

# The Outer Galactic Halo as Probed By RR Lyrae Stars – From the Palomar Transient Facility + Keck to LSST + TMT

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TMT Science Forum, Tucson, July 2014

# Palomar Transient Factory (PTF)

*A wide-angle, high cadence survey designed to systematically explore the transient & variable sky*

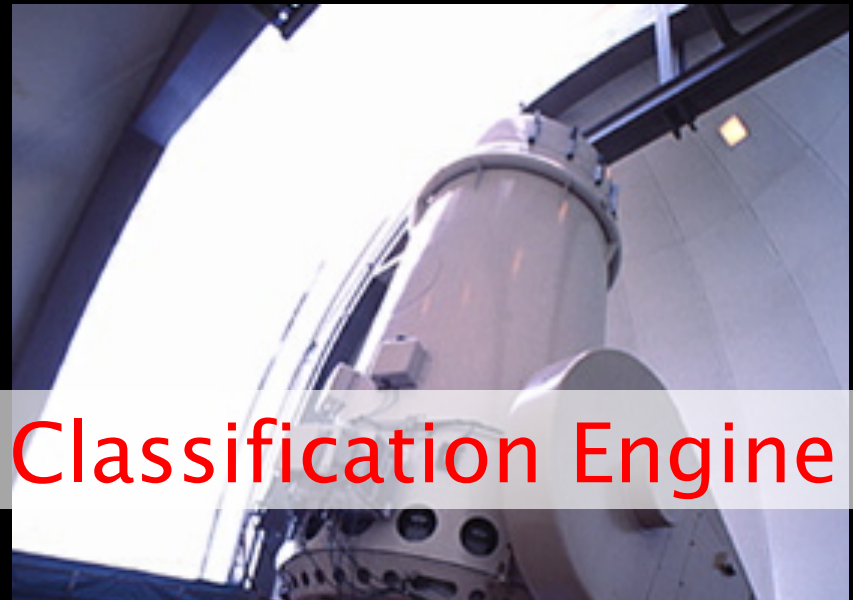


Discovery Machine + Classification Engine

