The Outer Galactic Halo as Probed By RR Lyrae Stars From the Palomar Transient Facility + Keck

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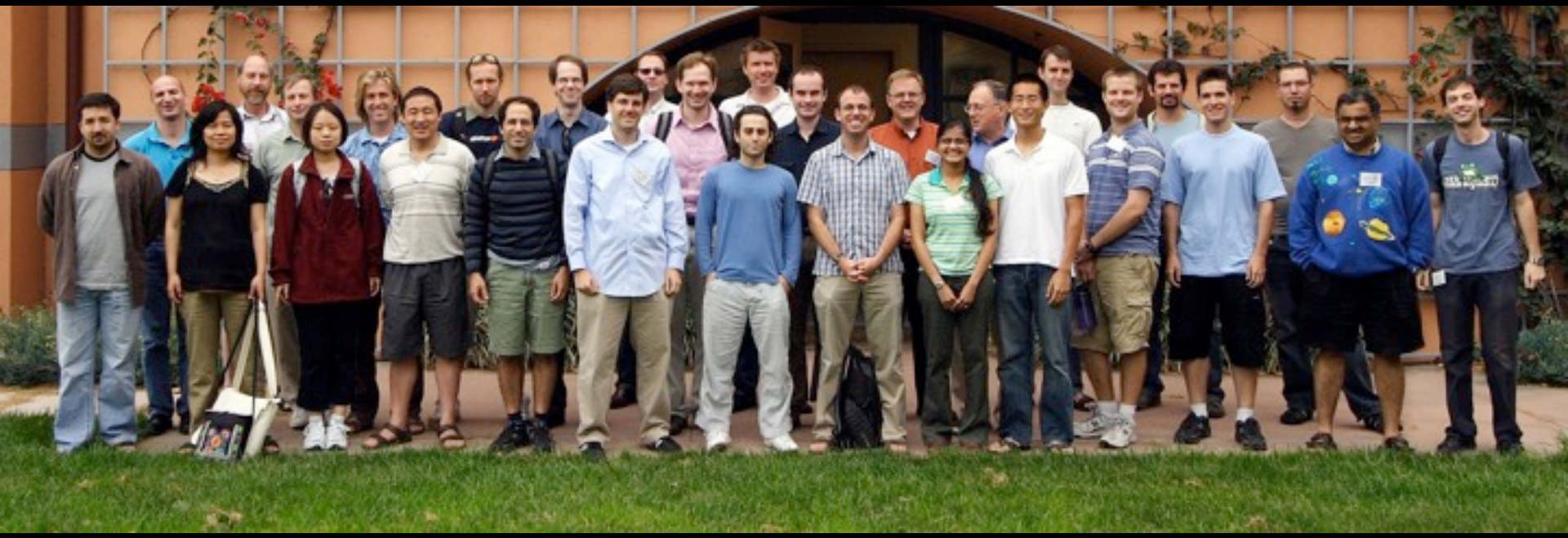
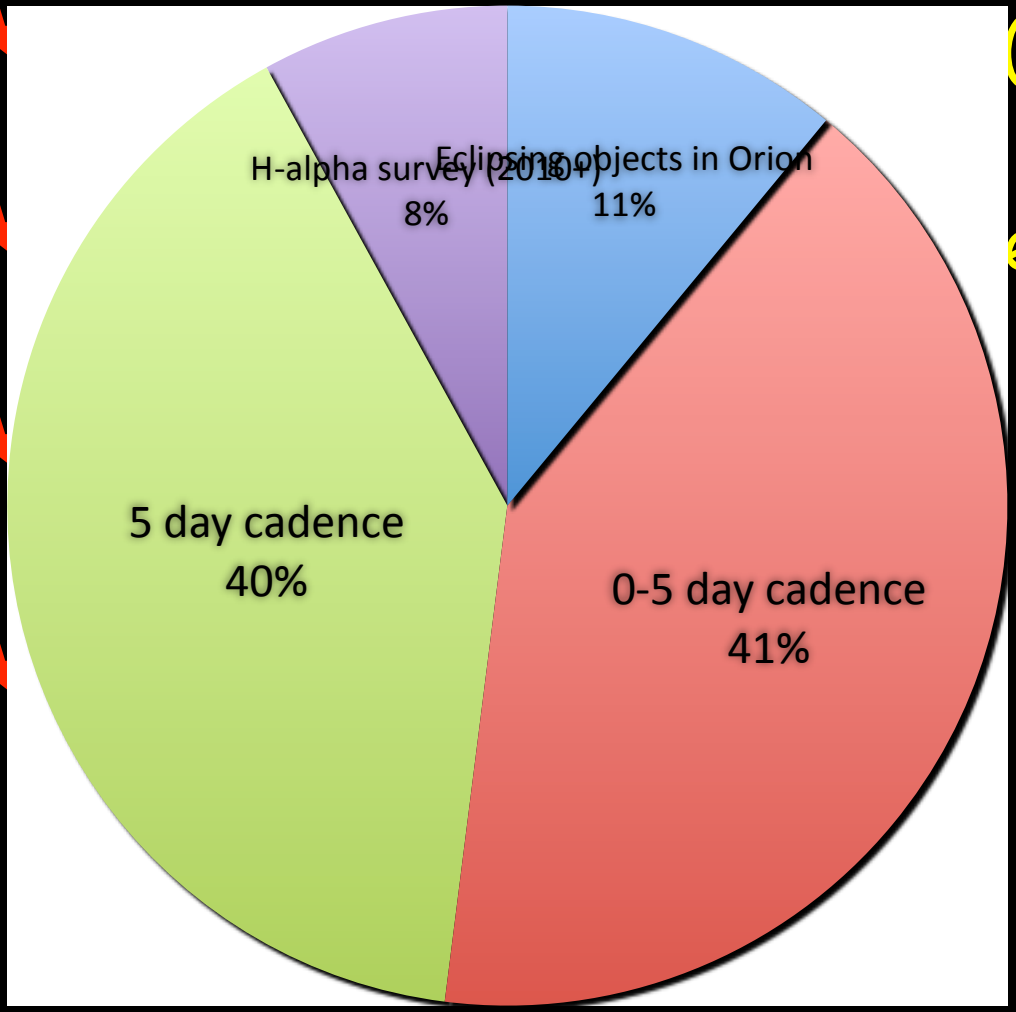
Dwarf Galaxies, Potsdam, Aug 2014

