The structure of the old Galactic Bulge revealed by Type II Cepheids

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Collaborators
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Acknowledgements
N. Cross, O. A. Gonzalez (IfA)

Why T2Cs?

Red Clump stars: at most 10 Gyr *(Girardi+ 2016)* MP and MR

MR: X shape (flared bar), rotation dominated

MP: spheroidal, dispersion velocity dominated

Zoccali+ (2016)

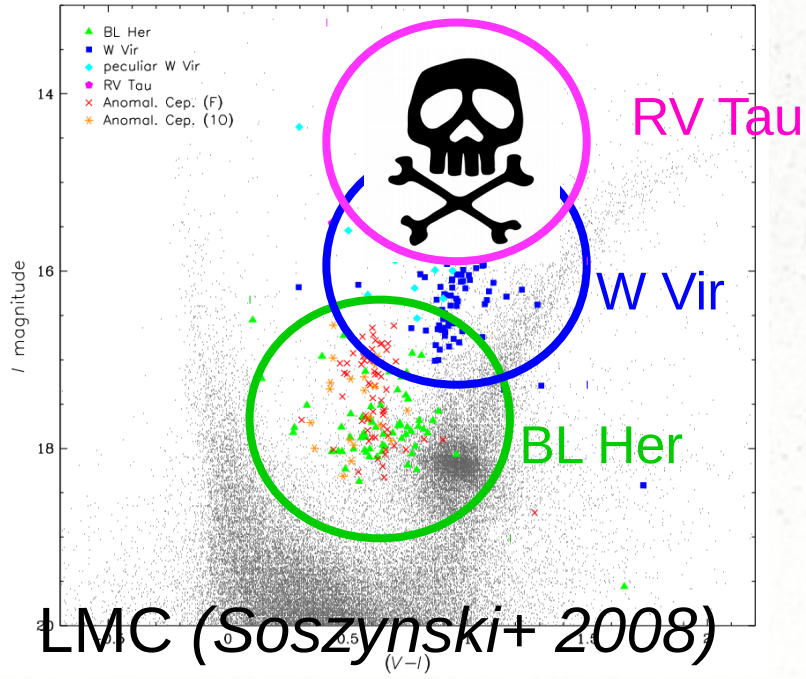
RRLs: at least 10 Gyr (what about He???)
similar structure and kinematics wrt MP RCs

T2Cs: as old as RRLs (or not??) less studied; brighter than RRLs (means more accurate proper motions from Gaia); but they are far fewer (~900)

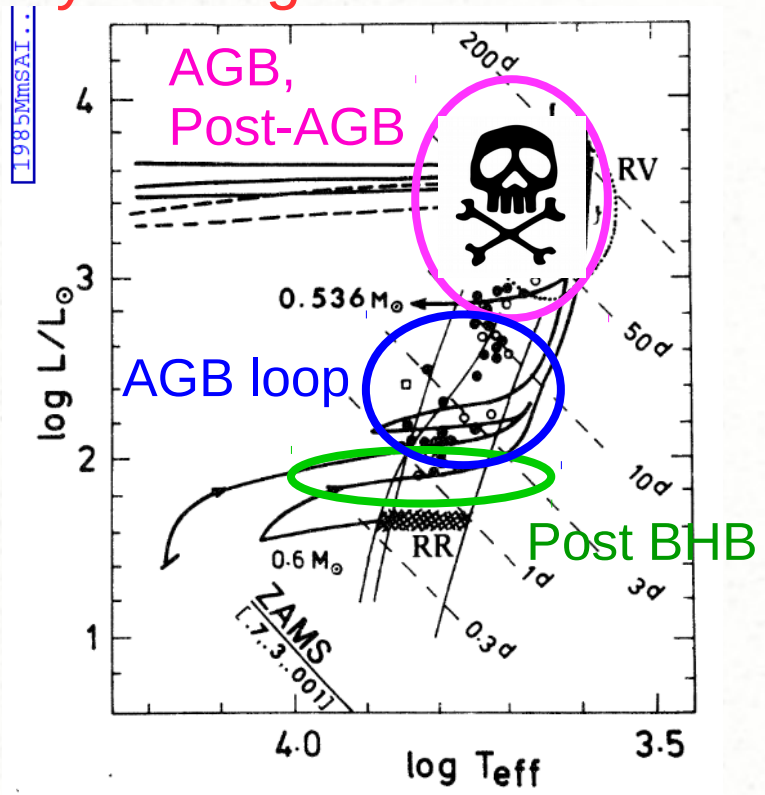
T2Cs: evolutionary and pulsational properties

What we know until few years ago...

- AGB, H shell+He shell burning
- ~0.5-0.6 M_{sun} ; < 1.0 M_{sun} (ZAMS)
- Old (>10 Gyr); [Fe/H] ~ -2 – 0
- P (BL Her)~ 1 – 5 d
- P (W Vir)~ 5 – 20 d
- P (RV Tau)~ 20 – 150 d



LMC *(Soszynski+ 2008)*

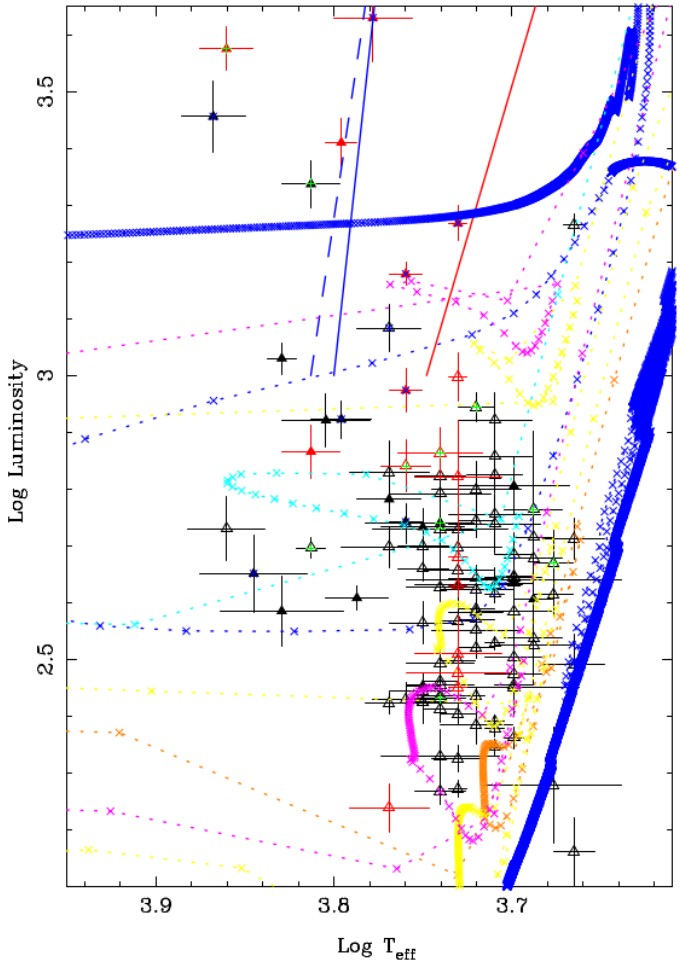


Gingold (1985)

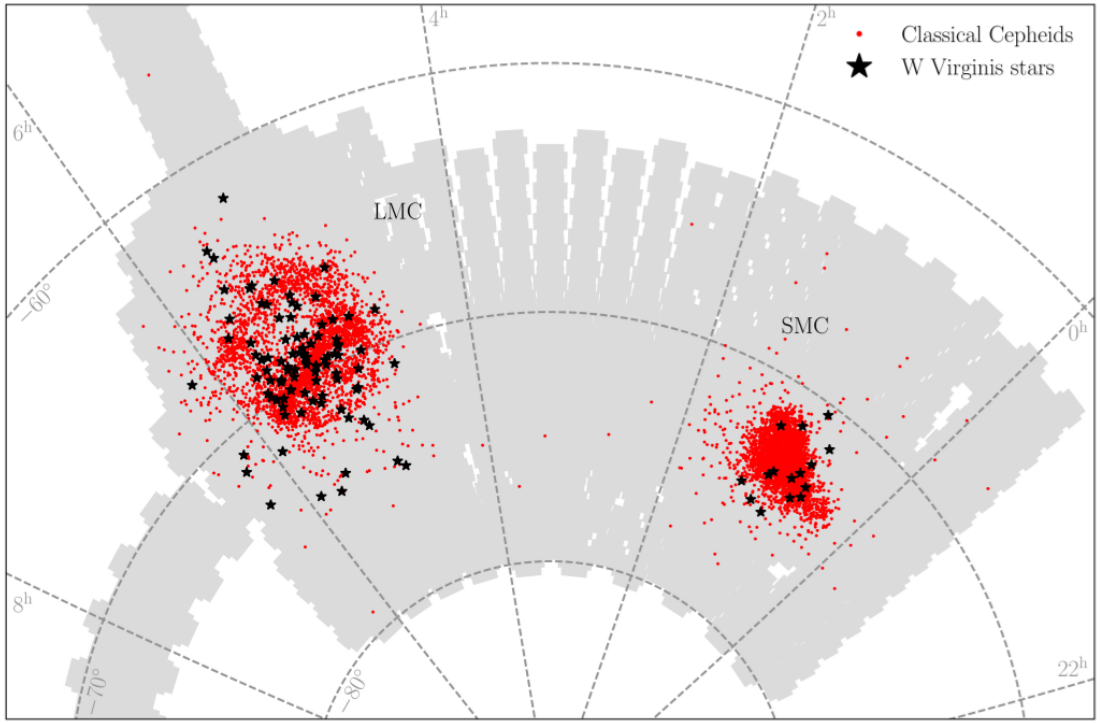
RV Tau: inhomogeneous class of stars (0.5 M_{sun} or > 1.0 M_{sun}); binary star evolution, **not good distance indicators** *(Matsunaga+ 2009, Groenewegen&Jurkovic 2017)*

T2Cs: evolutionary and pulsational properties

W Vir are not purely single old stars! (binarity, intermediate age..)



Groenewegen&Jurkovic 2017

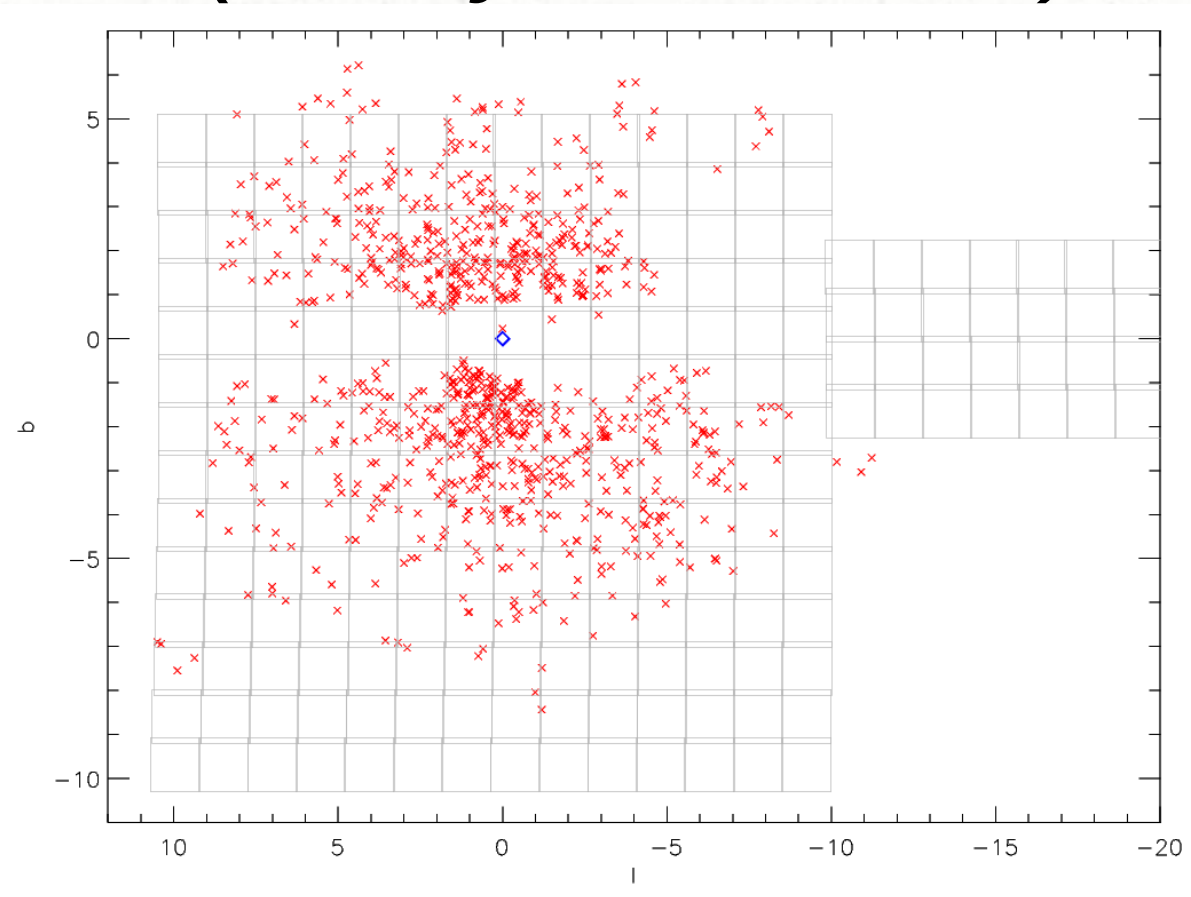


Iwanek+ 2018

Both empirical (3D distribution in the Magellanic Cloud) and theoretical evidence (no obvious evolutionary path)

