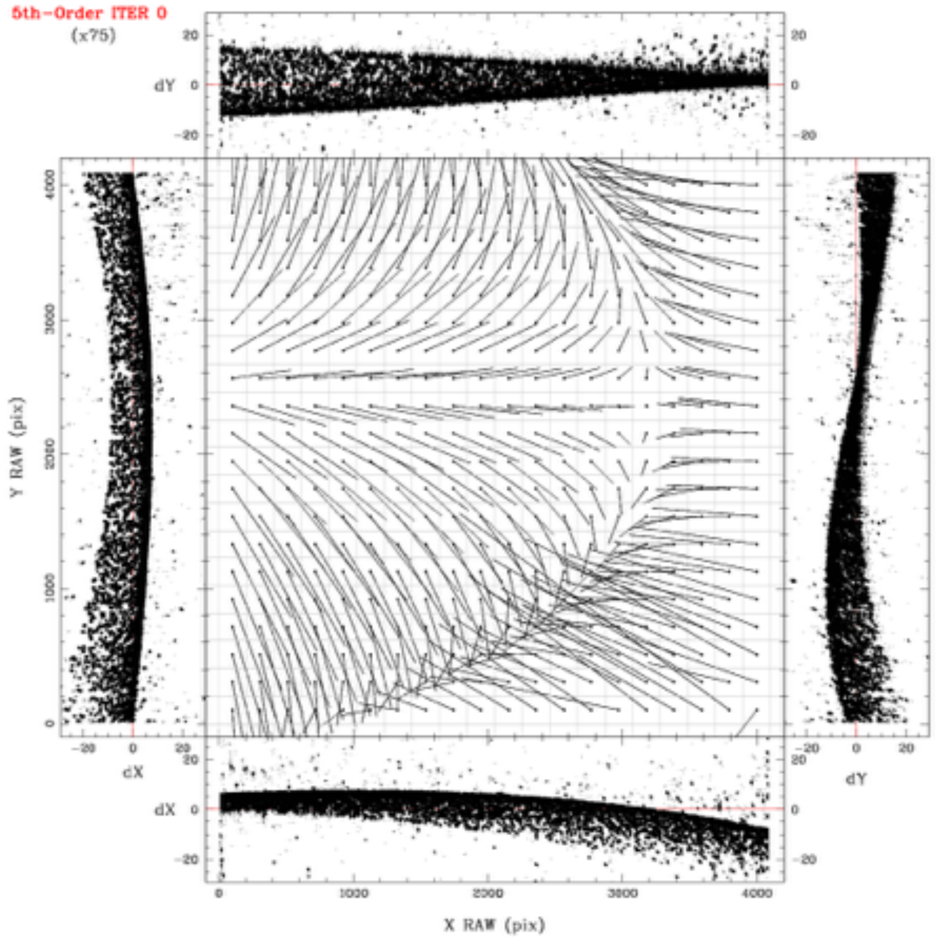
Use of WebbPSF spatially-varying models

125 MicroSIT-like single-chip images (>1M stars each) with random pixel-phase sampling and with a 10x10 pix dither pattern

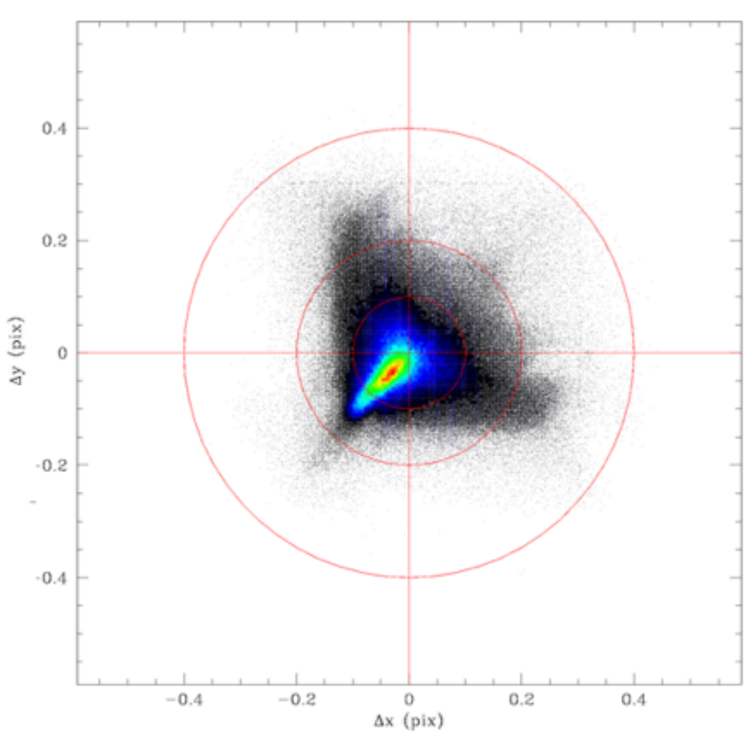
Input GD: 3rd order polynomial with ~1% corner-to-center distortion