PTF collaboration



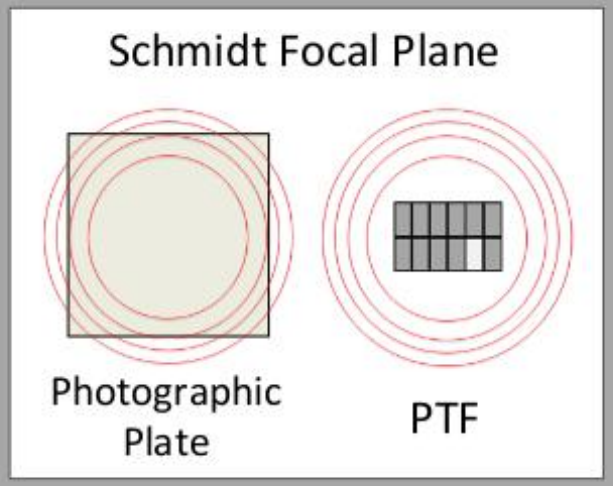
Caltech, LCOGT, Berkeley, LBL, IPAC, Columbia, Oxford, Weizmann

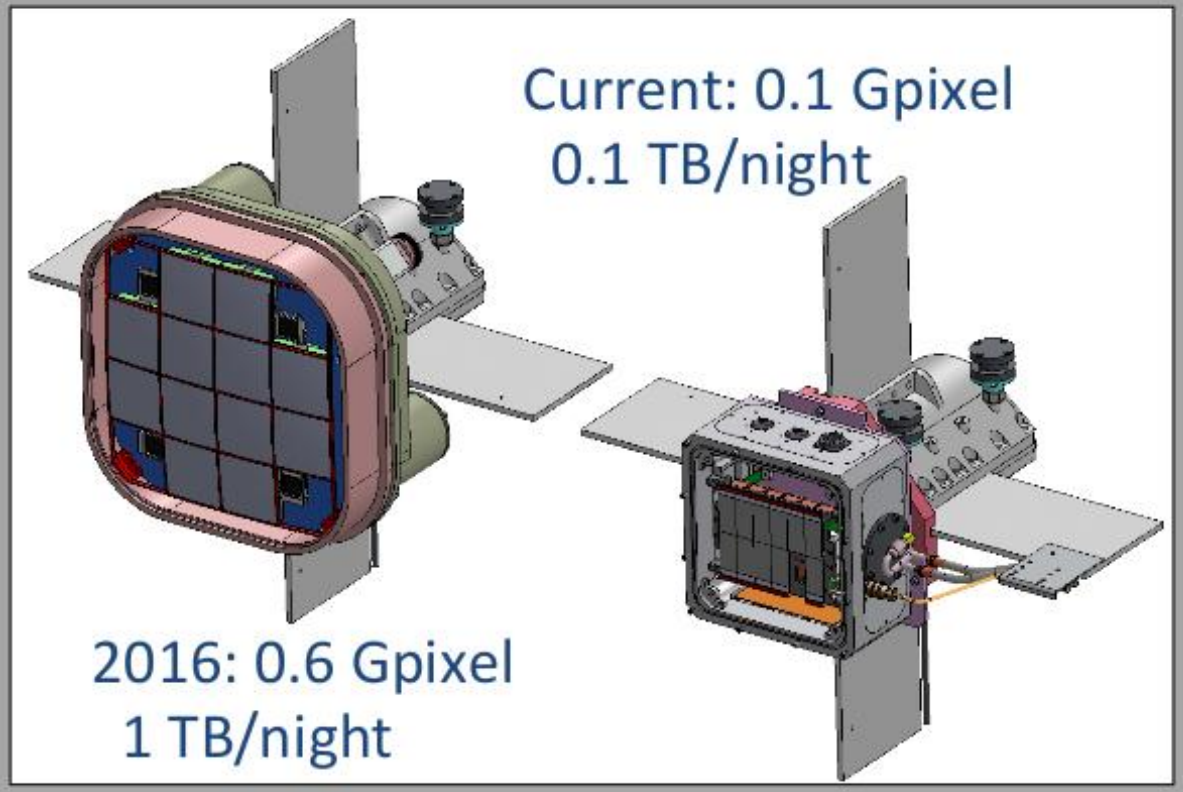
PTF projects



PTF Key Projects	
Transients in nearby galaxies	Search for eLIGO/neutrino EM counterpart
Thermonuclear SNe	Core Collapse SNe
Blazars/AGN	Tidal Disruption Flares
H-alpha Sky Survey	Orphan GRB afterglow
AM CVn	CVs
Galactic dynamics	RR Lyrae
Flare stars	Rotation in clusters
Nearby Star Kinematics	Eclipsing stars and planets
Asteroids	KBOs