~2000 Supernovae & ~80 papers to date



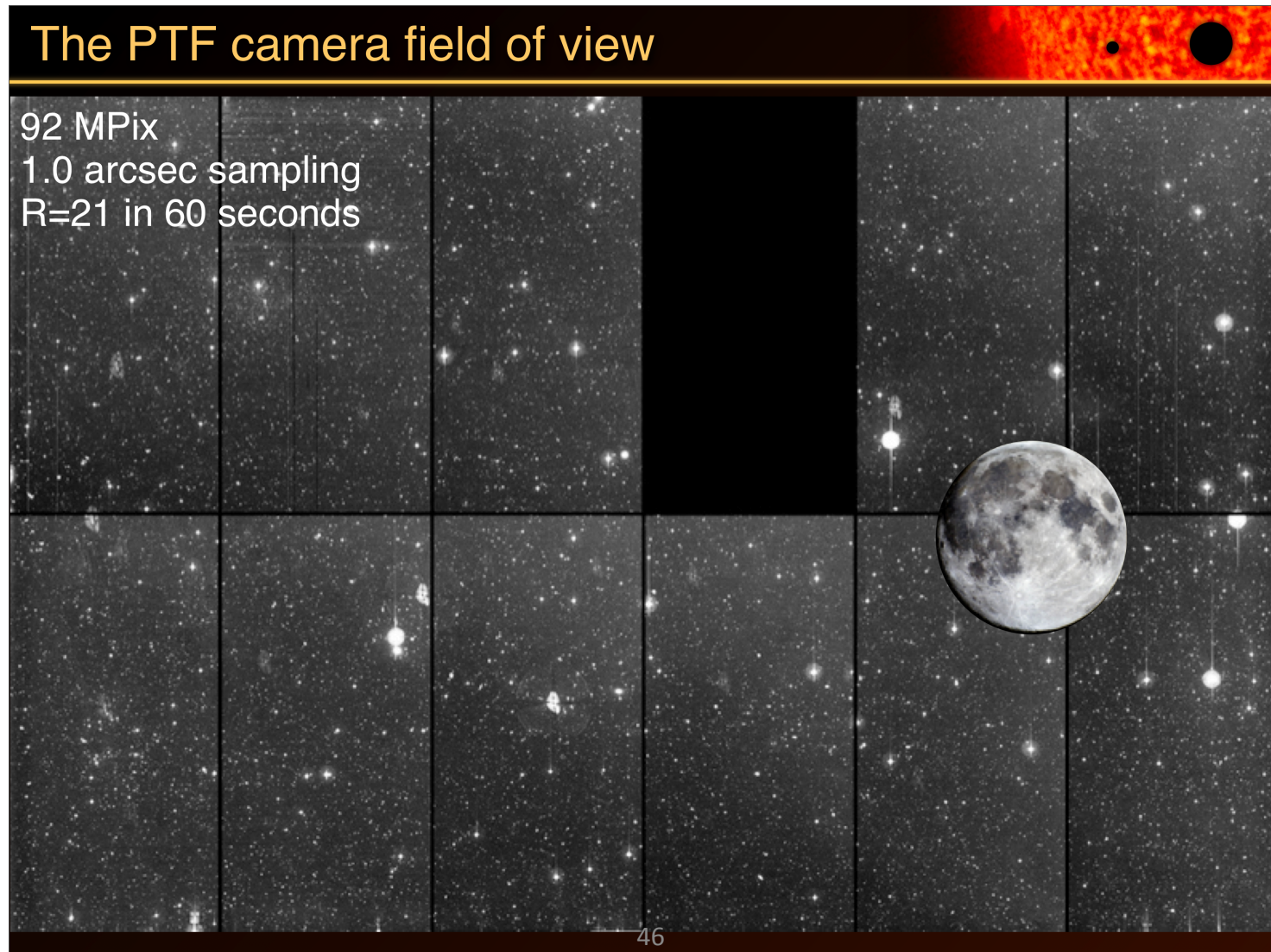
Palomar 48-inch

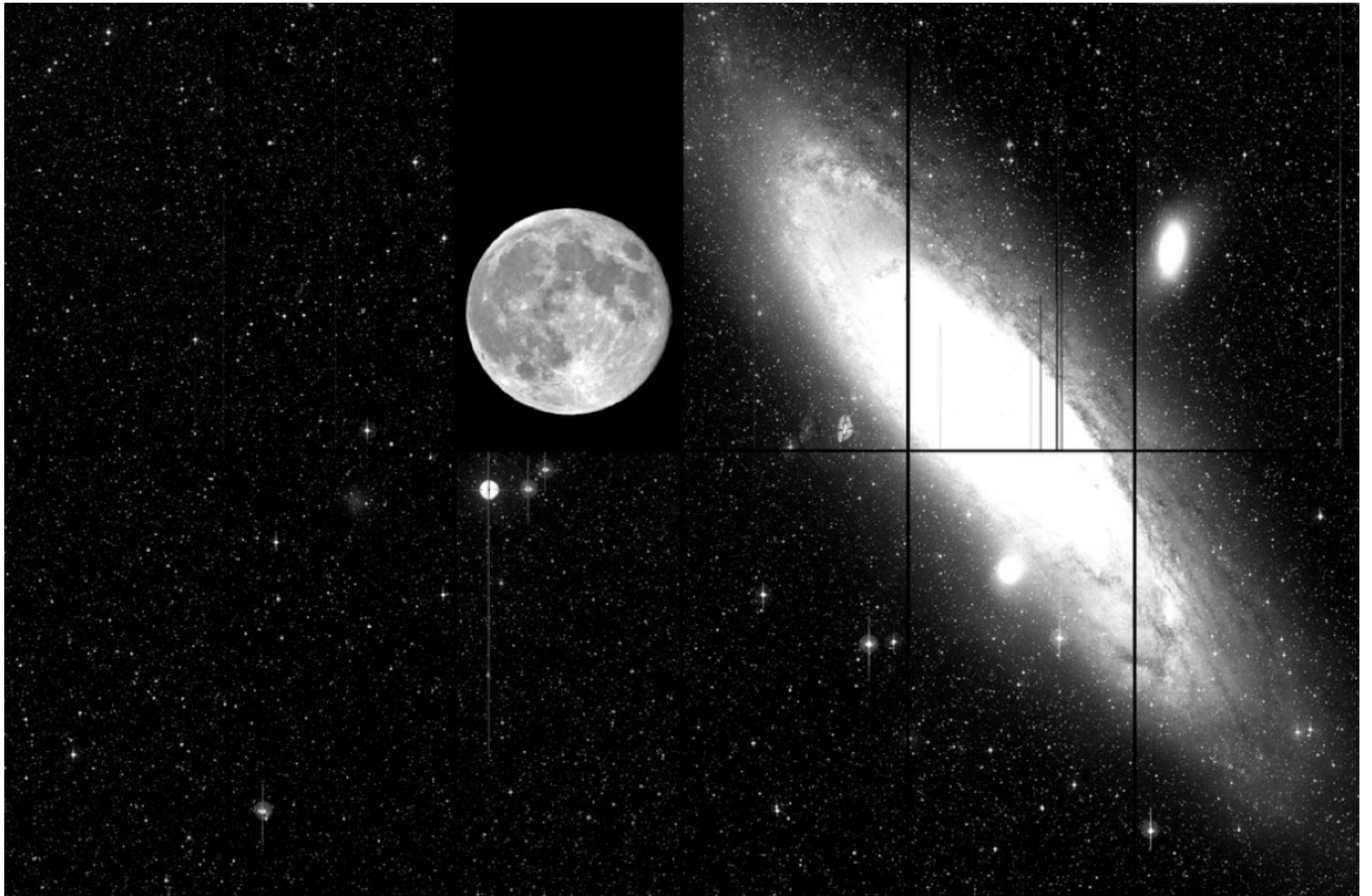


Palomar 60-inch

PI: Shri Kulkarni

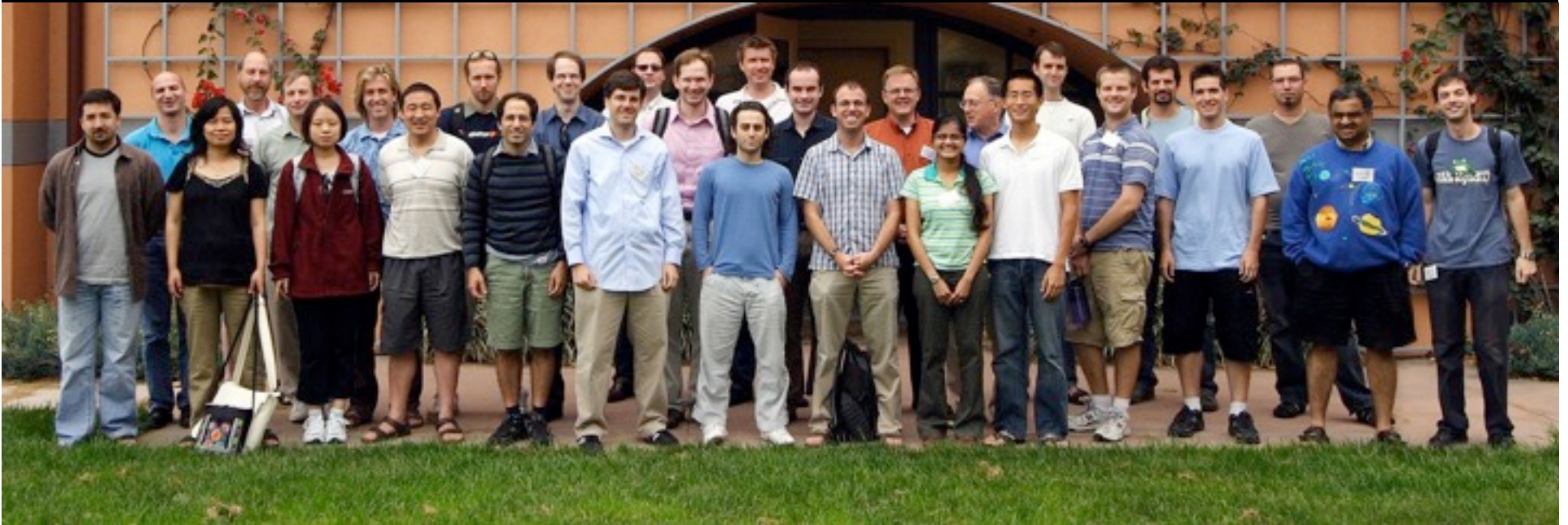
# Hardware







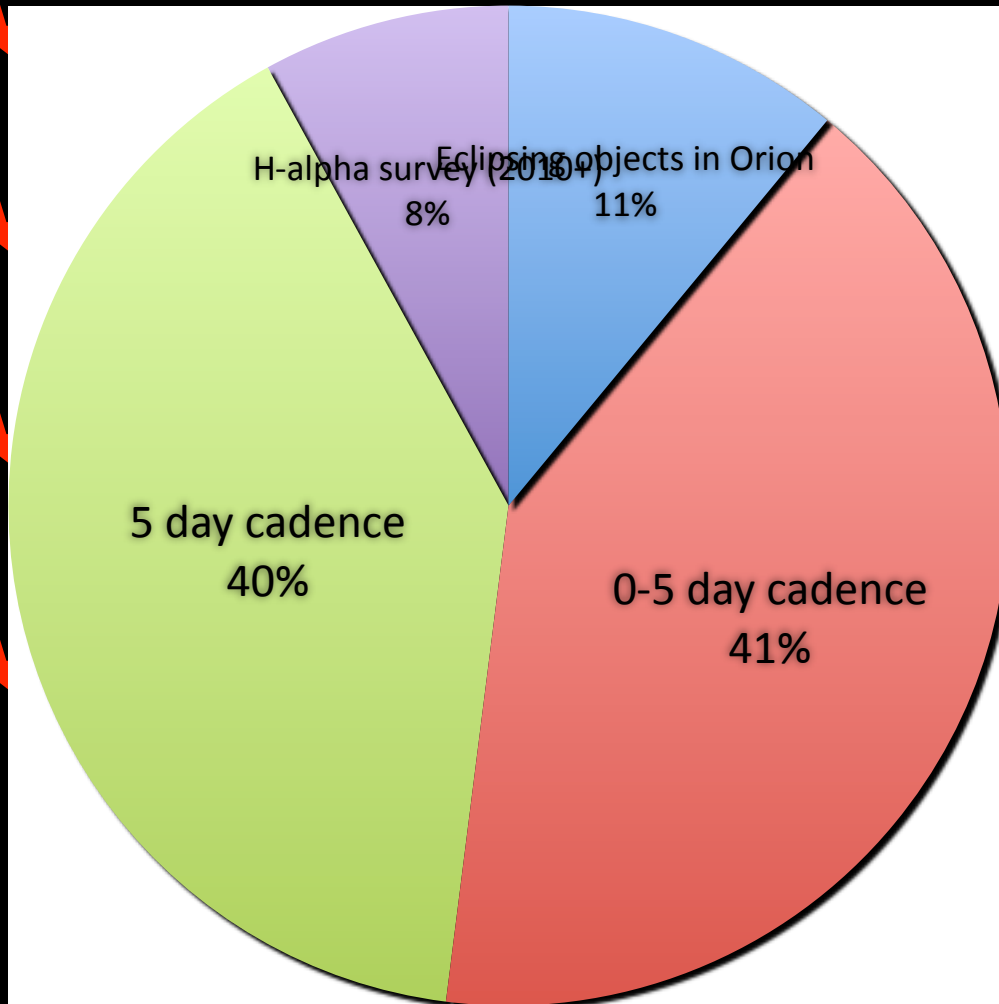
# PTF collaboration



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



# PTF projects

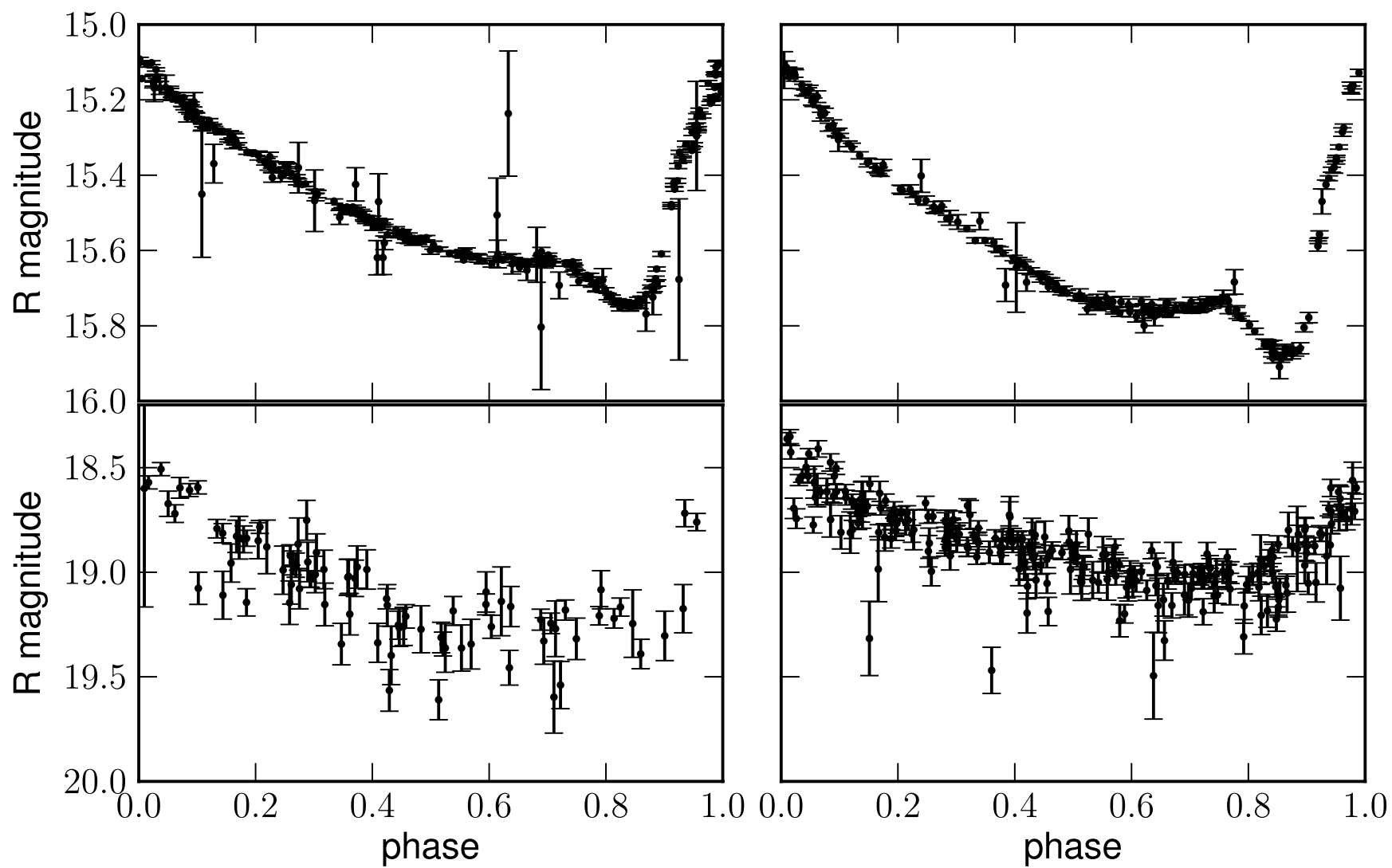


## PTF Key Projects

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

# Outer Halo RR Lyrae Stars

- Great “massless” probes of gravity field
- Can find out to  $\sim 110$  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 ,  $v_r(\text{H}\alpha)$  amp 110 km/se
- Must correct measured magnitude to mean mag, and measured  $v_r$  to systemic  $v_r$  – requires template light and velocity curves