Recovered using ~2000 expected Gaia stars in the field and 5th order polynomial

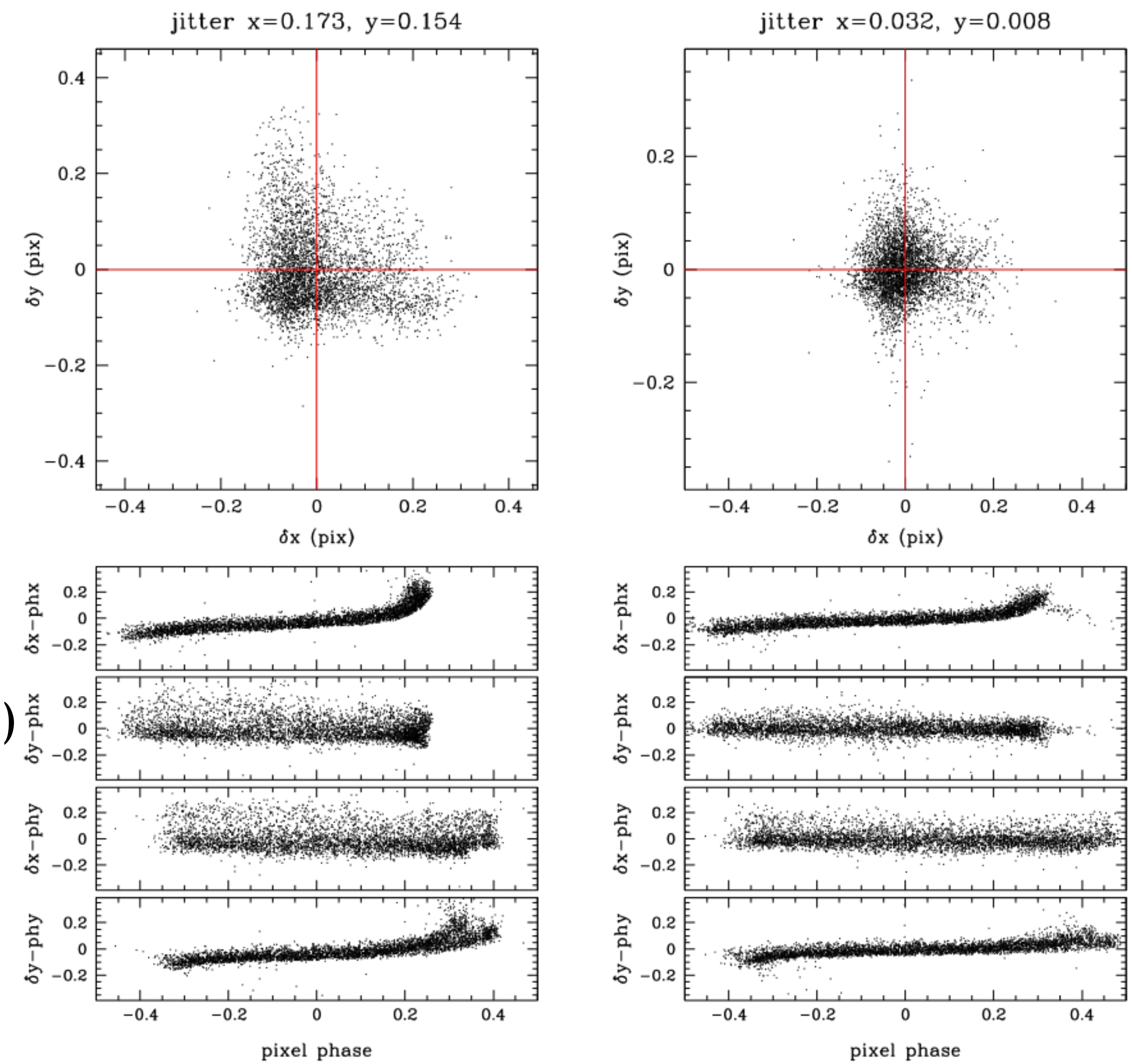
Input measured distortion
(combined residuals of all 125 images)



Final global position residuals (all 125 images)



Final single-image position residuals and pixel-phase errors for mild and small jitter RMSs



Significant jitter-induced pixel-phase errors
-> Need improved, time-dependent PSF models