The Next Big Step (2016): *Zwicky* Transient Facility (ZTF)





ZTF: *10 x's the throughput of PTF!*

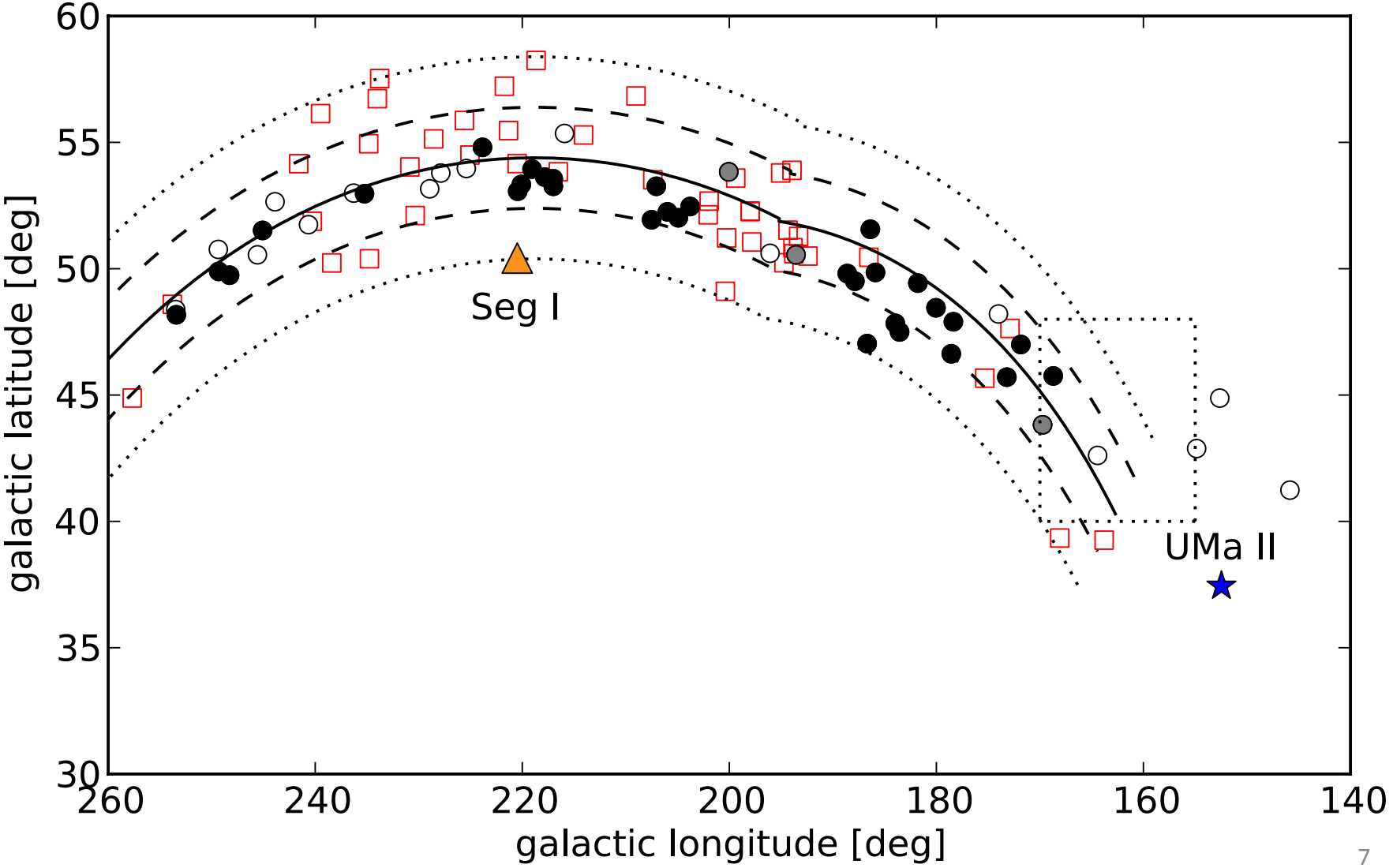
Outer Halo RR Lyrae Stars

- Great “massless” probes of gravity field
- Can find out to ~110 kpc in the PTF database in fields with most epochs and best photometry
- Stand out as variable blue stars, amplitude 0.6 to 1.0 mag in R, easy to find if have accurate photometry & enough (>25) epochs of observation
- PTF many epochs, so measures period, phase
- Keck measures radial velocities , vr(Hα) amp 110 km/sec
- Must correct measured magnitude to mean mag, and measured vr to systemic vr – requires template light and velocity curves

Advantages of RR Lyr as Halo Probes

- Mean R mag for metal-poor RR Lyr is almost constant, get distance accurate to 5% in halo with a 0.3 dex range in [Fe/H] around -1.8 dex included
- Out to 100 kpc, bright enough to get vr with Keck in less than 30 min – longer - phase blurring
- Can use as massless probes, dynamical mass of the Milky Way, when combined with a density distribution of RR Lyr, which also can be derived from the survey.
- Use to find and study streams
- Low contamination of other blue, variable stellar objects, a very small fraction of QSOs.