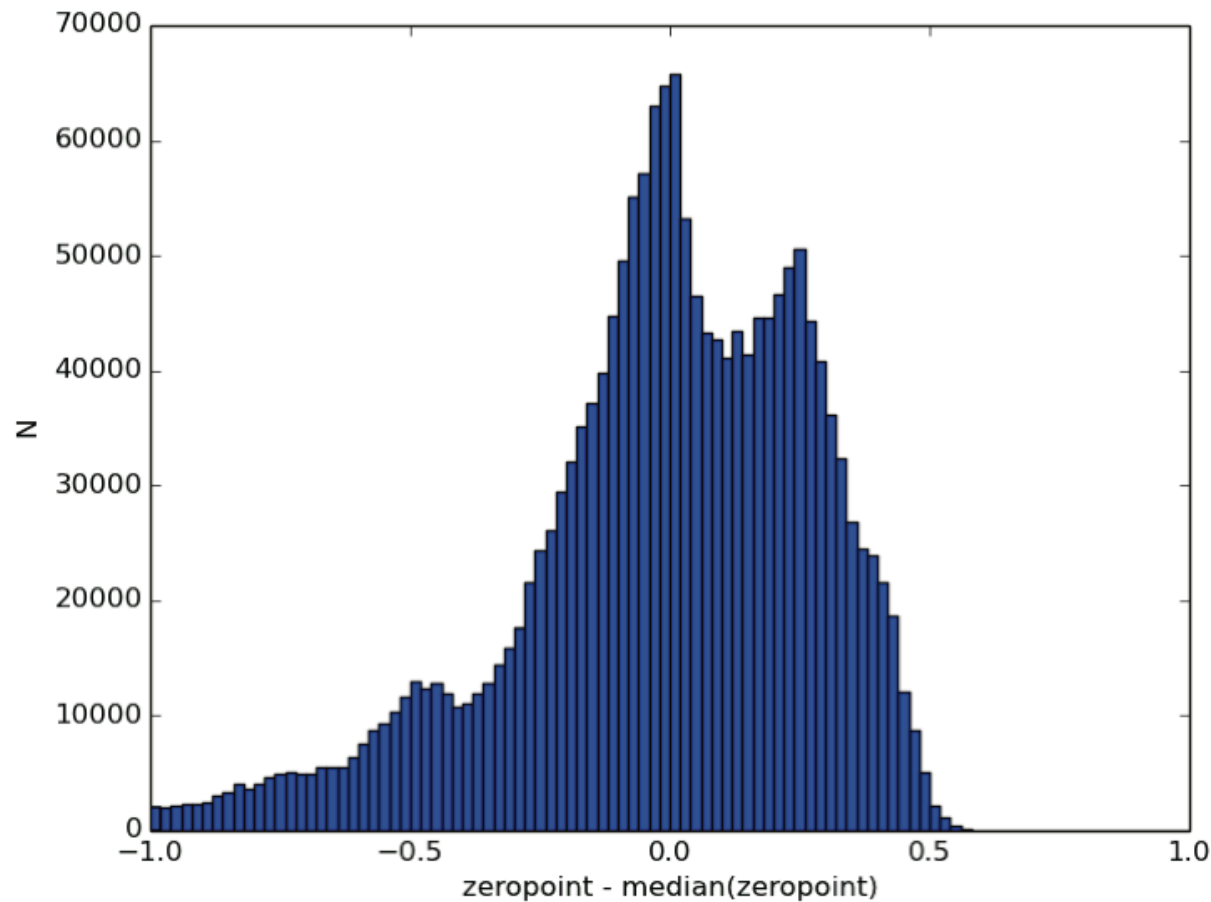
# Advantages of RR Lyr as Halo Probes

- Mean R mag for metal-poor RR Lyr is almost constant, get distance accurate to 7% in halo
- Out to 100 kpc, bright enough to get vr with Keck in less than 30 min
- Can use as massless probes, get a 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.

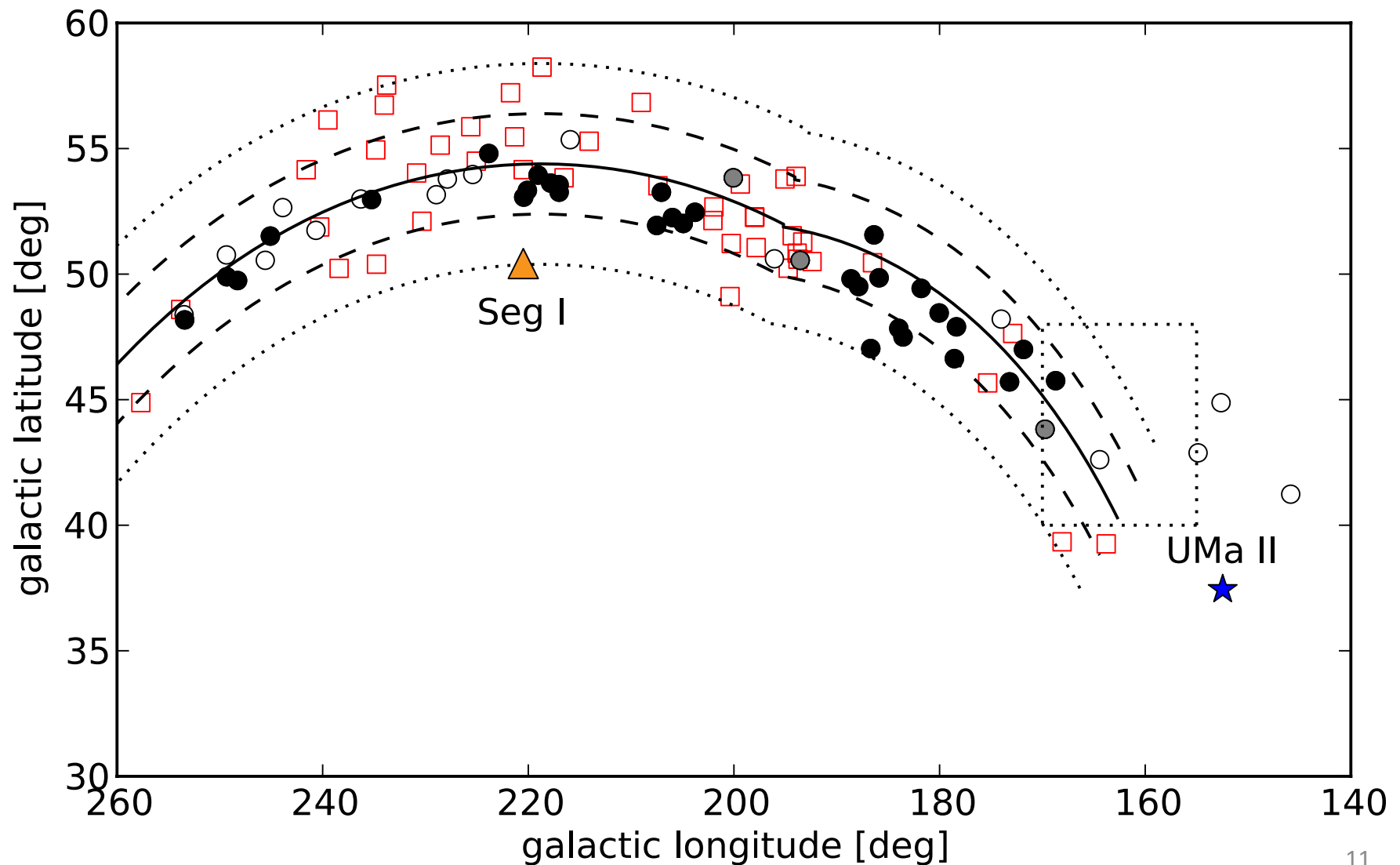
## PTF Limiting magnitude

- RR Lyr at 100 kpc has mean  $R = 20.6$
- PTF nominal  $5\sigma$  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 completeness)