First part: T2Cs from OGLE survey *(Braga+ 2018)*

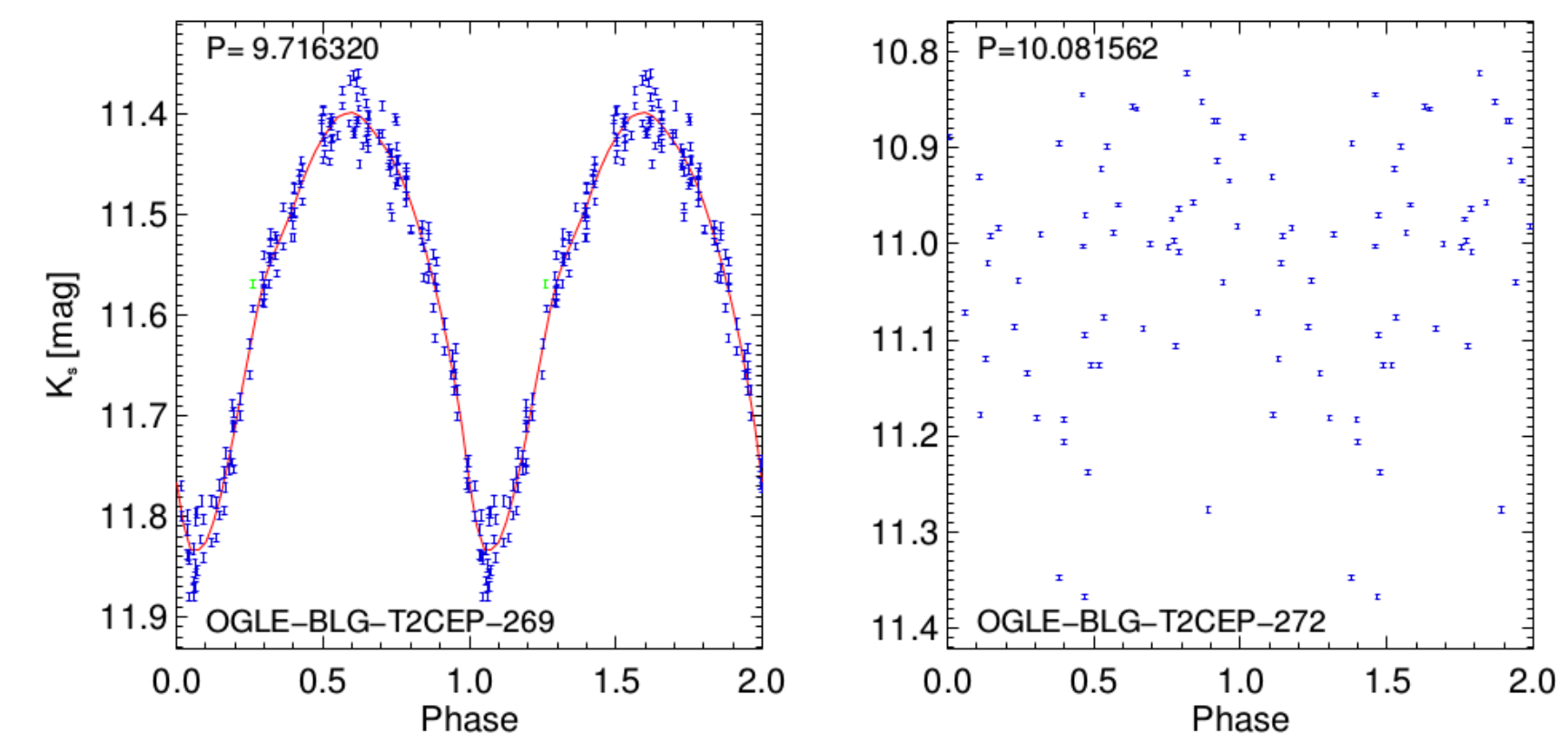
OGLE IV Bulge T2Cs
(Soszynski+ 2017)



Total: 924 – in VVV: 894

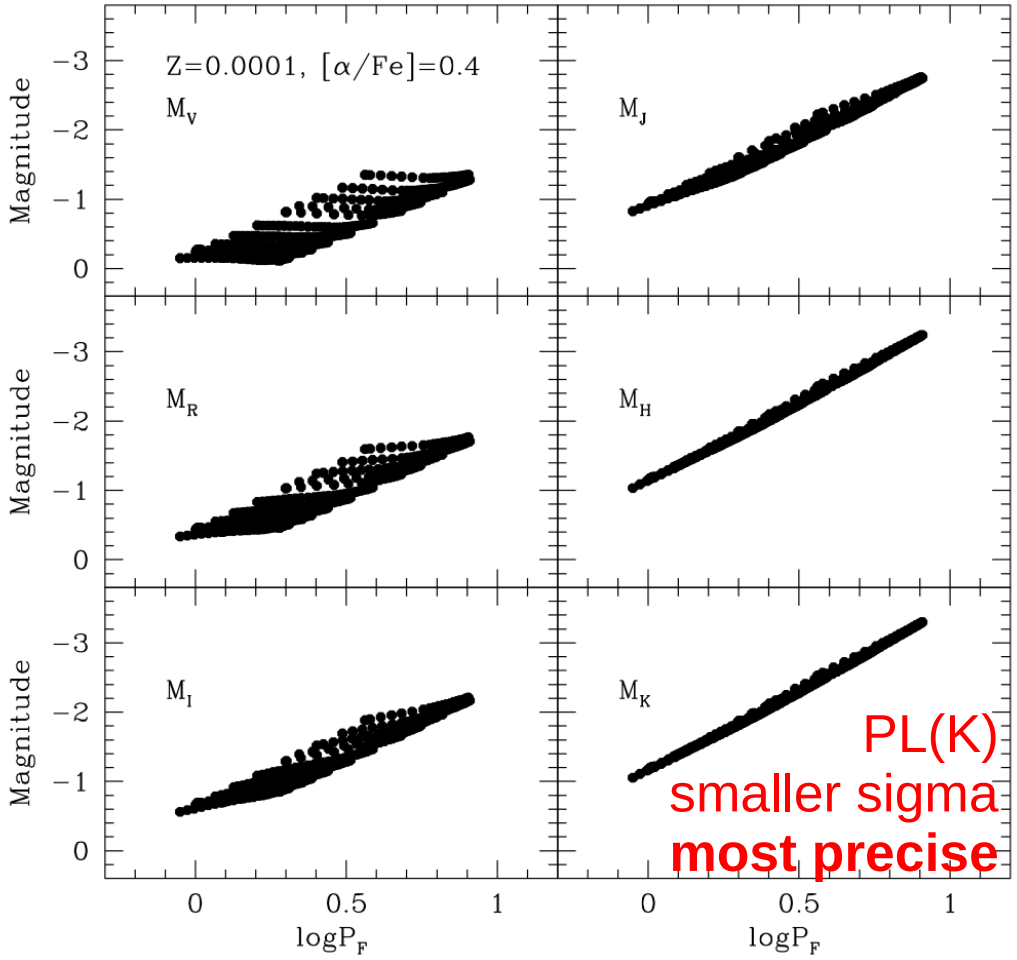
Photometry: PSF (R. Contreras); Aperture (CASU)

Sample light curves



High quality (amplitude can be estimated): 733 – Low quality: 161

Distance diagnostic: Period-Luminosity (PL) relations



Di Criscienzo+ (2007)

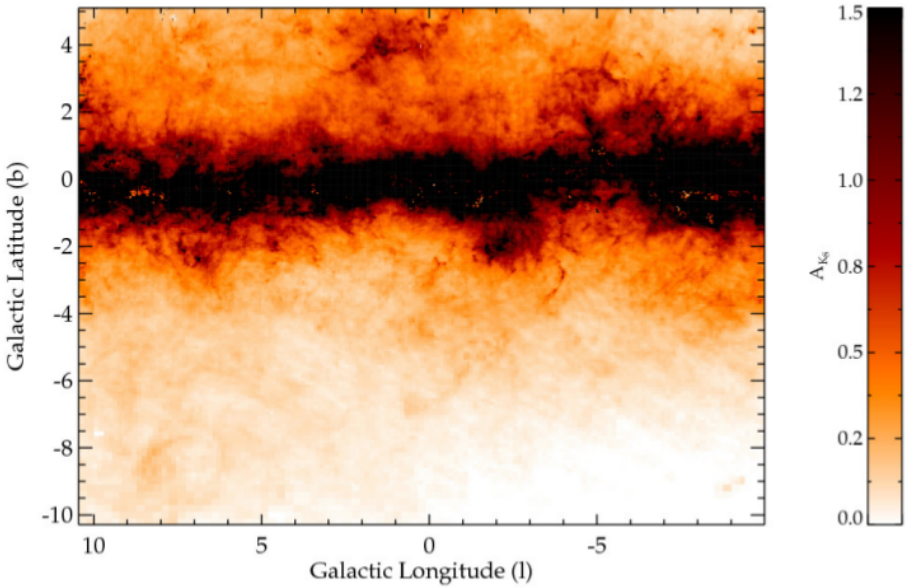
$$M_X = a + b * logP$$

Empirical PLs are affected by extinction and differential reddening...

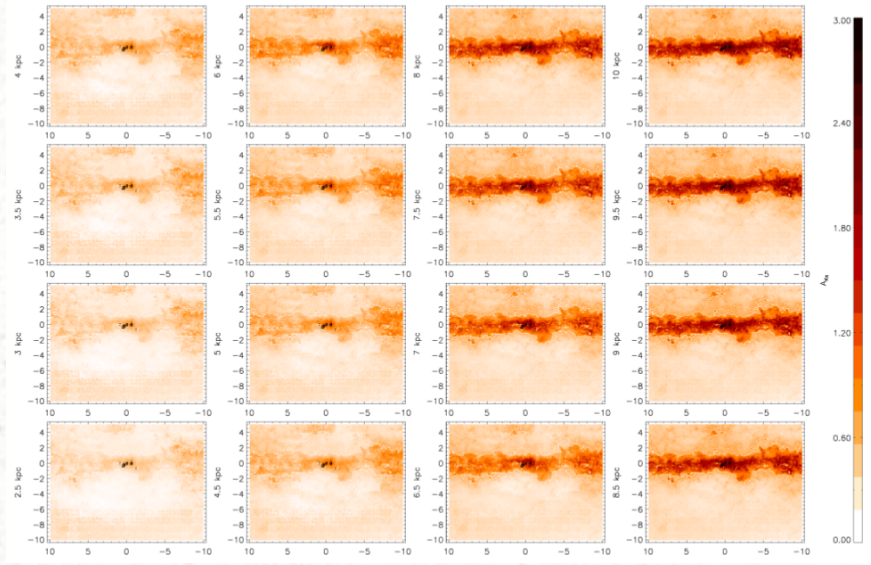
Metallicity coefficient often smaller than 0.1 mag/dex for T2Cs *(Matsunaga+ 2006, Di Criscienzo+ 2007, Groenewegen&Jurkovic 2017)*

Reddening

Reddening maps in native VVV data available, based on Red clump stars



Gonzalez+ (2012, G12)



Schultheis+ (2014, S14)

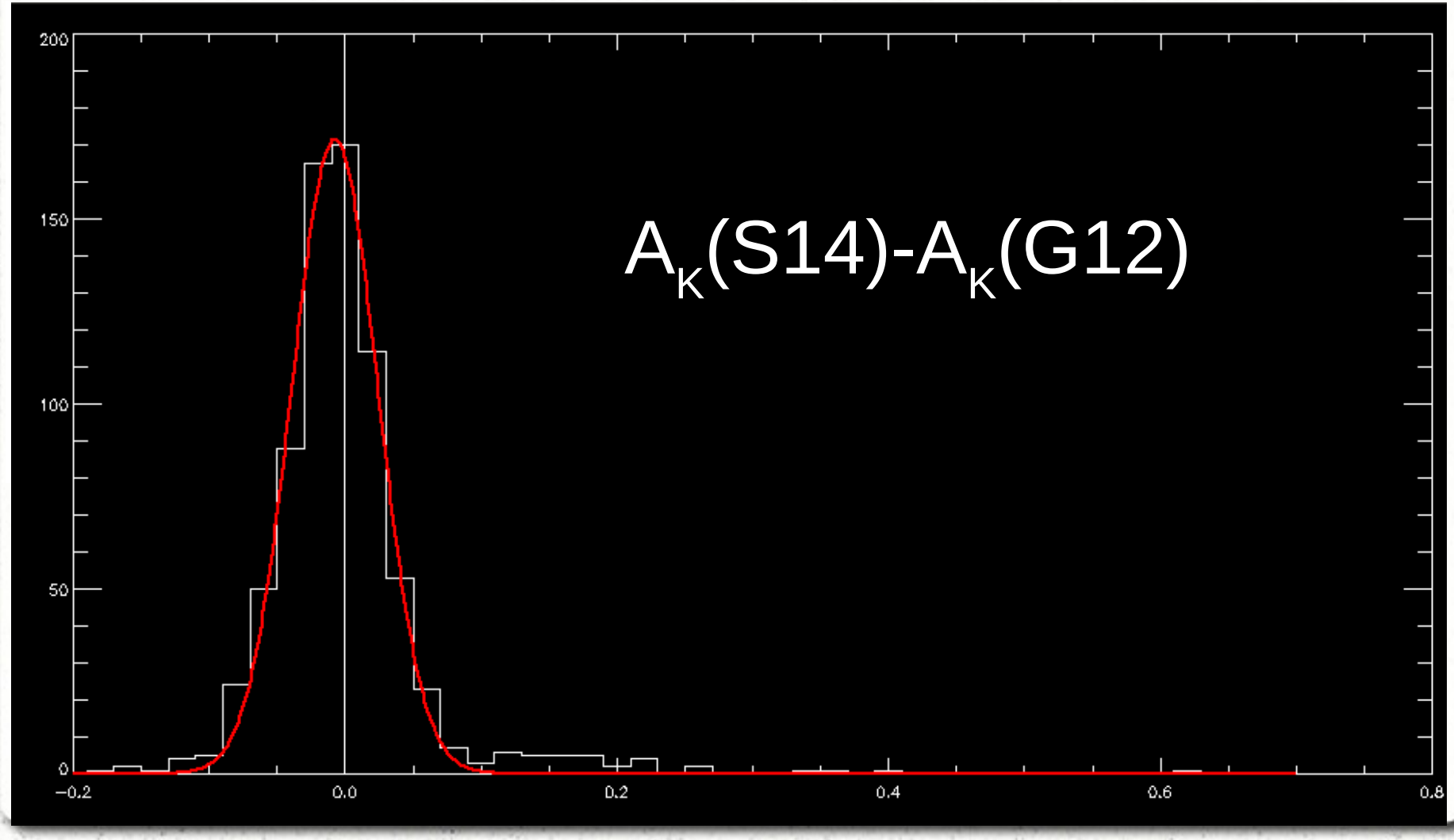
2D: first guess

3D: refine and iterate

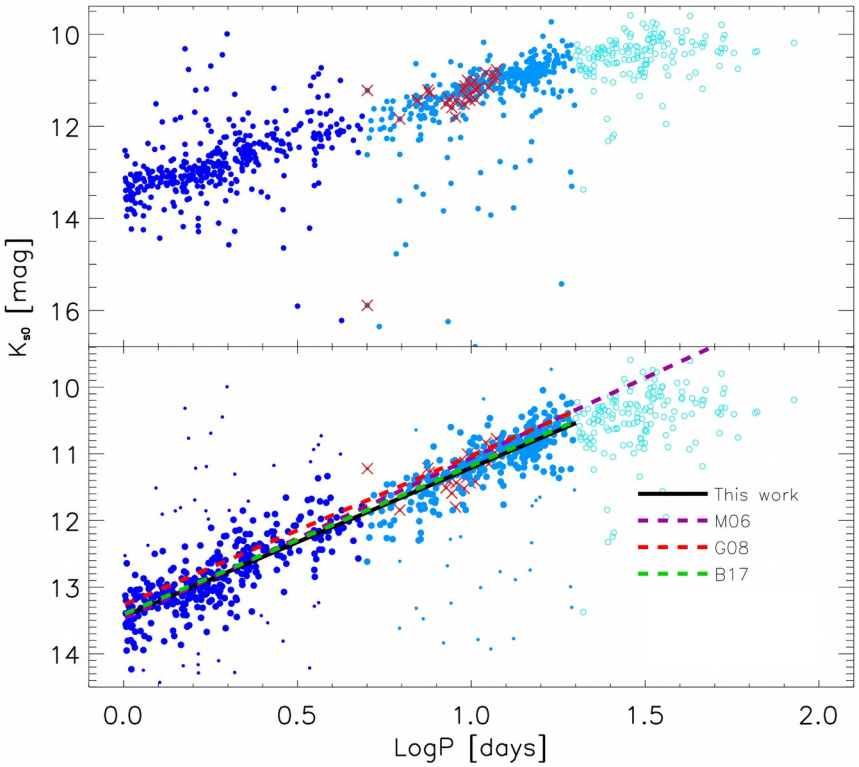
Reddening law *AK/E(J-K); AH/AK; AJ/AK...*
Alonso-Garcia+ (2017, VVV)