Orphan Stream as tracked with RR Lyraes out to 55 kpc, Sesar, Grillmair, Cohen et al, 2013



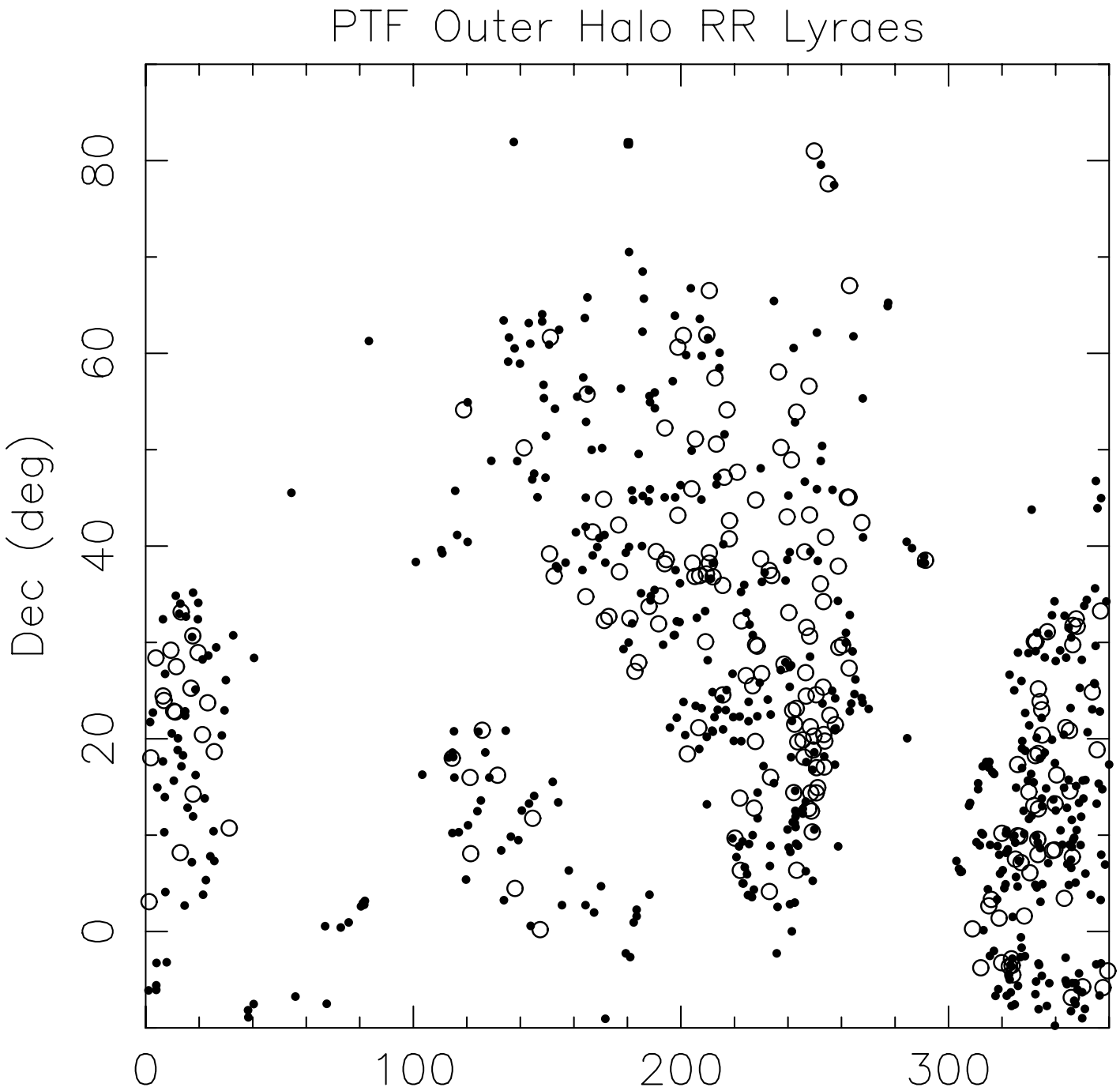
5 years of PTF + iPTF data

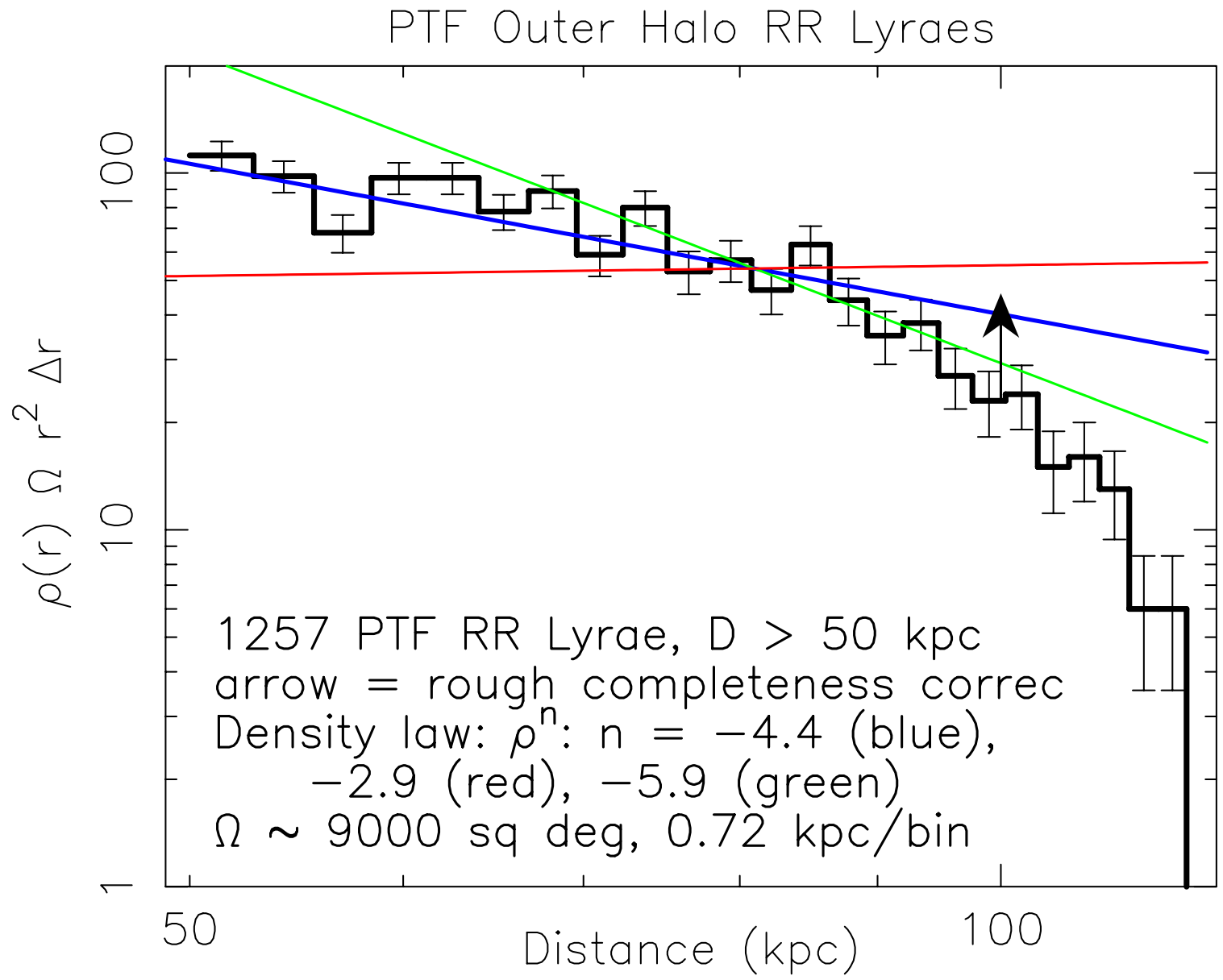
- We have found a sample of 1257 RR Lyr (ab) beyond 50 kpc in ~9,000 sq deg (~20% of the sky) with 25 or more epochs of observation. We exclude RR Lyr in known dSph, Sgr stream, etc
- ~180 of these are beyond 90 kpc, max ~ 115 kpc

- We are working on the density distribution
- We are working on the completeness corrections
- We have started a spectroscopic program at Keck to determine vr for the RR Lyr beyond 70 kpc
- We are using RR Lyr to study structure in the outer halo and determine the mass of the MW
- GAIA will yield proper motions

Outer Halo RR Lyr Sample Details

- This project to date has not had any observing time on the P48 Palomar Schmitd assigned to it.
- We search the PTF data archive using images taken for other projects, mostly supernova searches. The last 1.5 years of PTF data has NOT been used.
- Thus we have random pencil beams (each 7.3 sq deg) through the halo at $|b| > 30$ deg.
- Total solid angle ~9,000 sq deg with 25 or more epochs with R filter


PTF Outer Halo RR Lyraes
Dec (deg)
0
20
40
60
80
0
100
200
300


PTF Outer Halo RR Lyraes
100
10
1
ρ(r) Ω r² Δr
1257 PTF RR Lyrae, D > 50 kpc
arrow = rough completeness correc
Density law: ρⁿ: n = −4.4 (blue),
−2.9 (red), −5.9 (green)
Ω ~ 9000 sq deg, 0.72 kpc/bin
50
Distance (kpc)
100