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

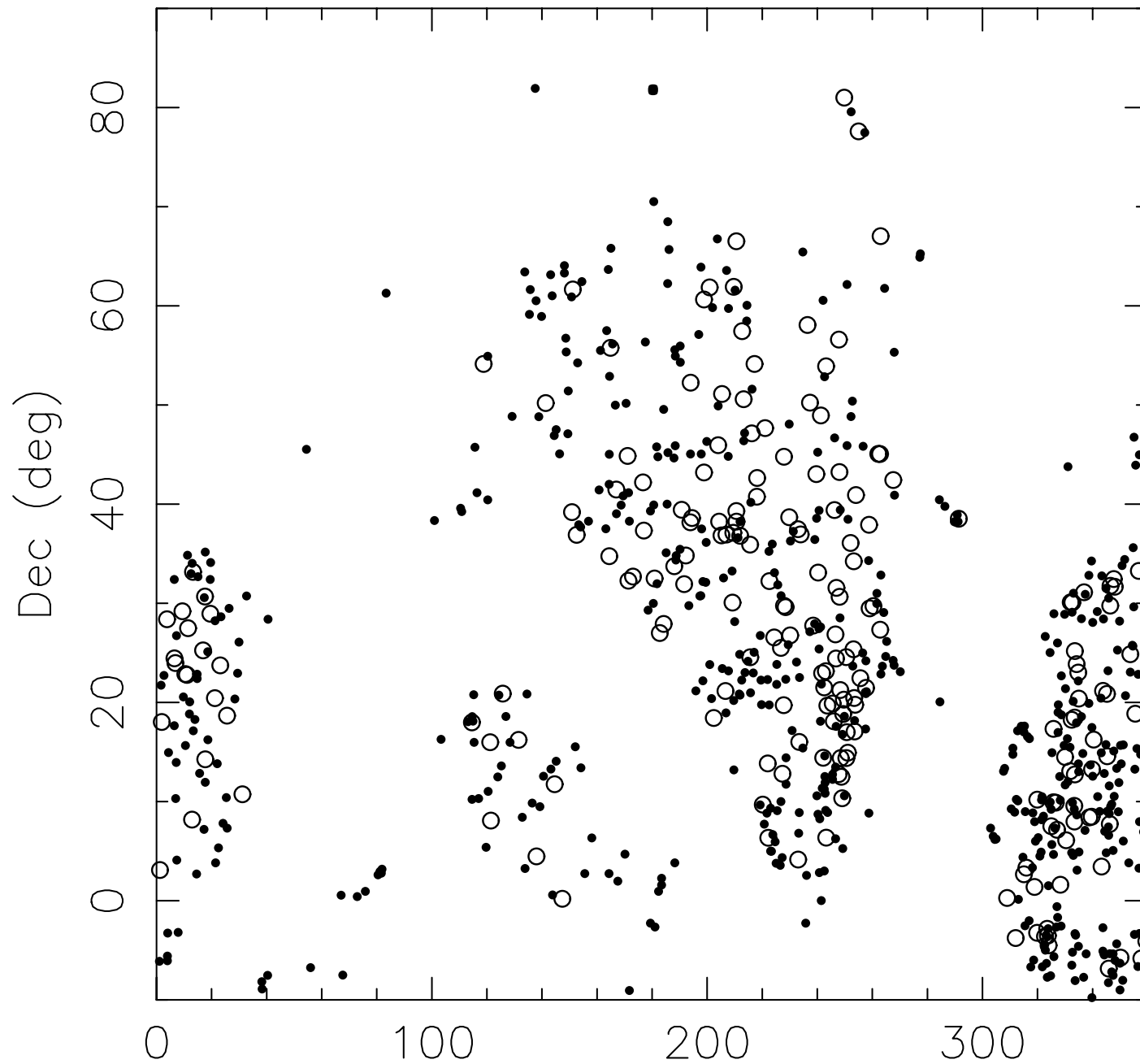


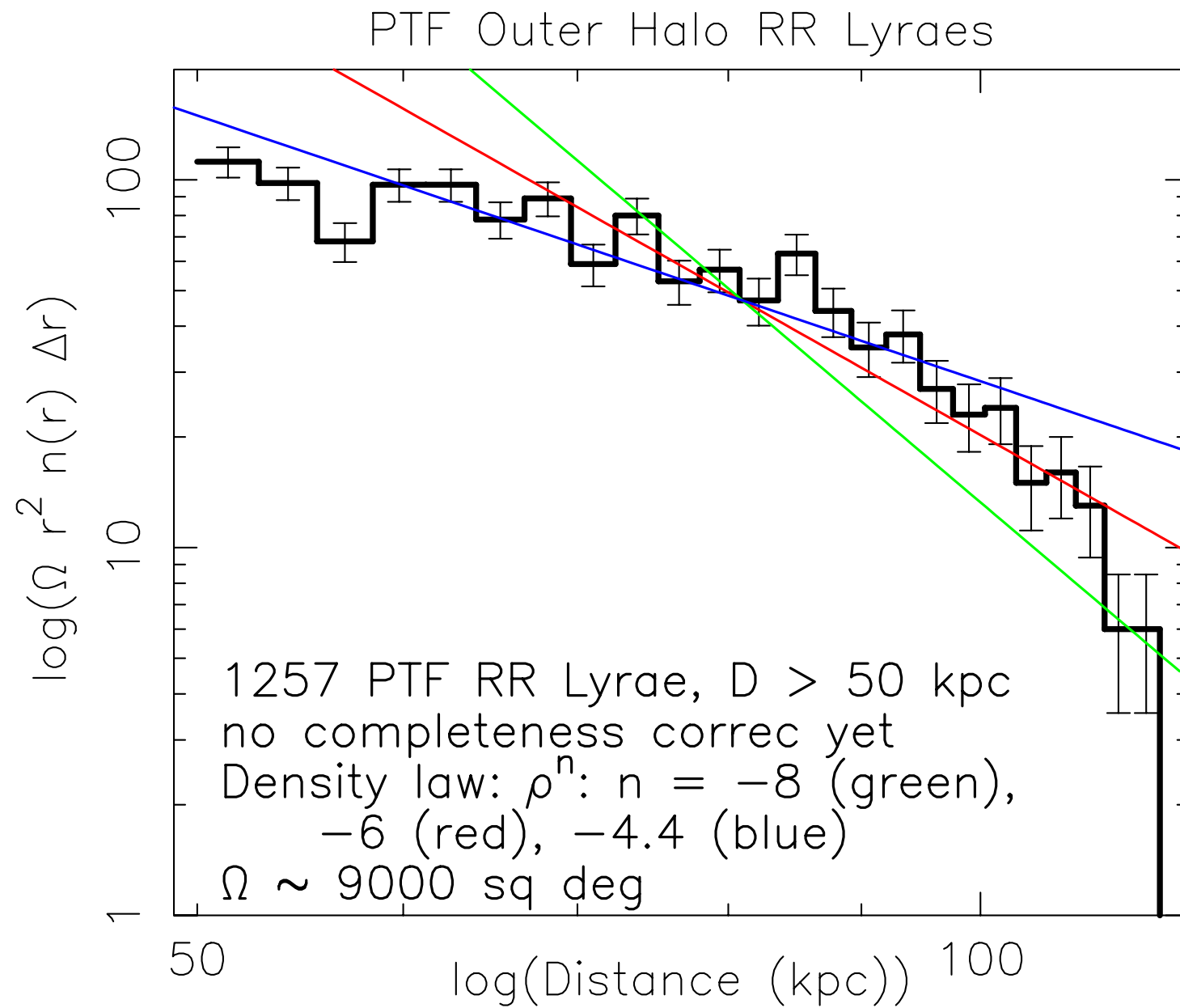


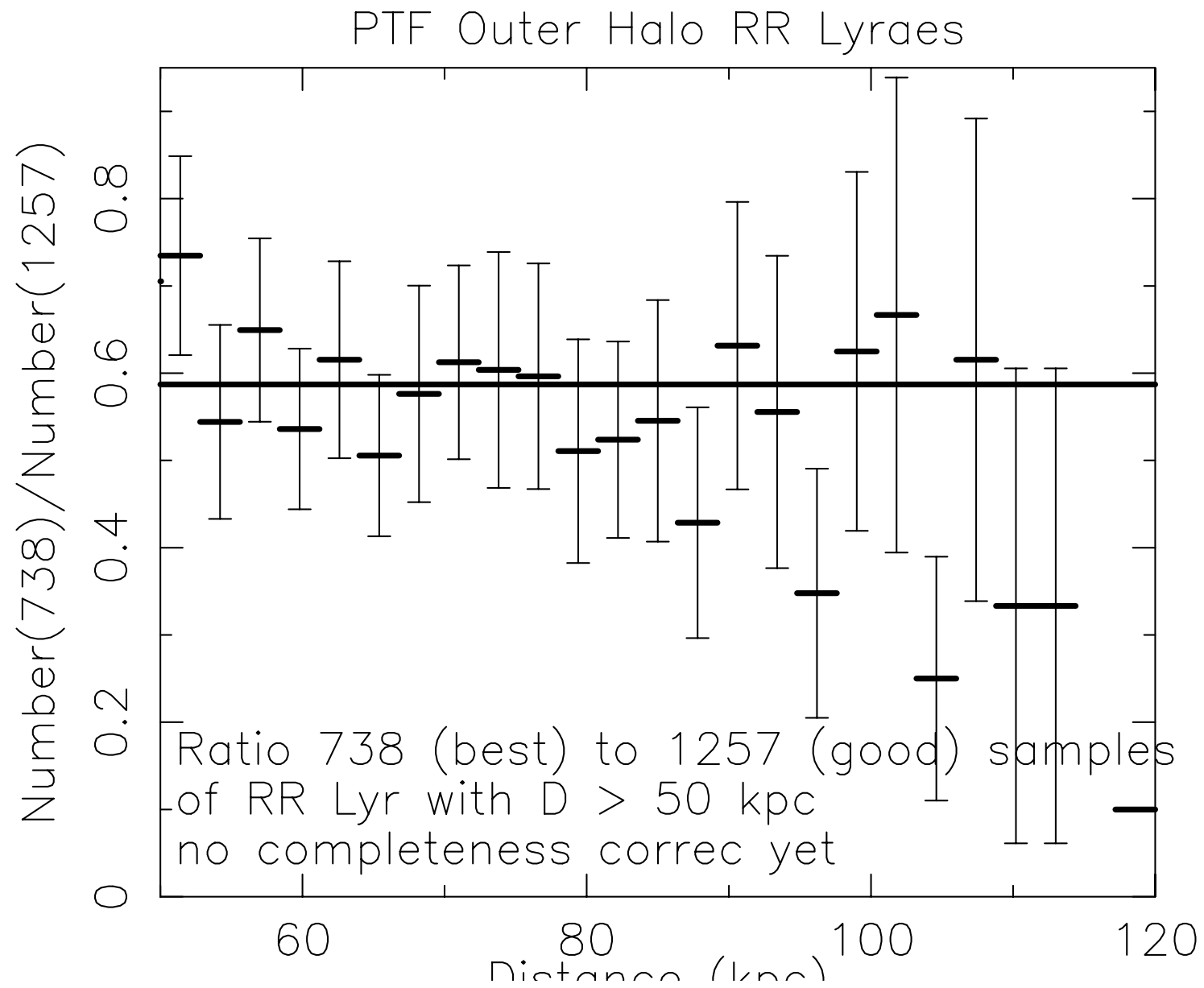
## 5 years of PTF + iPTF data

- We have found a sample of  $\sim 1300$  RR Lyr beyond 50 kpc in  $\sim 9,000$  sq deg with more than 30 epochs of observation ( $\sim 20\%$  of the sky) – excludes RR Lyr in known dSph etc
- $\sim 180$  of these are beyond 90 kpc, max  $\sim 115$  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  $v_r$  for the RR Lyr beyond 70 kpc
- We are using RR Lyr to study structure in the outer halo
- GAIA will yield proper motions