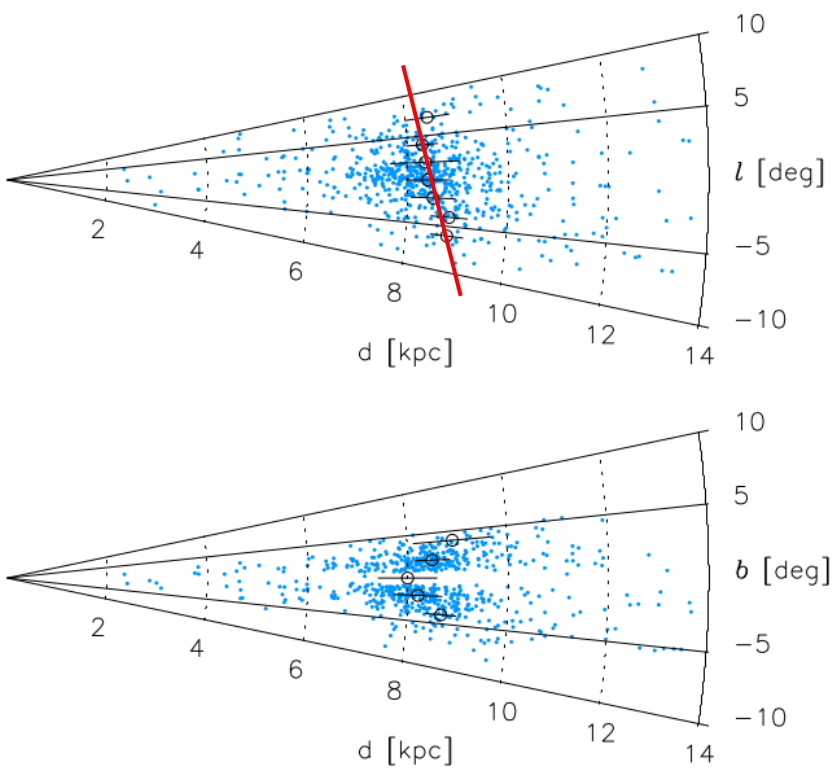
Reddening

Δ=0.007 mag!! ; S14-G12 > 0 at > ~8.5 kpc ; S14-G12 < 0 at > ~8.5 kpc



PL(K_s) relation

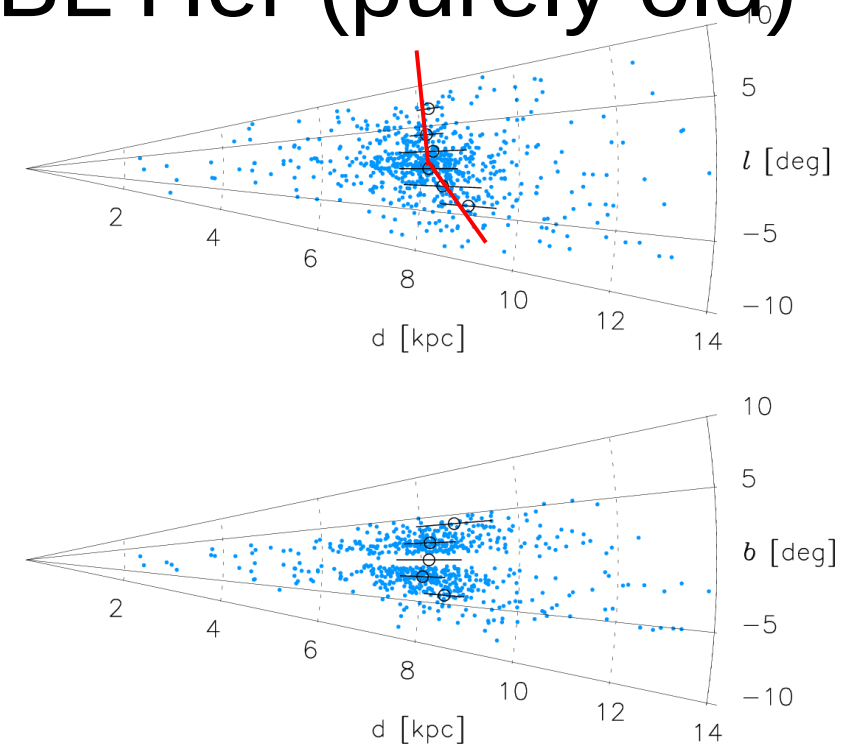




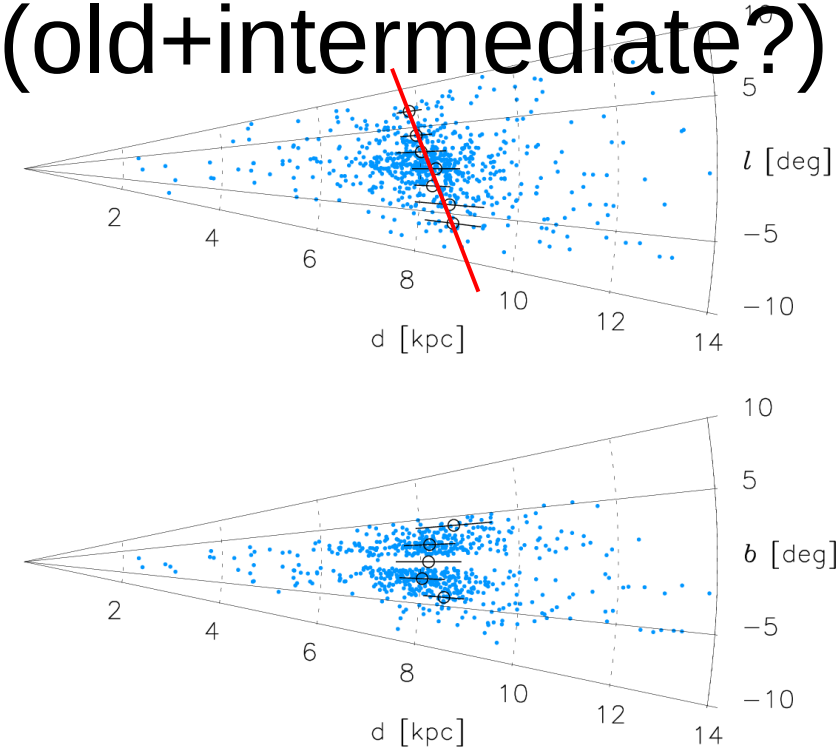
$K_s = (10.66 \pm 0.02) - (2.21 \pm 0.03) \cdot (\log P - 1.2)$
$- (0.020 \pm 0.003) \cdot l + (0.050 \pm 0.008) \cdot |b|$ mag

PL(K_s) relation

BL Her (purely old)



W Vir (old+intermediate?)



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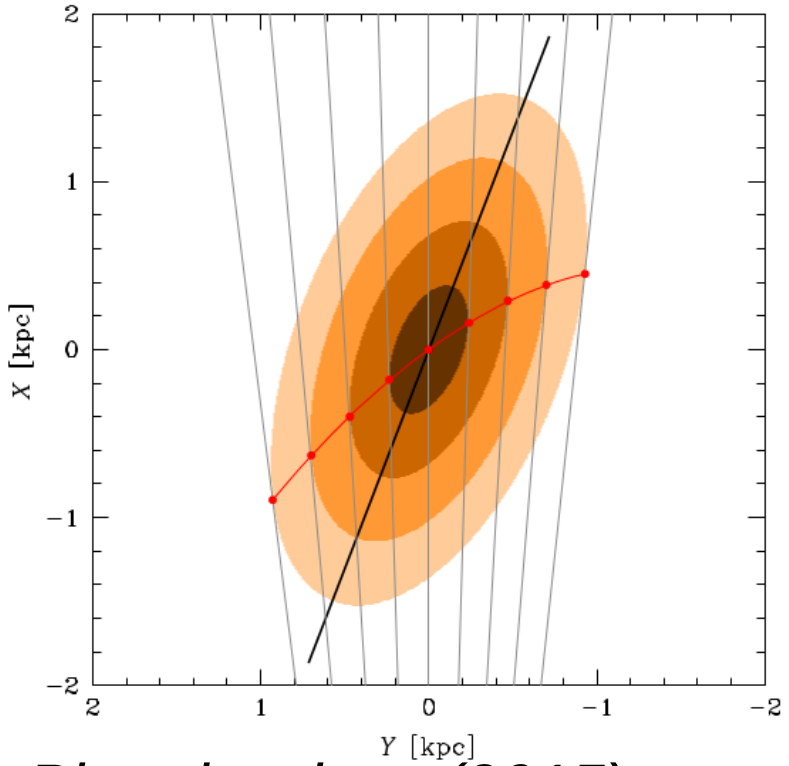
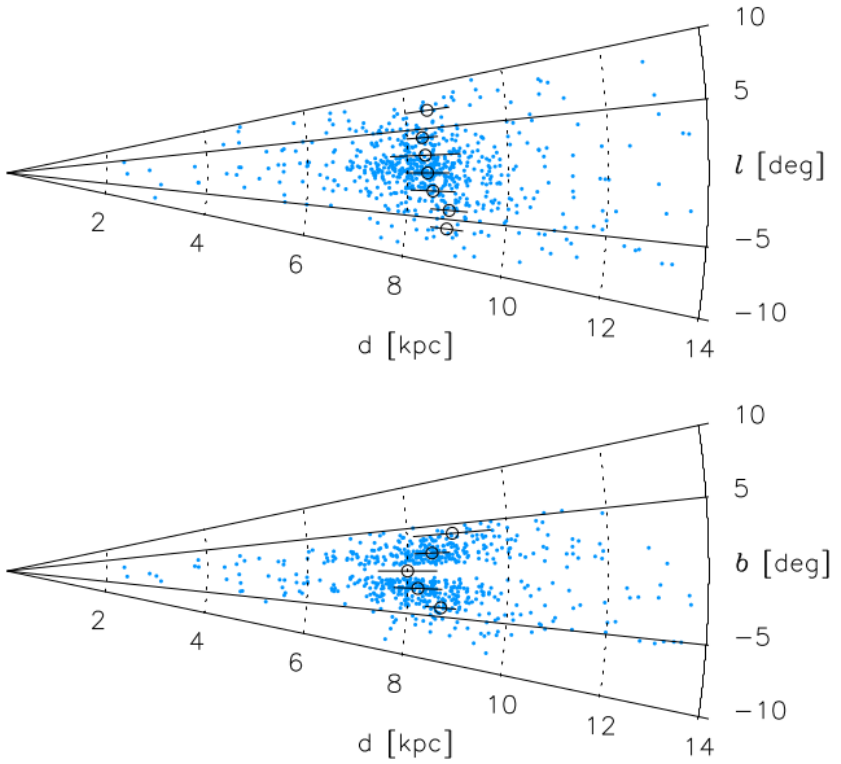
$- (0.020 \pm 0.003) \cdot l + (0.050 \pm 0.008) \cdot |b|$ mag

PL(K_s) relation
Tilted like RRLs in OGLE





Pietrukowicz+ (2015)

$K_s = (10.66 \pm 0.02) - (2.21 \pm 0.03) \cdot (\log P - 1.2)$
$- (0.020 \pm 0.003) \cdot l + (0.050 \pm 0.008) \cdot |b|$ mag

First big question

Do WVs and RRLs belong to the same population within the Bulge??