Outer Halo Density Distribution

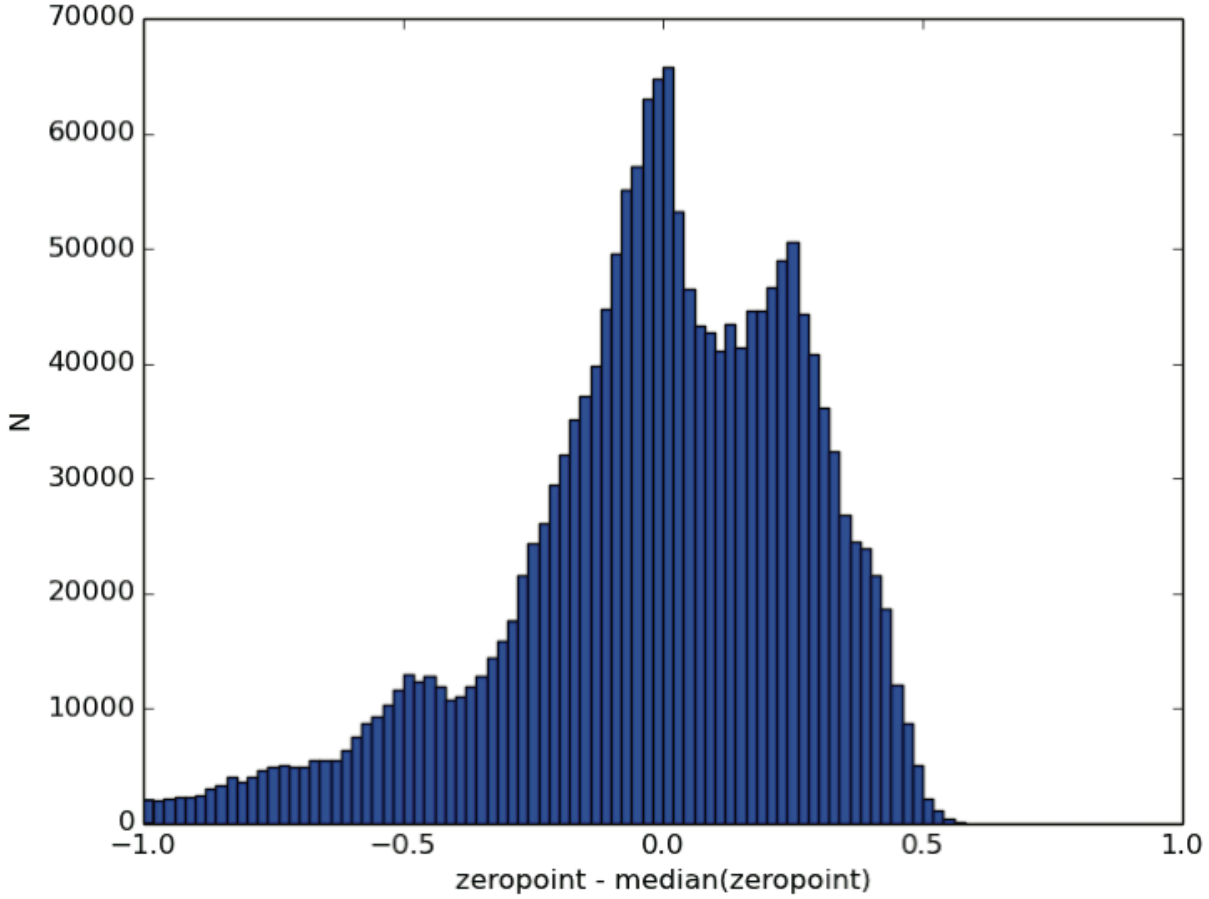
- Beyond 50 kpc, power law slope ~ -4.4
- Predicted density ρ(RR Lyr)/kpc^3 at 50 kpc from double power law halo models for SDSS Stripe 82 (Watkins et al, Sesar et al 2009)= 2.0 x 10^{-2}
- Observed at 50 kpc from PTF (1/5 of sky covered) from previous slide = 2.0 x 10^{-2}/kpc ^{3}.
- Observed power law slope and observed number at 50 kpc – agree well with others.