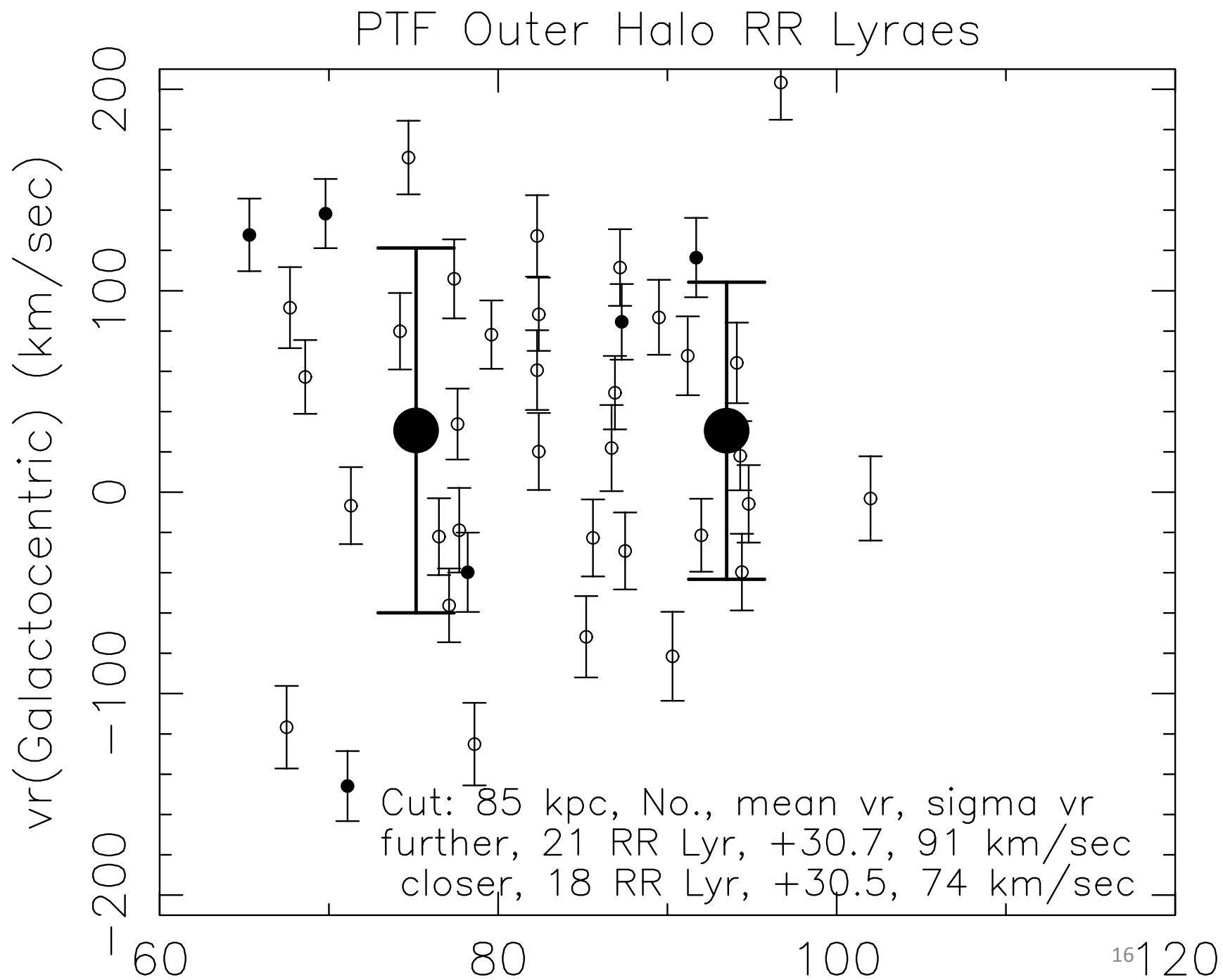
# PTF Outer Halo RR Lyraes









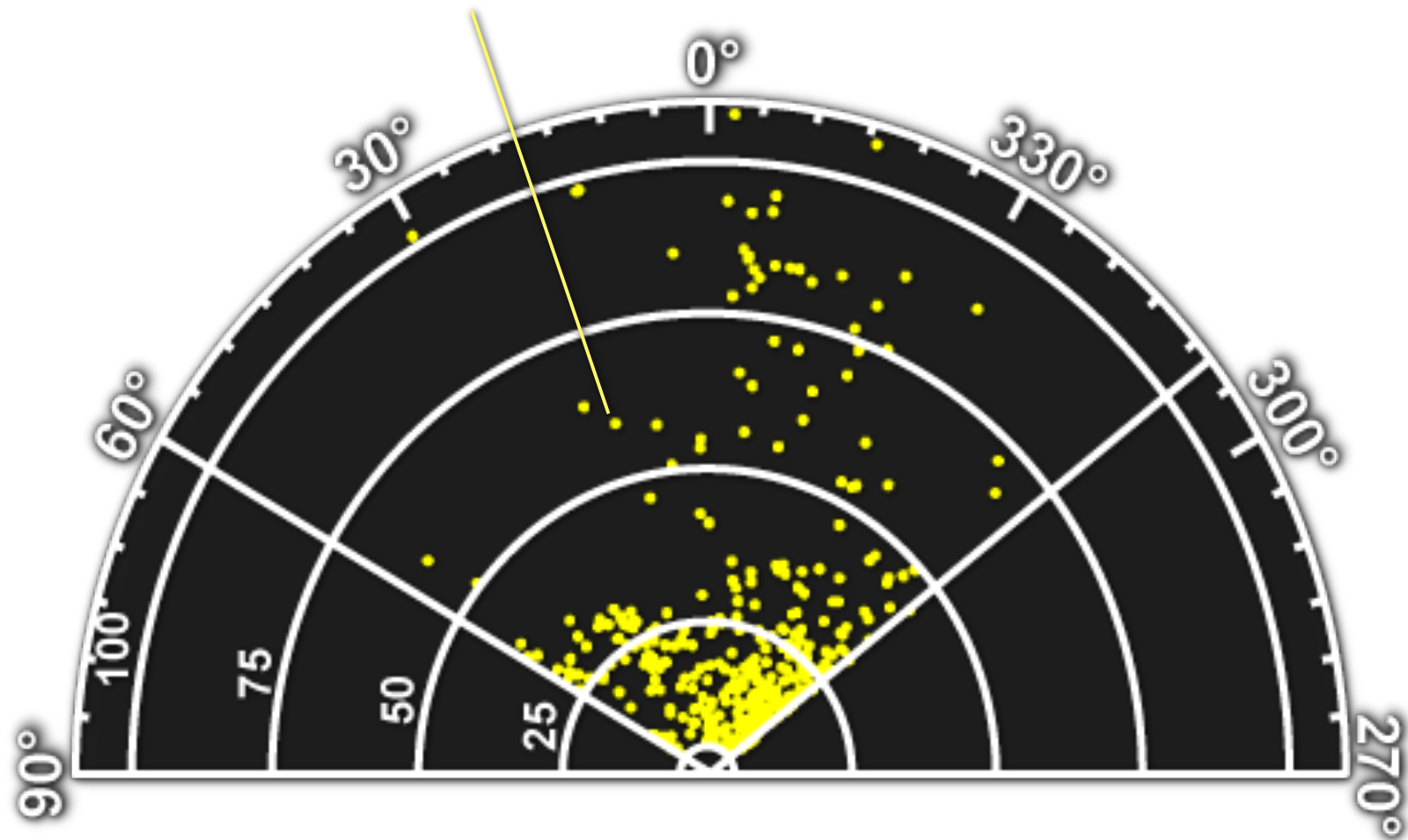


# Reaching beyond 110 kpc

- $\langle R \rangle = 20.6$  is D 100 kpc
- Only  $\sim 180$  beyond 90 kpc in  $\sim 9,000$  sq deg
- Need deep survey, many epochs, very high sky coverage = LSST !!
- Can't integrate spectra too long due to vr phase blurring, need bigger telescope than Keck to get vr of very distant RR Lyr
- NEED TMT AND LSST to construct the best possible map of the extreme outer halo of our galaxy

Backup slides

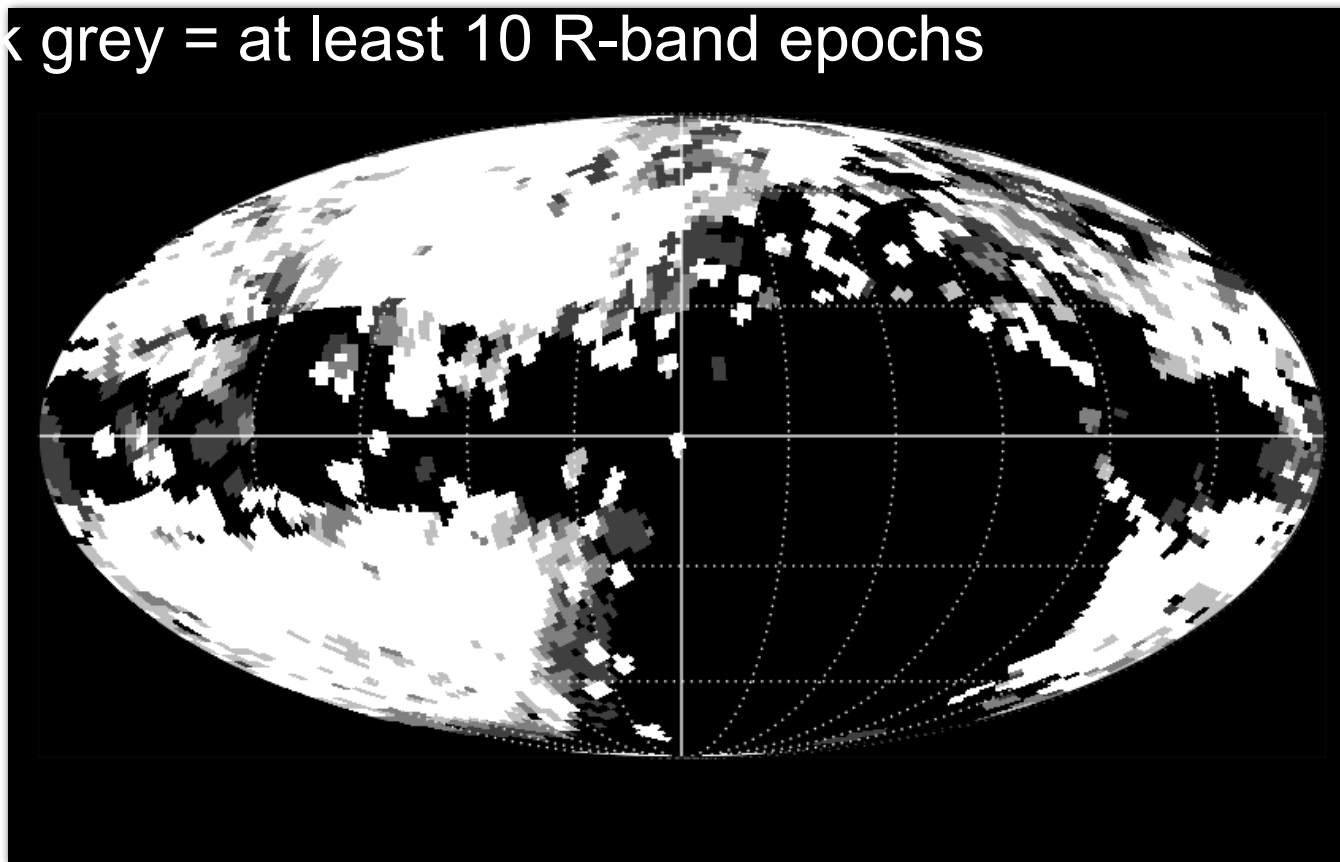
RR Lyrae stars in SDSS Stripe 82 (Sesar et al. 2010)