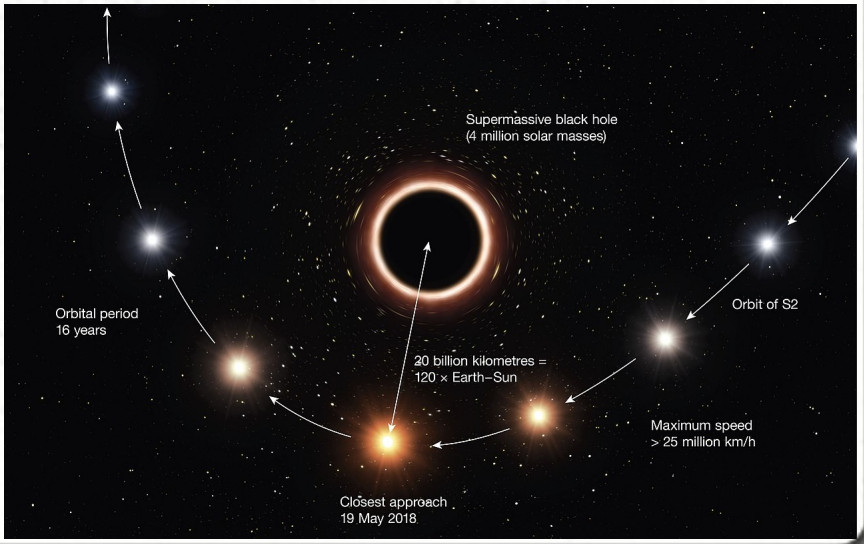
GC Distance

IAU recommended: 8.5 kpc

Literature: 7-9 kpc; Recommended: 8.2-8.3 kpc *(de Grijs&Bono 2016; Bland-Hawthorn 2016)*

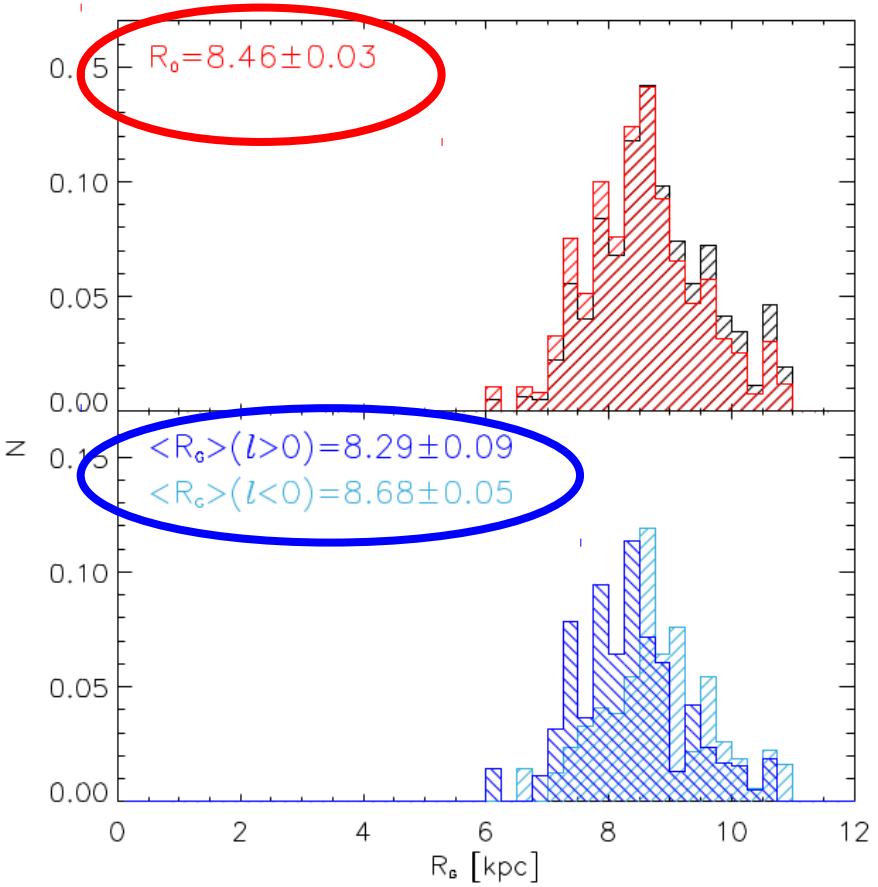
RRLs, T2Cs: well-clustered around 8.30 kpc *(Dékány+ 2013; Pietrukowicz+ 2015; Bhardwaj+ 2017b)*

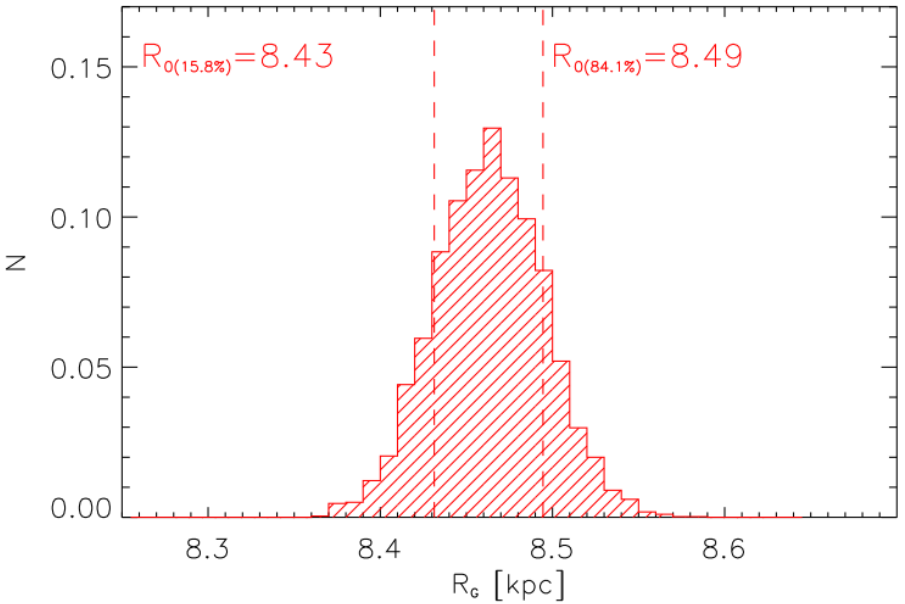
SMBH: 8.127 kpc *(GRAVITY Collaboration+ 2018)*



GC distance (PLK+reddening map)

RESAMPLING: random selections in l and b, repeated 5000 times.



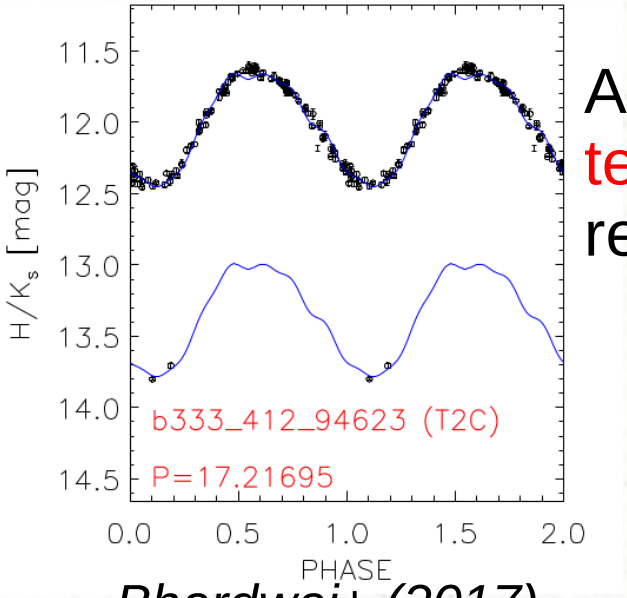


A_K/E(J-K)=0.428 *(Alonso-Garcia+ 2017)* → 8.46 kpc

A_K/E(J-K)=0.528 *(Nishiyama+ 2009)* → 8.30 kpc

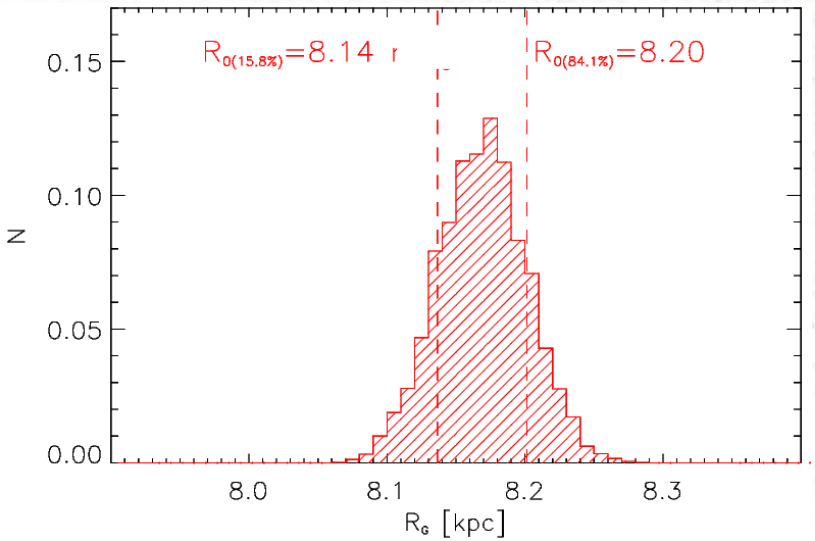
Previous estimates based on RRLs and T2Cs: ~8.30 kpc with *Nishiyama+ (2009)*

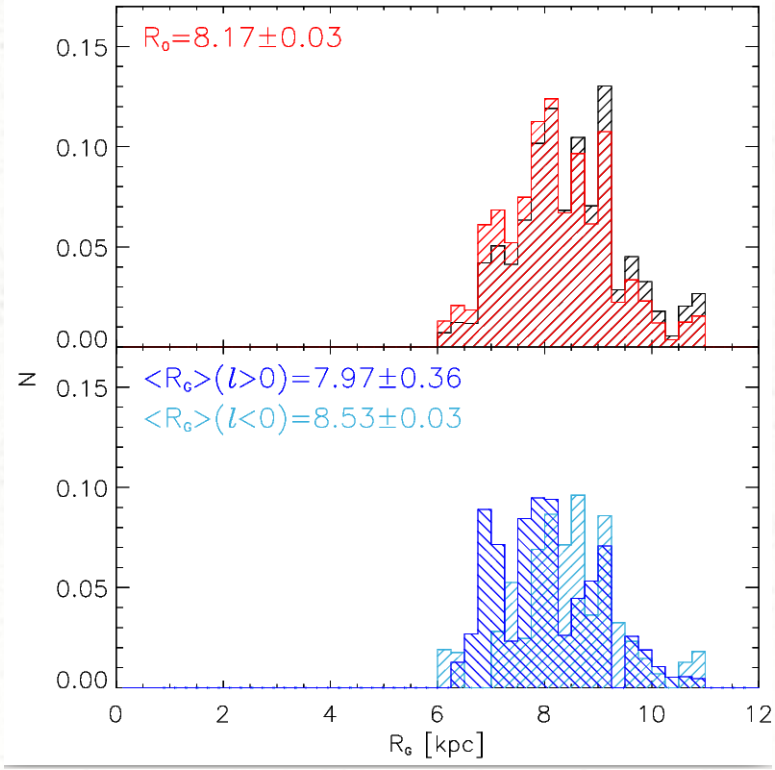
GC distance (template+PLK+PLH relations)



Bhardwaj+ (2017)

Accurate H-band measurements with templates → simultaneous PLH+PLK relation → solve for extinction and distance





A$_K$/E(J-K)=0.428 *(Alonso-Garcia+ 2017)* → 8.17 kpc

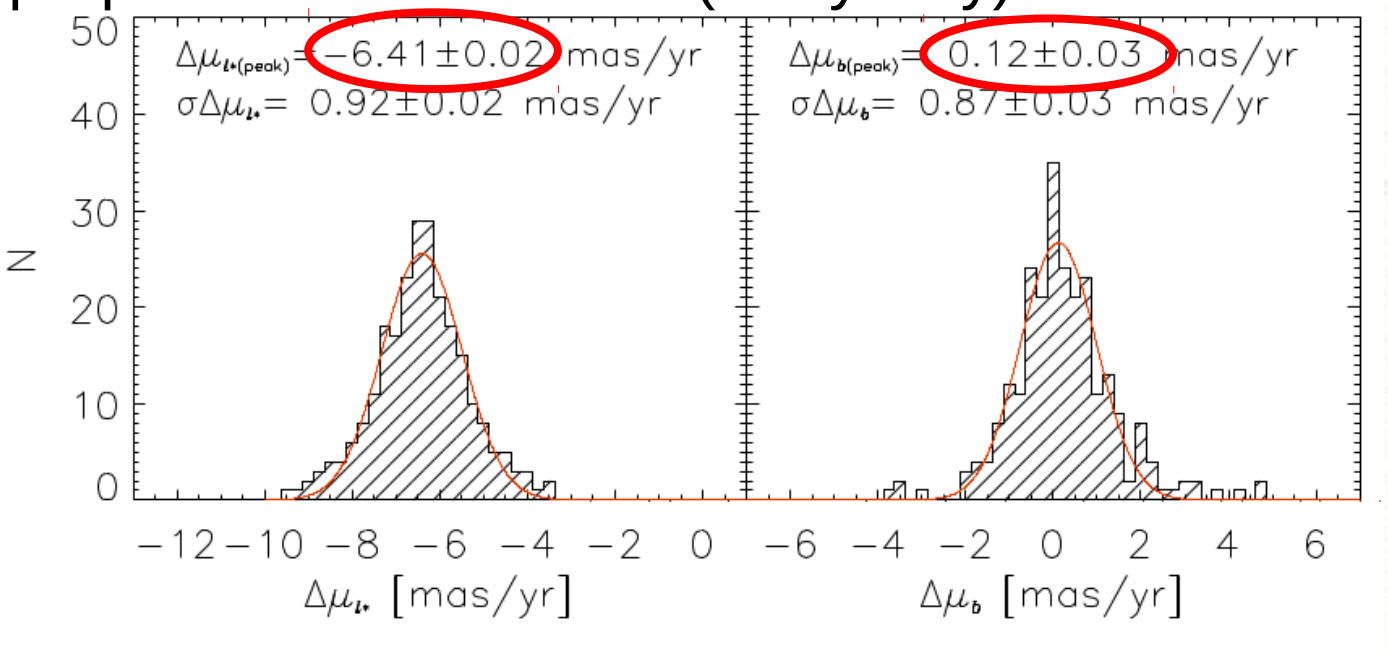
Second big question

Which reddening map/technique? (amount of dust)

Proper motions (selection on distance)

Gaia proper motions: absolute (quasar)

PSF proper motions: relative (Milky way)



Proper motions (selection on distance)