PTF Limiting magnitude

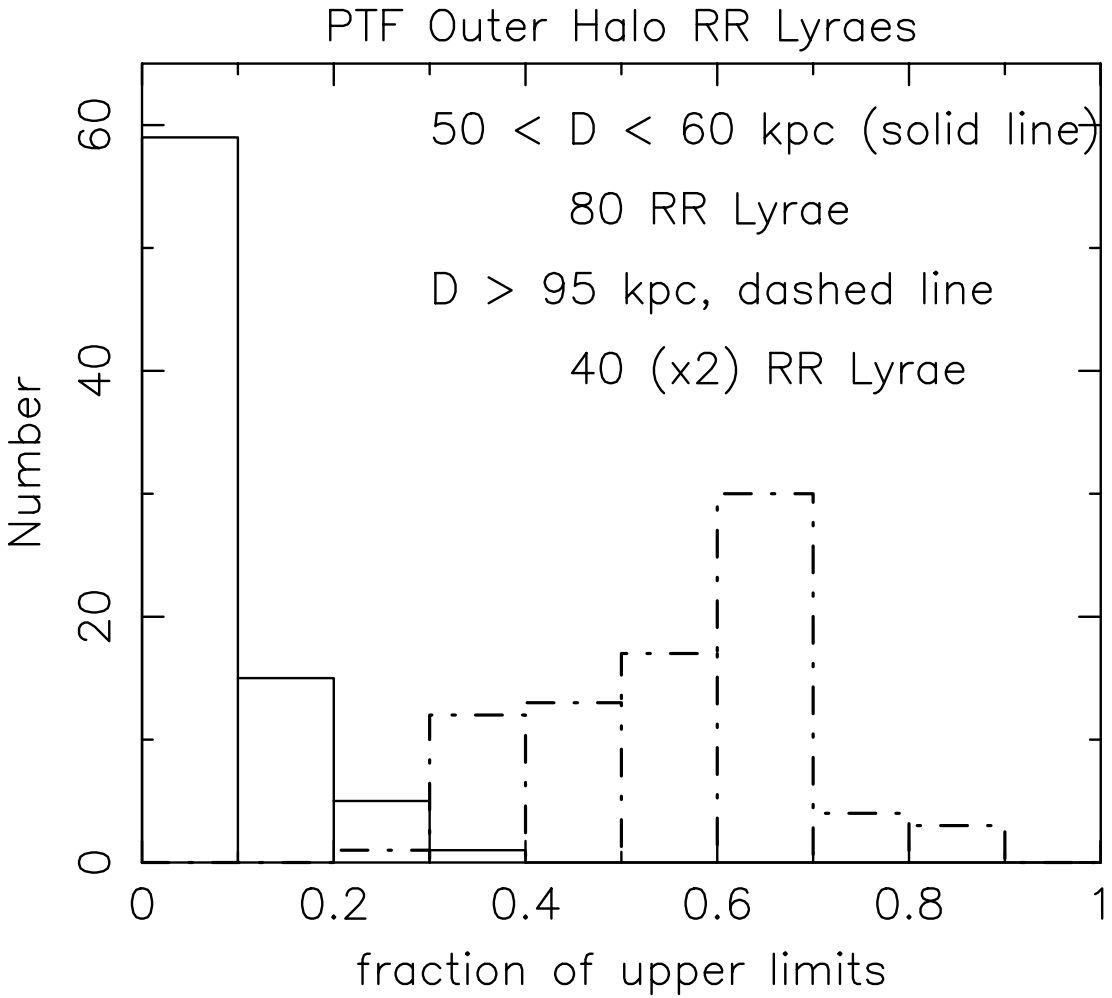
- RR Lyr at 100 kpc has mean R = 20.6

- PTF nominal 5σ limit (60 sec exp, R) is 20.6 under average conditions
- Fields with the largest number of epochs are likely to have many epochs where the limiting magnitude is slightly fainter and we can reach out slightly further

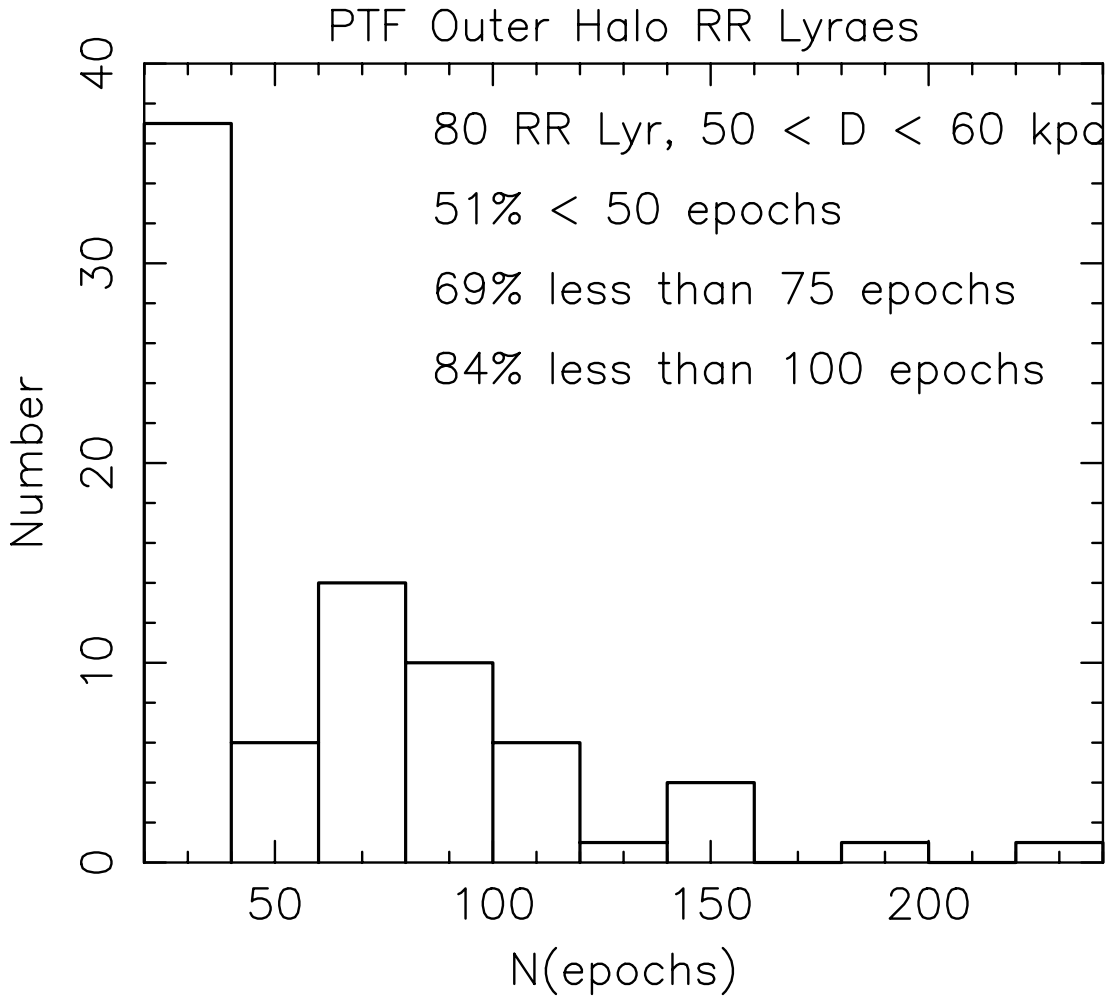
Range of photometric zeropoint within the PTF database due to weather conditions, long tail to left due to clouds, bad seeing (affects completenes)



As approach faint limit of PTF, high fraction of observations are only upper limits



Minimum number of epochs is 25; RR Lyr near 100 kpc must have 50 epochs to have 25 R values