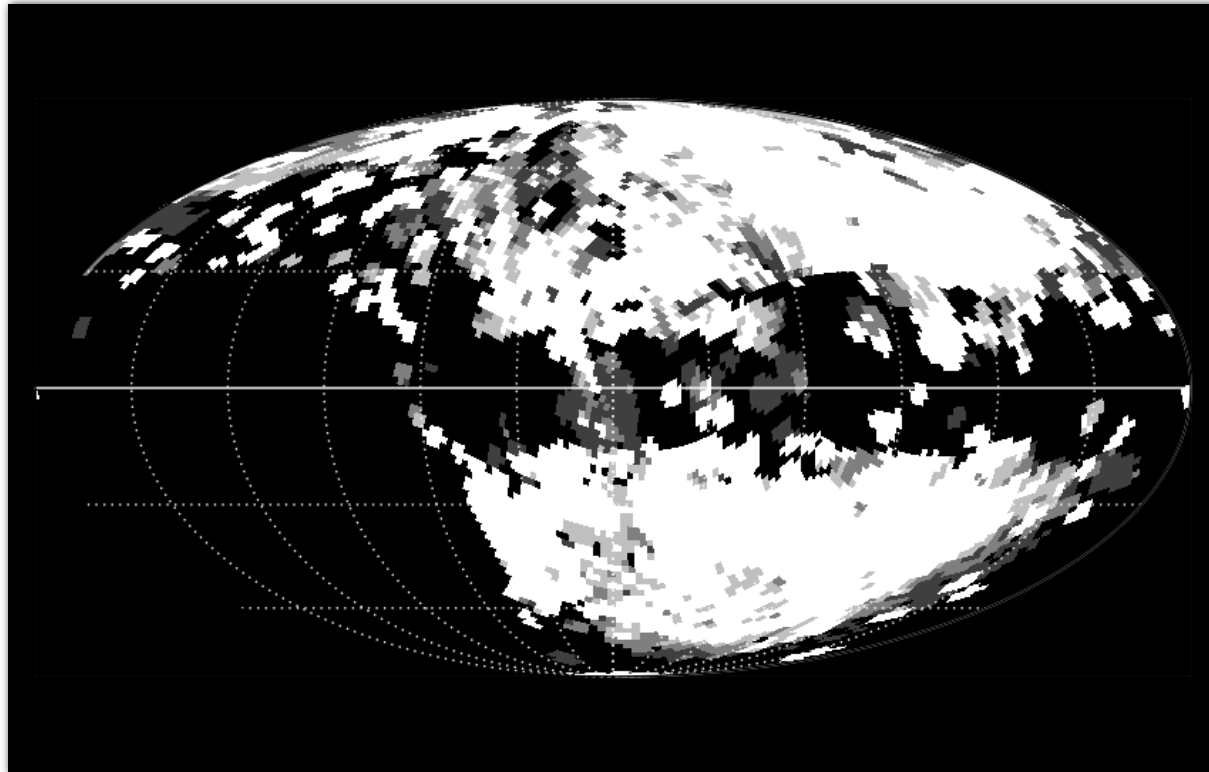
Where to look? Beyond 30 kpc from the Sun.

IPTF + PTF coverage centered at  $(l,b) = (0,0)$

dark grey = at least 10 R-band epochs

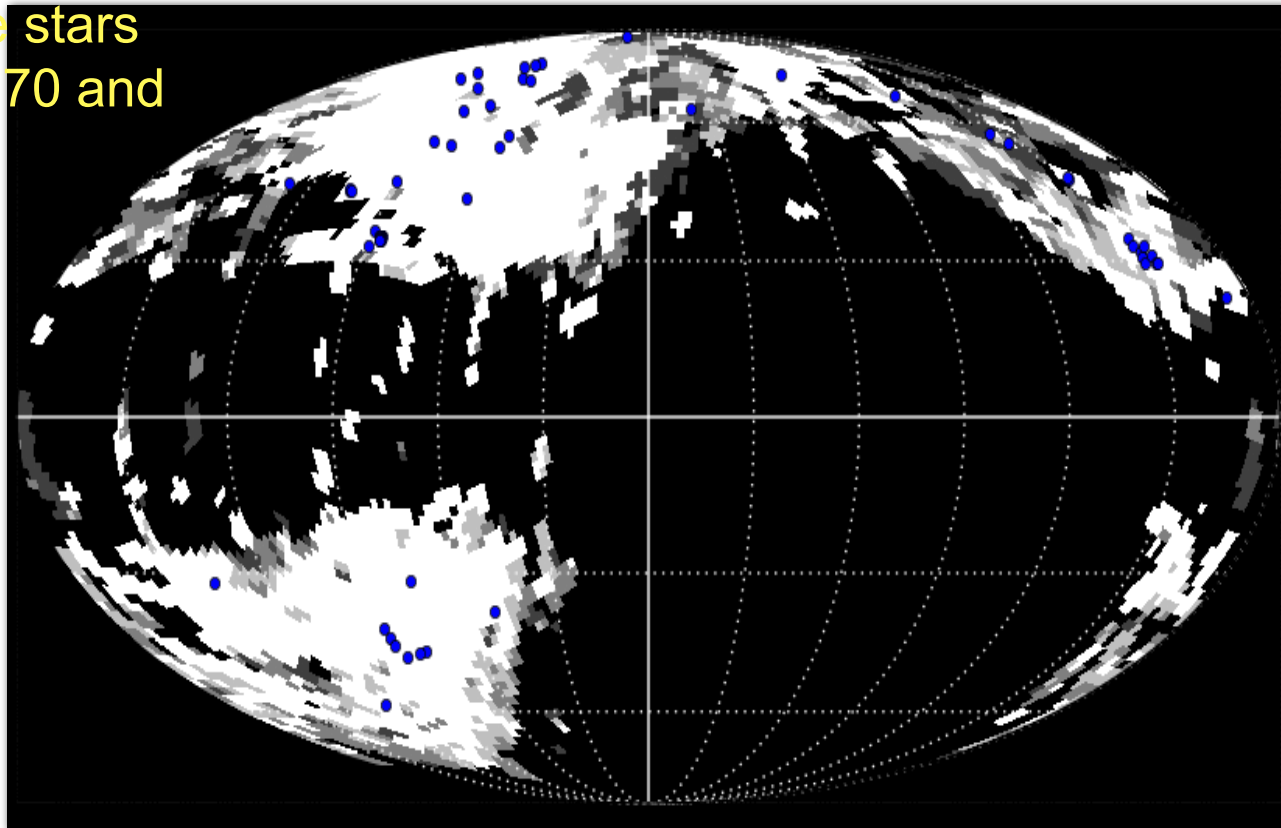


IPTF + PTF coverage centered at  $(l,b) = (180,0)$



# Palomar Transient Factory RR Lyrae Stars ( $\sim 1300$ RR Lyr $50 < R < 100$ kpc)

RR Lyrae stars  
between 70 and  
100 kpc



8 RR Lyrae Stars at  $\sim 85$  kpc in  $45$   
 $\text{deg}^2$