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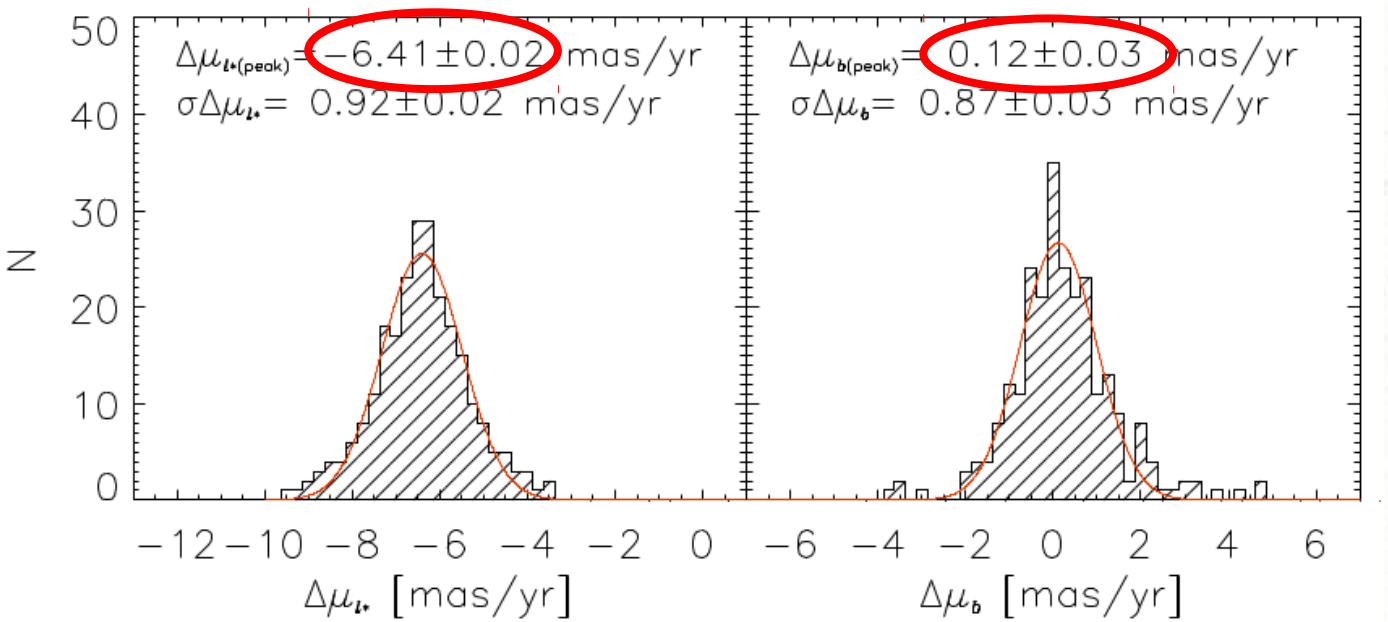
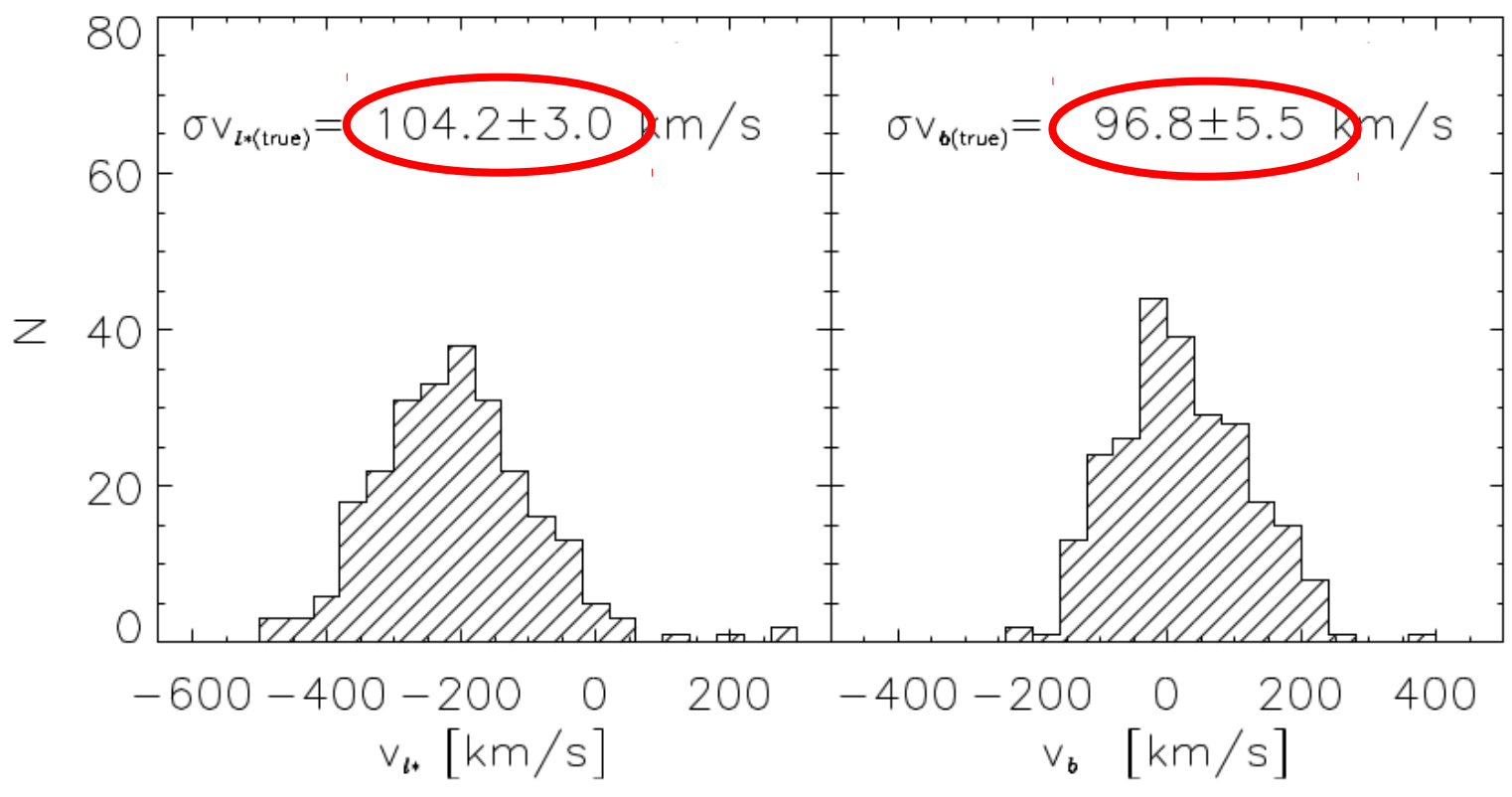


Source minus Reference	Easterly Motion (mas yr^{-1})	Northerly Motion (mas yr^{-1})	l Motion (mas yr^{-1})	b Motion (mas yr^{-1})
Sgr A* minus J1745−283.....	−3.151 ± 0.018	−5.547 ± 0.026	−6.379 ± 0.026	−0.202 ± 0.019
J1748−291 minus J1745−283.....	−0.052 ± 0.035	−0.126 ± 0.061	−0.131 ± 0.060	−0.021 ± 0.037

Reid+ (2004)

Velocities

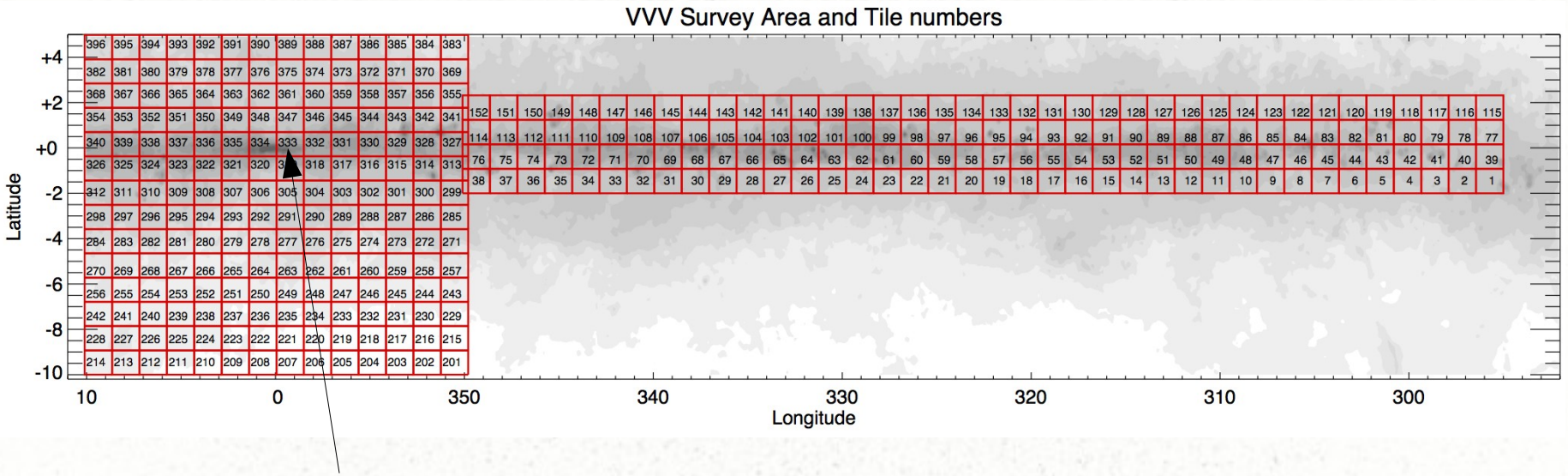


Kinematically hot dominated… but evidence of deviation… weak net rotation (triaxial)? Not enough statistics to separate BLHer and WVir

Second part: new T2Cs from VVV
(Braga+ 2019, in prep.)

Galactic center

PSF photometry by R. Contreras

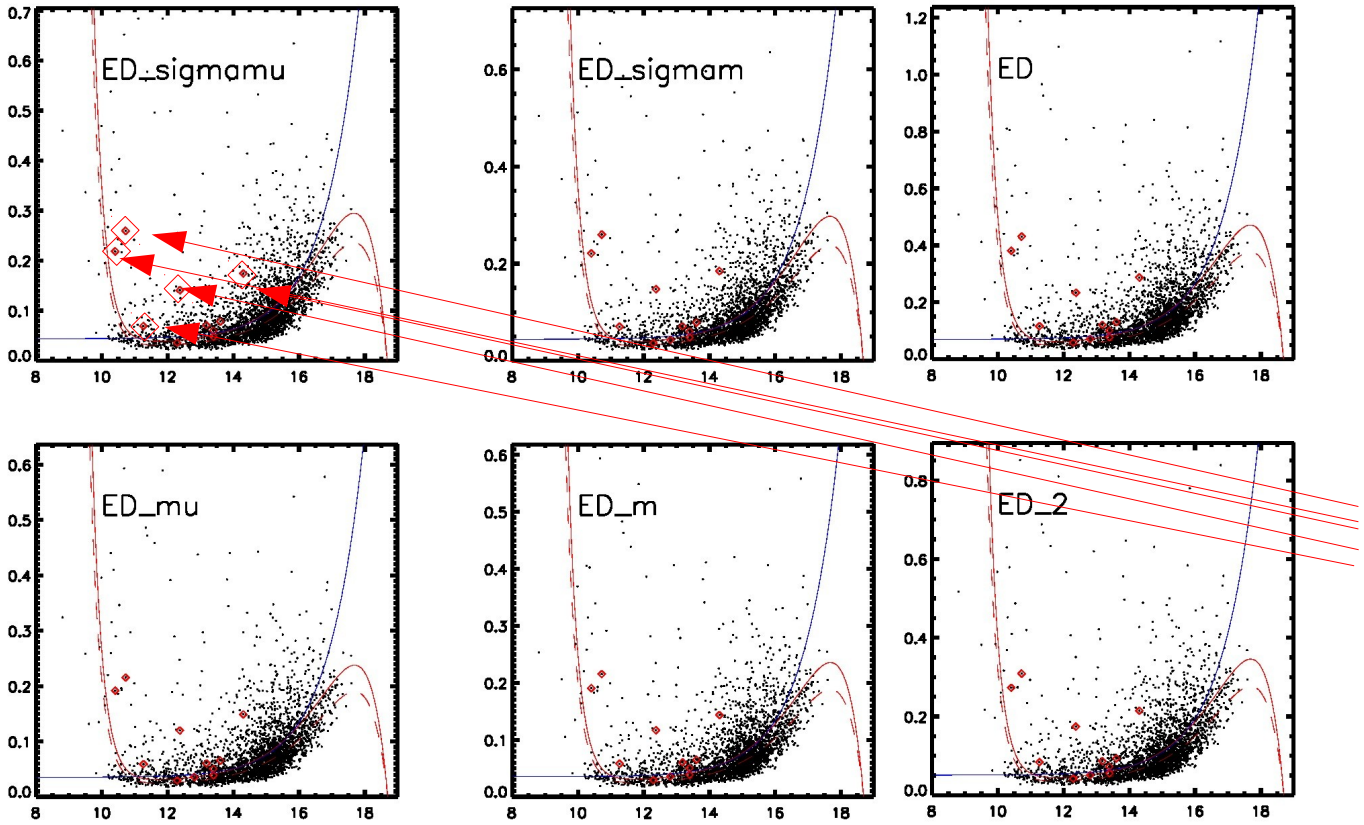


Innermost tile: b333

~5,000,000 sources

Periodicity search

1) Source rejection with even statistics *(Ferreira Lopes+ 2015,2016,2017)*



Known Cepheids from *Matsunaga+ 2016*

!!! Low-amplitude variables with high noise could be lost in this step !!!

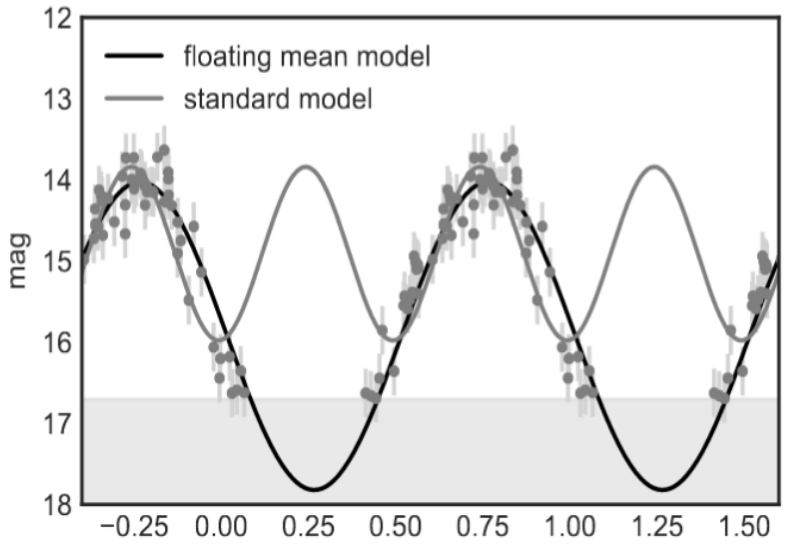
Periodicity search

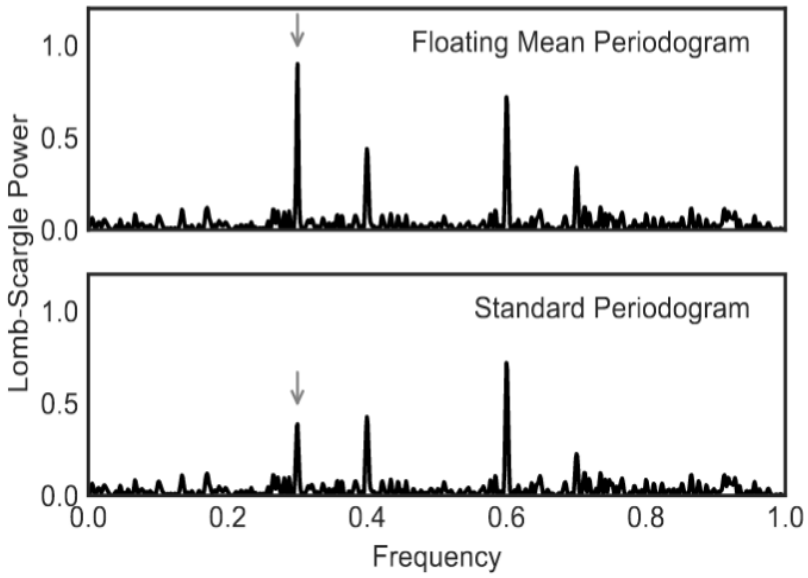
2) Period search

•Lomb-Scargle *(Scargle 1982)*

•Generalized Lomb-Scargle: floating mean *(Zechmeister&Kurster 2009)*

•Bayesian Lomb-Scargle *(Mortier+ 2015)*… NO: suppresses information on frequency aliases *VanderPlas (2017)*



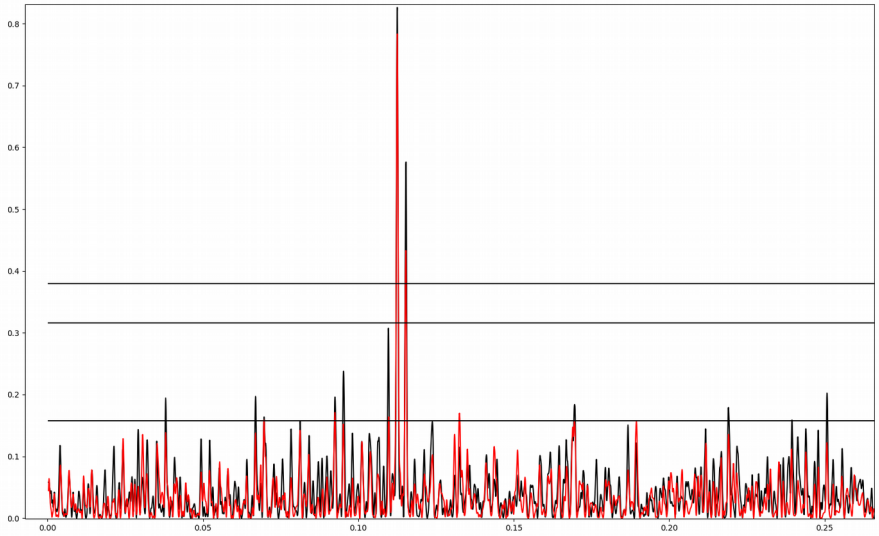


VanderPlas (2017)

Reject sources for which the highest peak in GLS is not among the 10 highest peaks of the LS

Periodicity search

3) Peak significance: reject sources if either the highest peak is too low (<10σ) or there are too many peaks above 5σ (noise). Accept automatically if highest peak is above 12σ.