PTF RR Lyr Completeness Corrections

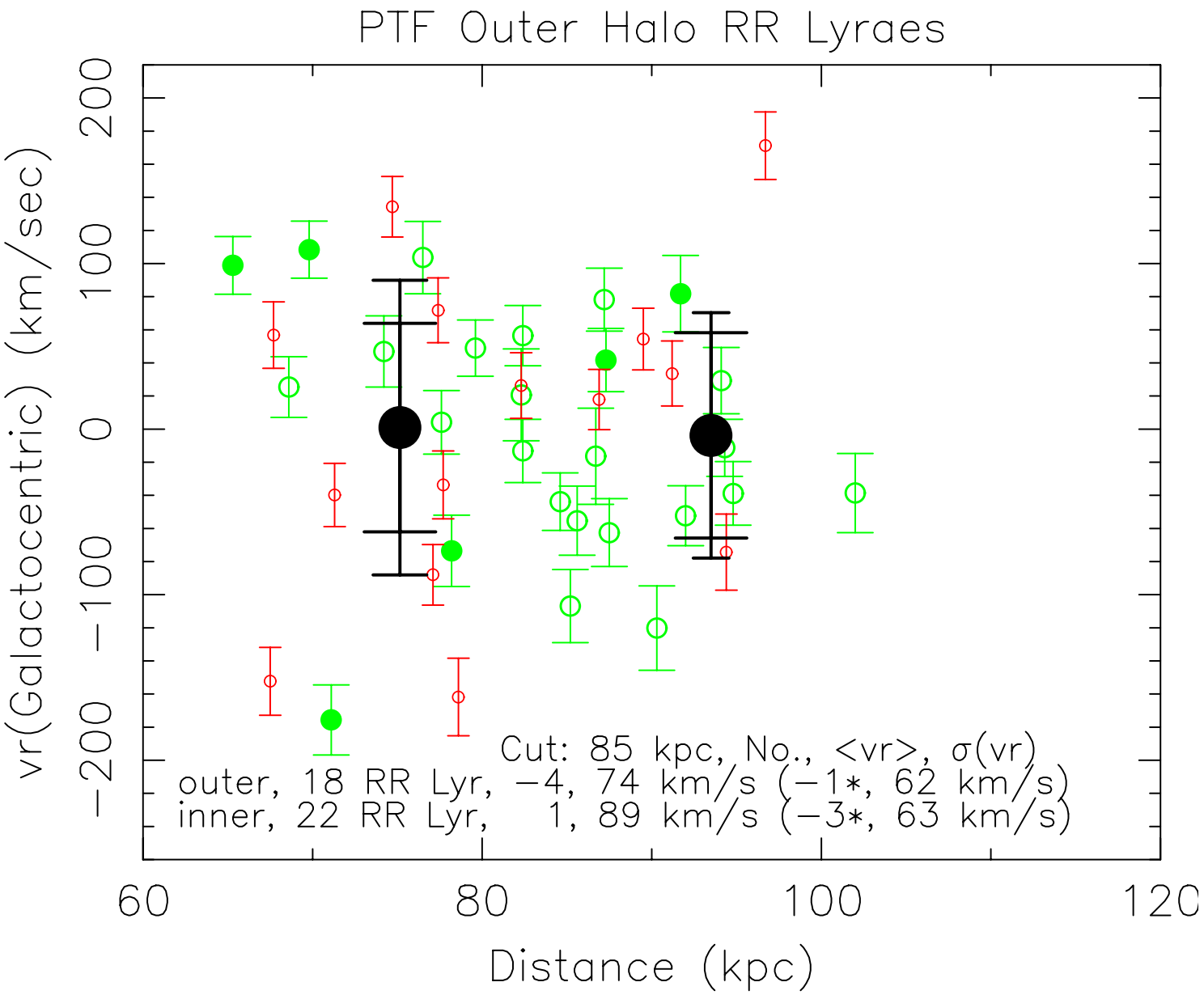
Believe very small (~5%) until close to PTF limit.

Simulations underway but no result yet

Evaluate approximate value based on number of epochs observed/field and fraction of upper limits in PTF database as a function of <R>

Result – factor of 2 at 100 kpc.

With this, no evidence for change in slope out to Galactocentric radius = 100 kpc.


PTF Outer Halo RR Lyraes
vr(Galactocentric) (km/sec)
200
100
0
−100
−200
60
80
100
120
Distance (kpc)
Cut: 85 kpc, No., <vr>, σ(vr)
outer, 18 RR Lyr, −4, 74 km/s (−1*, 62 km/s)
inner, 22 RR Lyr, 1, 89 km/s (−3*, 63 km/s)

Summary (1)

We have used RR Lyr found in the PTF, eliminating those in all known structures, to study the outer halo of the Milky Way.

The outer halo between 50 kpc and 100 kpc has ρ propto $r^{-4.4}$. The power -4.4 matches well that found in the inner halo beyond 30 kpc in previous work. This is in conflict with the results of Deason et al and suggests that their many inferences about the mass of the MW and its accretion history may be incorrect.

Summary(2)

Compared to existing samples of halo tracers (i.e. BHB stars), our sample has the advantage of smaller distance errors, and less contamination by QSOs, etc.

We find the outer halo to be quite cold with a relatively low $\sigma(v_r)$ if we ignore 4 outliers of our 40 v_r values obtained thus far with Deimos/Keck. We get, for R > 65 kpc, about 80 km/sec if they are included and about 60 km/sec if they are excluded.