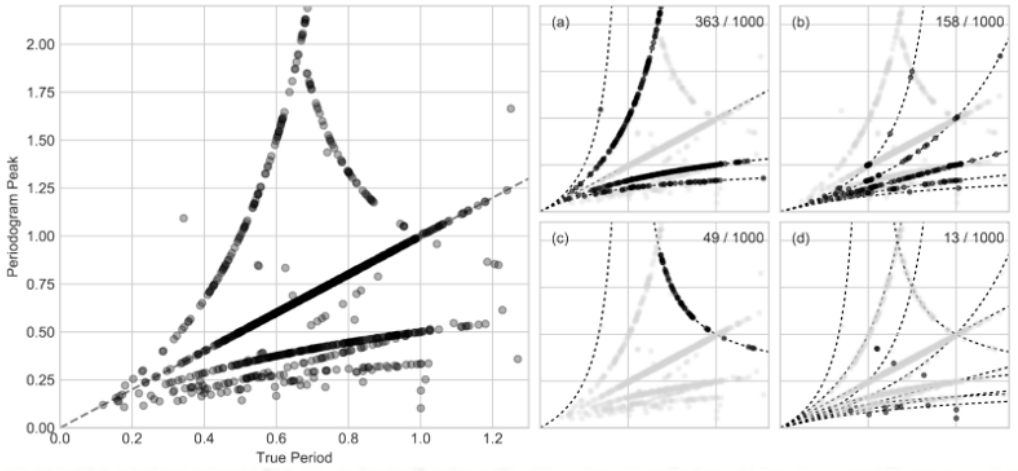


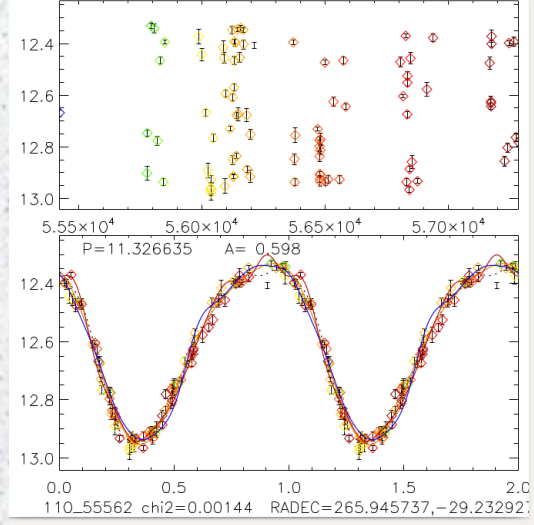
...more rigorous methods are heavily time-consuming

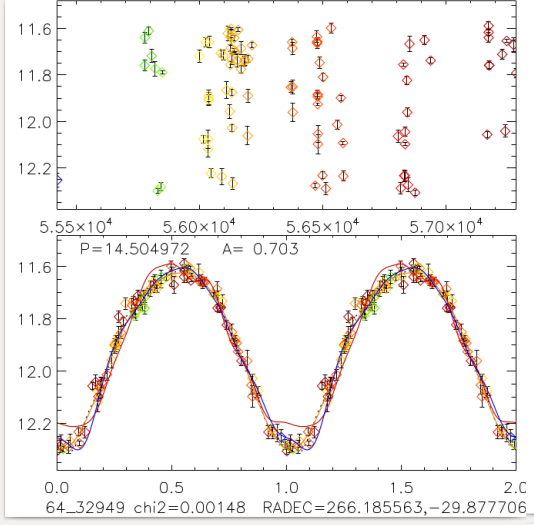
4) De-aliasing *(VanderPlas 2017)*

$$P_{obs} = \left| \frac{m}{P_{true}} + n\delta f \right|^{-1}$$

search for secondary peaks at these frequencies and minimize χ^2 of the phased light curve...




P=11.326635 A= 0.598
110_55562 chi2=0.00144 RADEC=265.945737,-29.23292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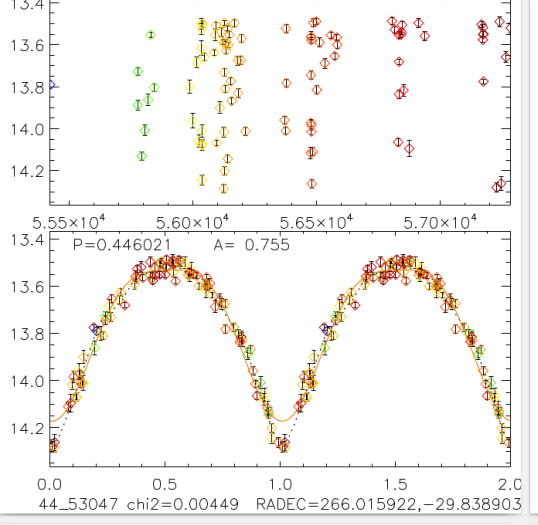
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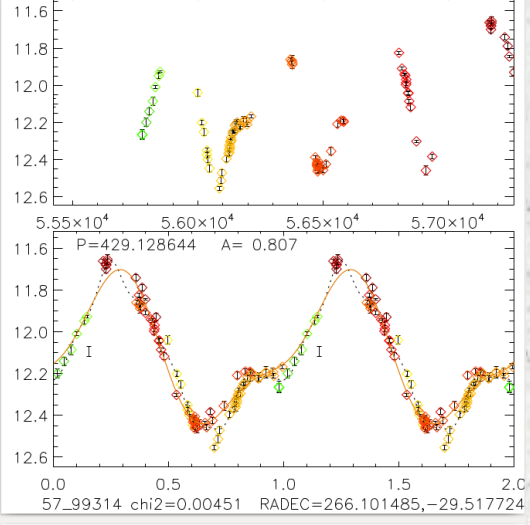
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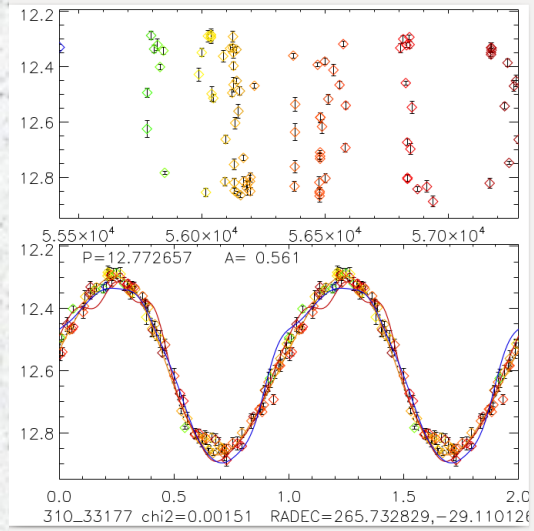
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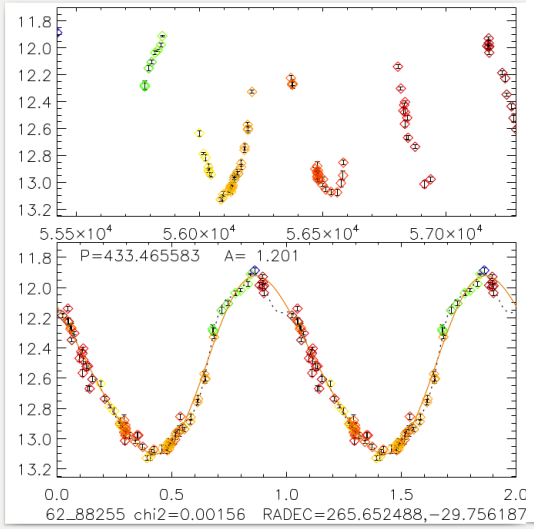
310_33177 chi2=0.00151 RADEC=265.732829,-29.110126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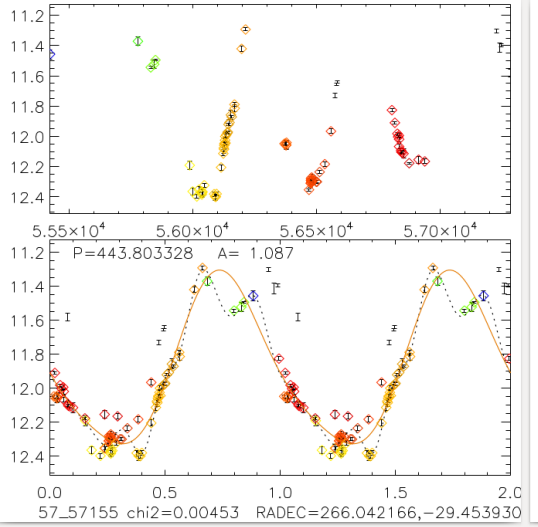
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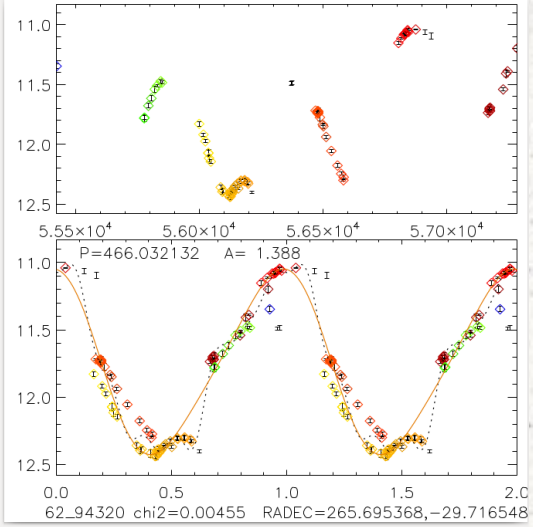
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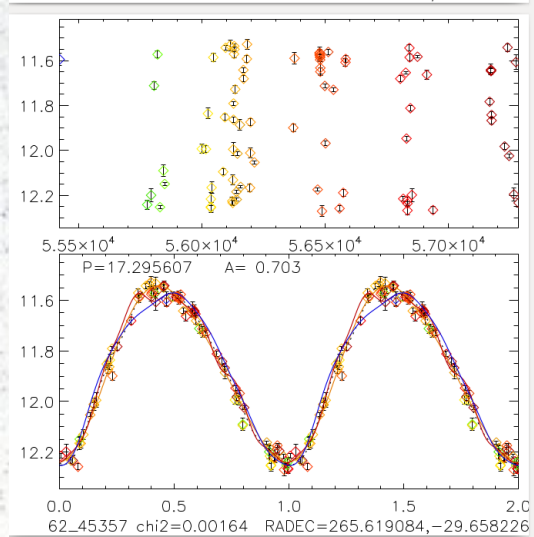
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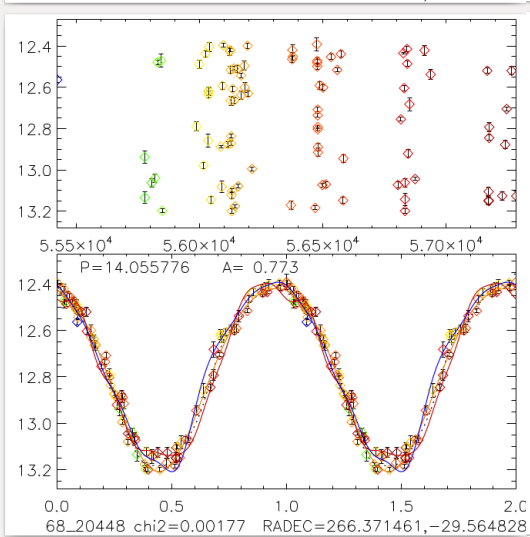
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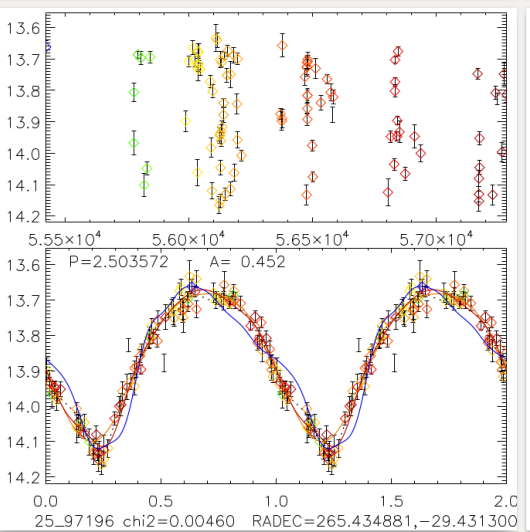
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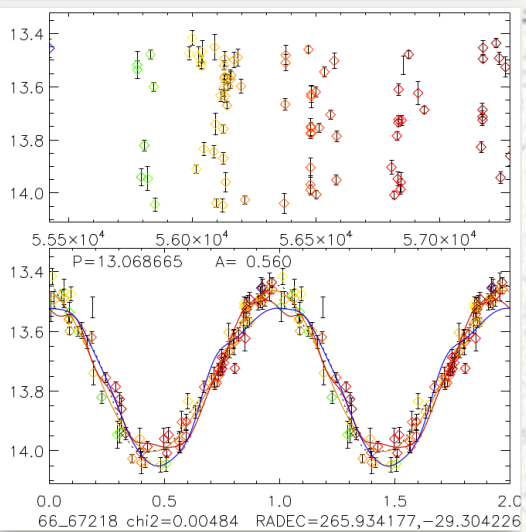
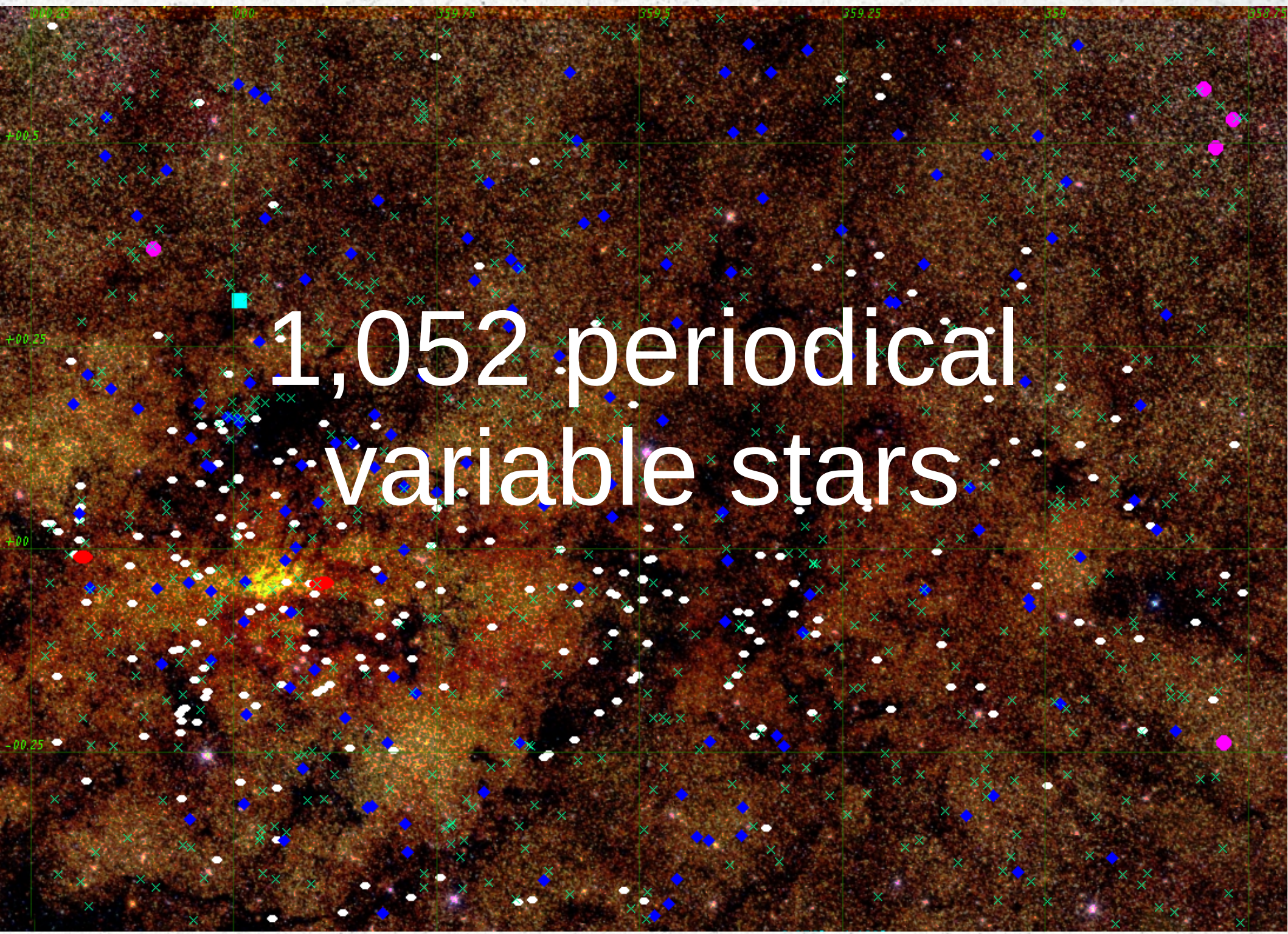
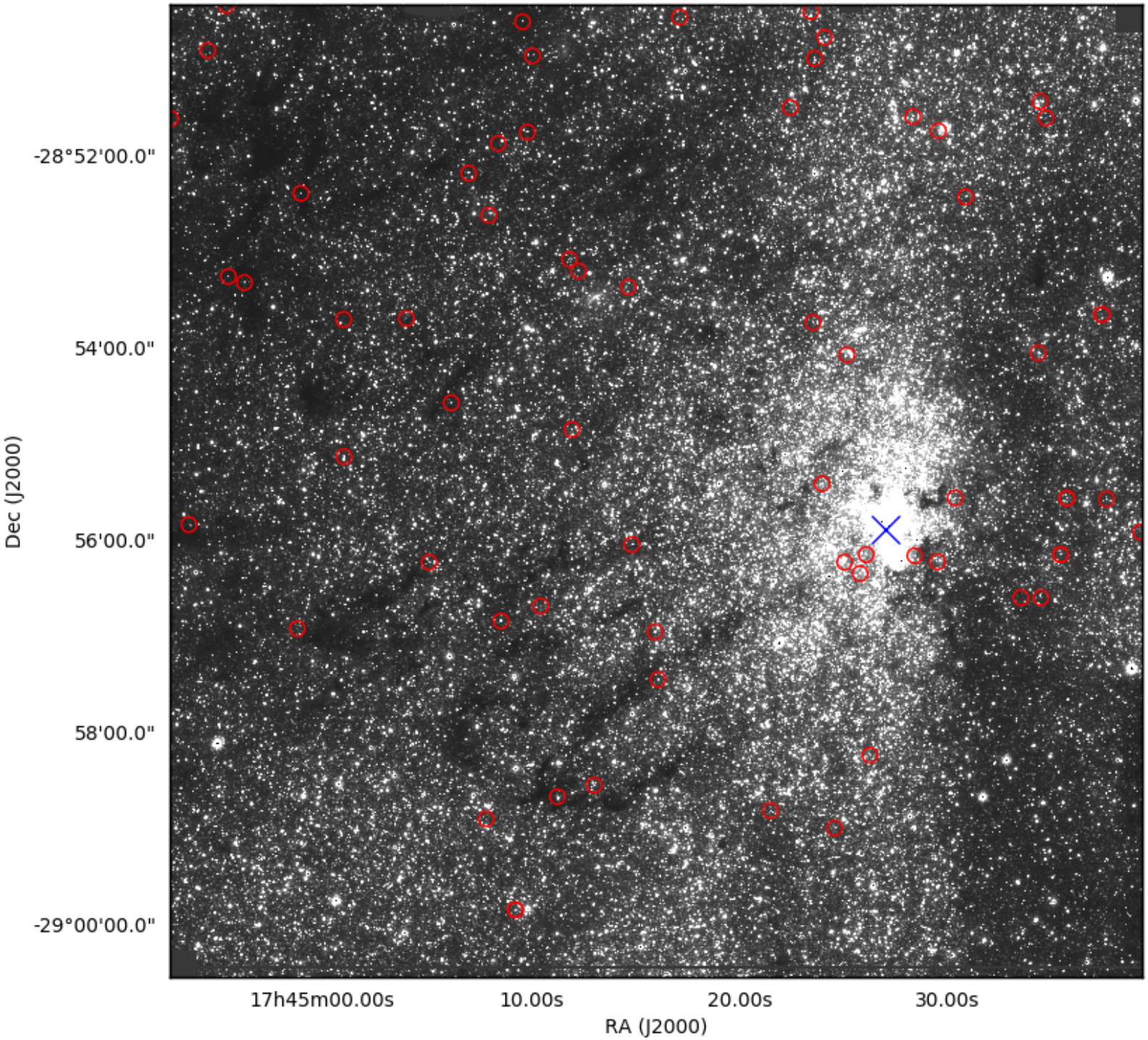
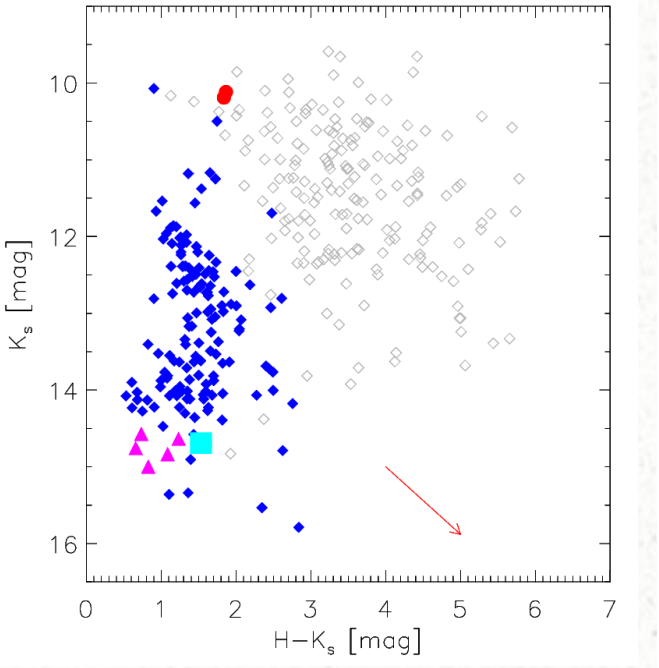
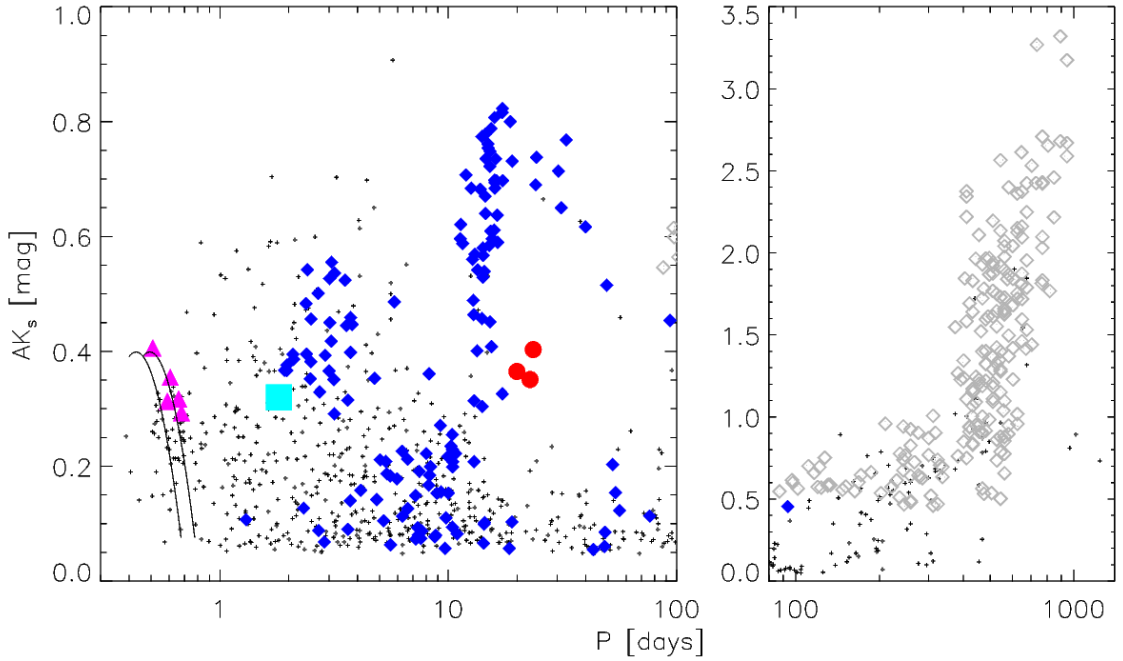

P=13.068665 A= 0.560
66_67218 chi2=0.00484 RADEC=265.934177,-29.304226


1,052 periodical
variable stars

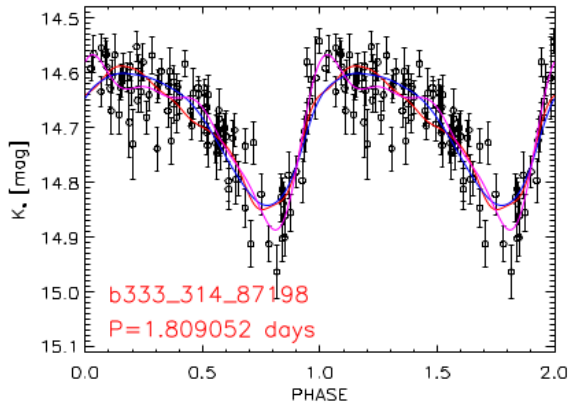

-28°52'00.0"
54'00.0"
56'00.0"
58'00.0"
-29°00'00.0"
Dec (J2000)
17h45m00.00s
10.00s
20.00s
30.00s
RA (J2000)

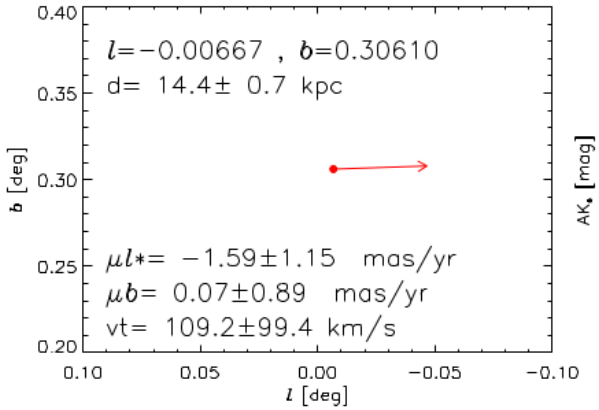
135 T2Cs, 195 Miras, 47 DEBs

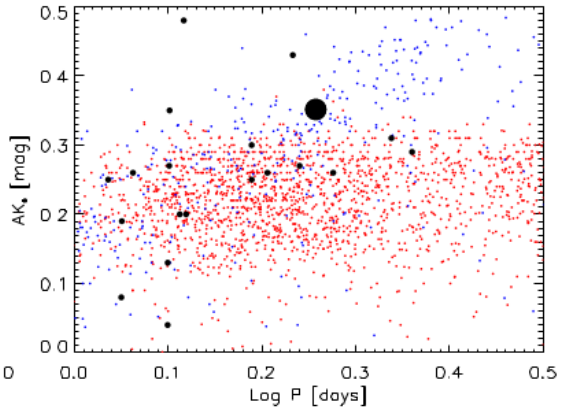




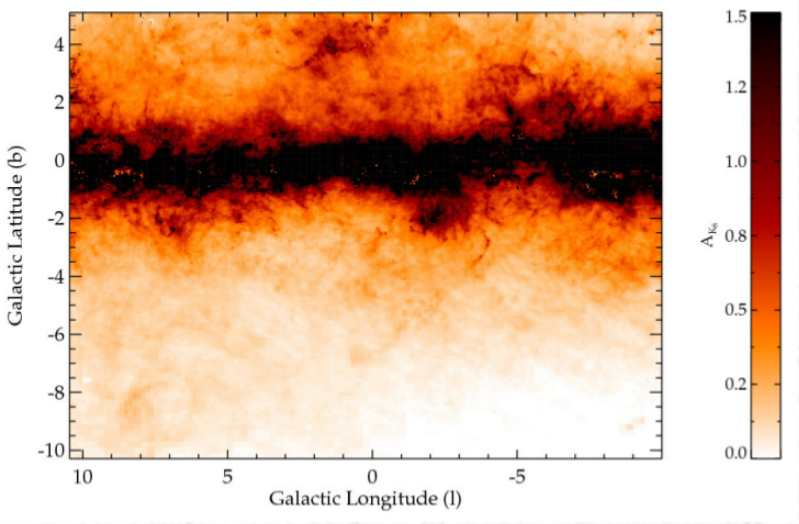
First Anomalous Cepheid towards the Galactic Center



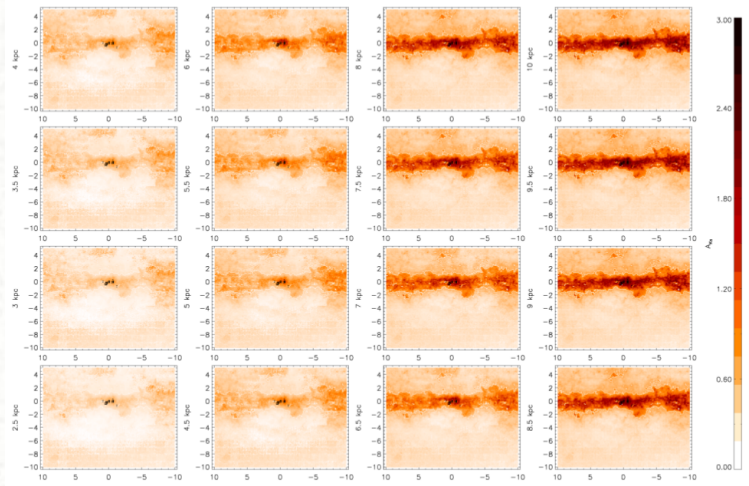




Distances (reddening map)

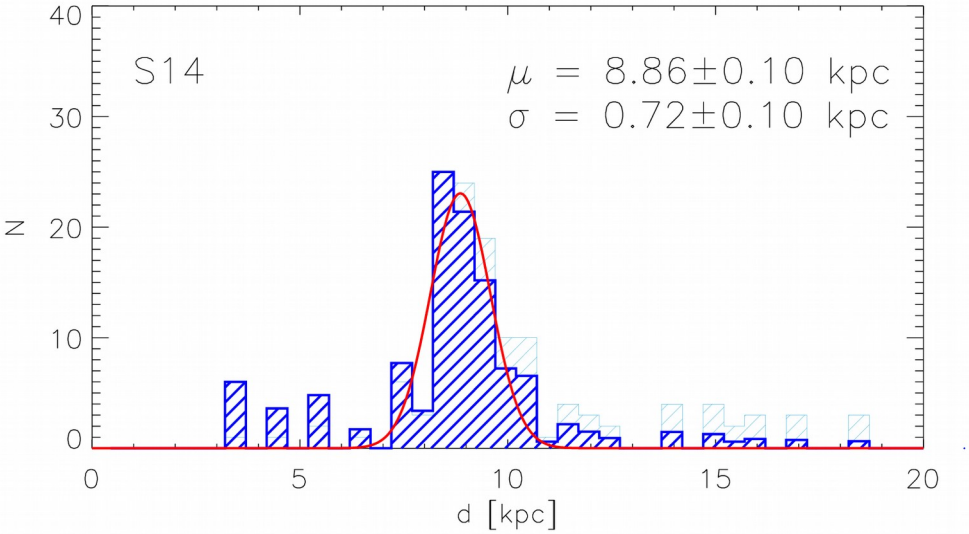


G12: pixel:2'x2'

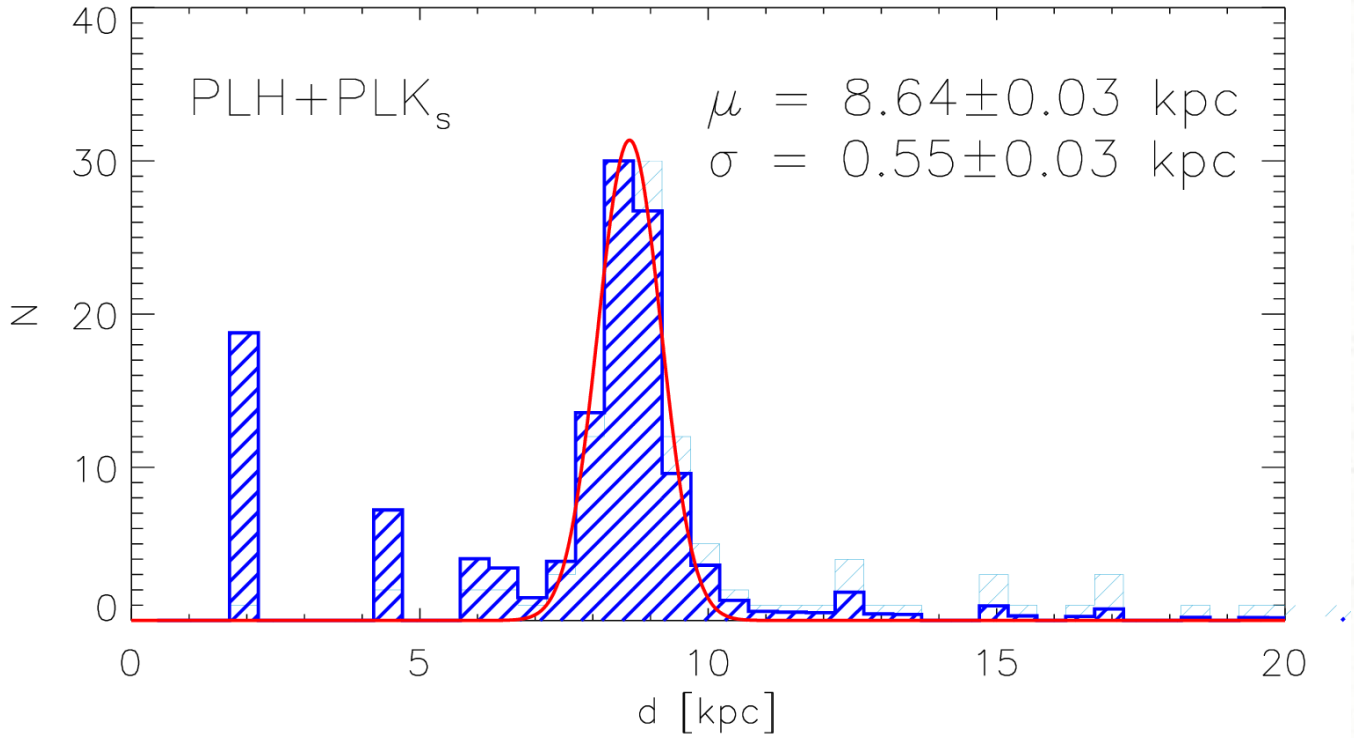


S14: pixel:6'x6'

Correct mean magnitude by extinction, then derive distance with PL



Distances (PLH+PLK relations)



- Extinction KILLS accuracy: AH/AK=1.73 (Nishiyama 2009) vs 1.88 (Alonso-Garcia 2017) = 1.2 kpc difference!

Third big question

Which reddening law?
(type of dust)

Conclusions

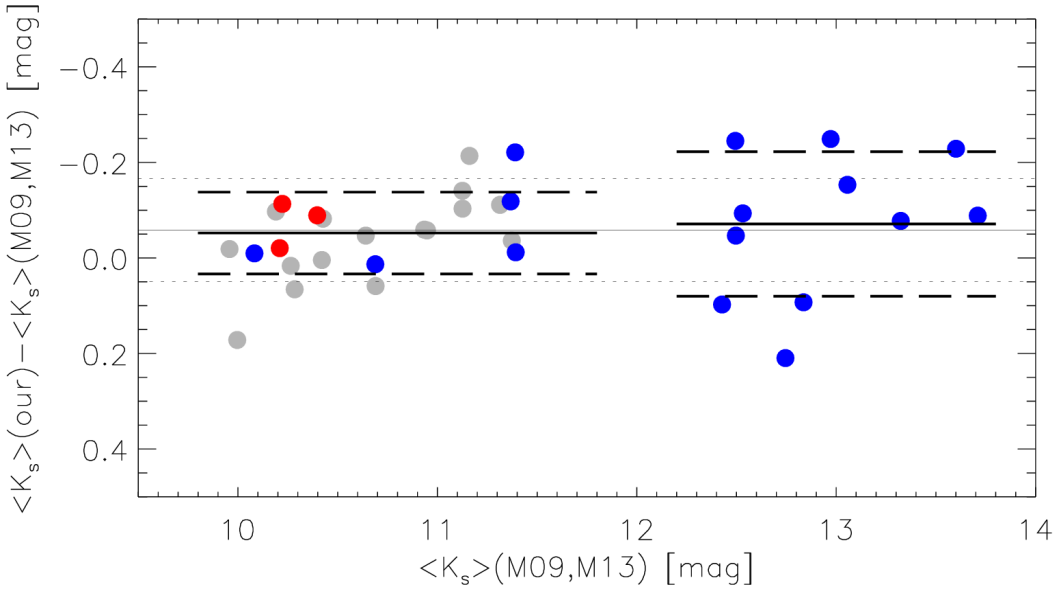
- T2Cs distribution is tilted (both BL Her and W Vir, but more clear for the latter)
- T2Cs trace a mostly kinematically hot population (but with slight excess velocity in longitude)
- 131 new T2Cs and 195 new Miras (we retrieved all *Matsunaga+ (2013)* T2Cs and 9 *Matsunaga+ (2009)* Miras).
- OGLE T2Cs: Distances overestimated with respect to literature, clearly affected by A_K/E(J-K)
- VVV new T2Cs: Distances even more overestimated with respect to literature. AH/AK is critical

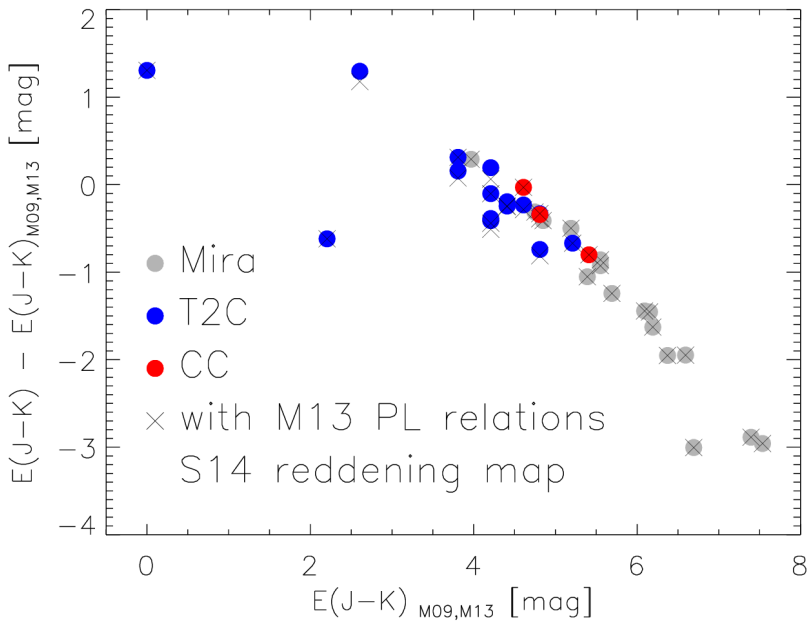
Slide for Ivo

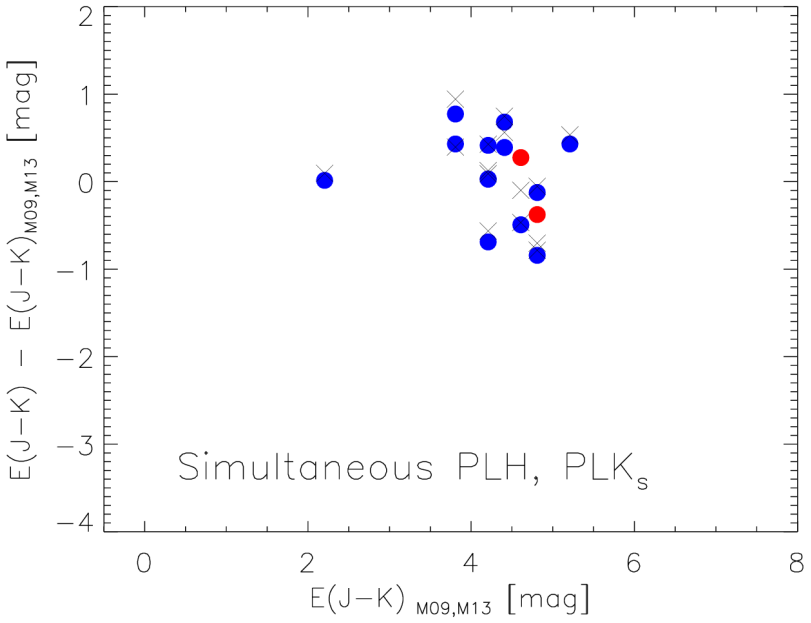
Careful with T2Cs: they might not be strictly old (both problem and opportunity)

Dust is our enemy

- Different tracers (RCs, RRLs, individual estimates for T2Cs, CCs, Miras…)
- Different photometric systems (VVV, IRSF)
- Reddening maps too coarse or not dependent on distance (Gonzalez, Schultheis, Nataf, Hajdu, Surot)


<K_s>(our)−<K_s>(M09,M13) [mag]
−0.4
−0.2
0.0
0.2
0.4
10
11
12
13
14
<K_s>(M09,M13) [mag]


E(J−K) − E(J−K)M09,M13 [mag]
2
1
0
−1
−2
−3
−4
0
2
4
6
8
E(J−K) M09,M13 [mag]
Mira
T2C
CC
with M13 PL relations
S14 reddening map


E(J−K) − E(J−K)M09,M13 [mag]
2
1
0
−1
−2
−3
−4
0
2
4
6
8
E(J−K) M09,M13 [mag]
Simultaneous PLH, PLK_s