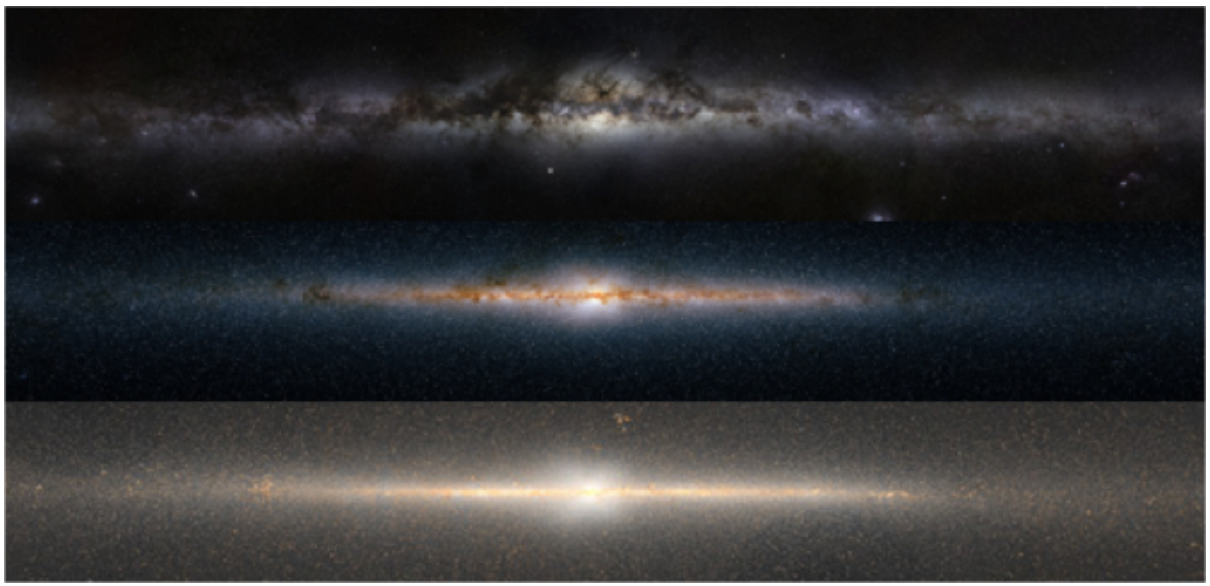
The Extinction and Extinction Curve Toward the Bulge and Implications for the WFIRST Microlensing Campaign



David M. Nataf
Davis Fellow, Johns Hopkins University
January 27th, 2018

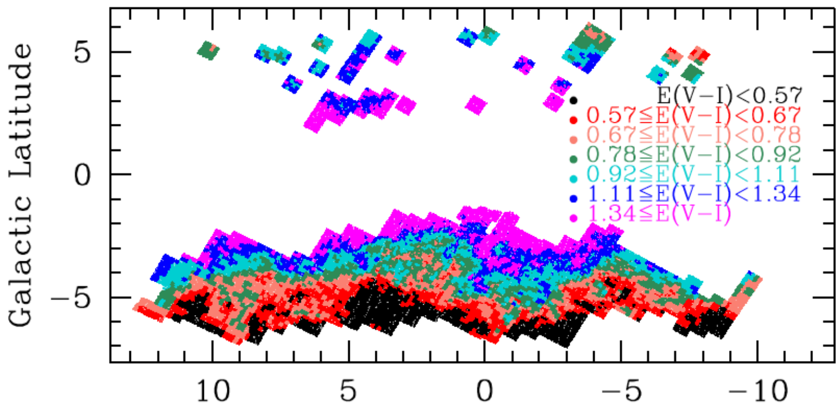
Thank you to OGLE

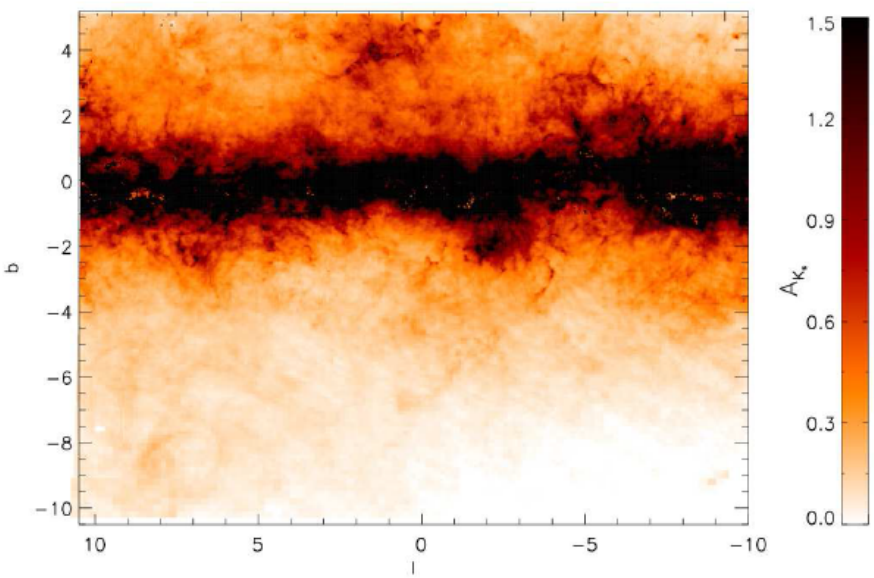
- *"The safest general characterization of the literature on the extinction toward the Galactic bulge is that it largely consists of a series of footnotes to OGLE."*

(Stanek 1996, Stutz et al. 1999, Udalski 2003, Sumi 2004, Nataf et al. 2013, Pietrukowicz et al. 2015, etc etc etc)

What we currently know and don't know about extinction toward the bulge

- The mean bulk reddening has been measured in the optical (Nataf et al. 2013, with OGLE data) and near-IR (Gonzalez et al. 2012, with VVV data). Resolution is a few arcminutes.
- We are missing higher-resolution maps, sensitivity in gradients along the line of sight (as just stated by Clément Ranc !), reliable estimates of errors due to differential reddening, and maps of extinction curve variations.



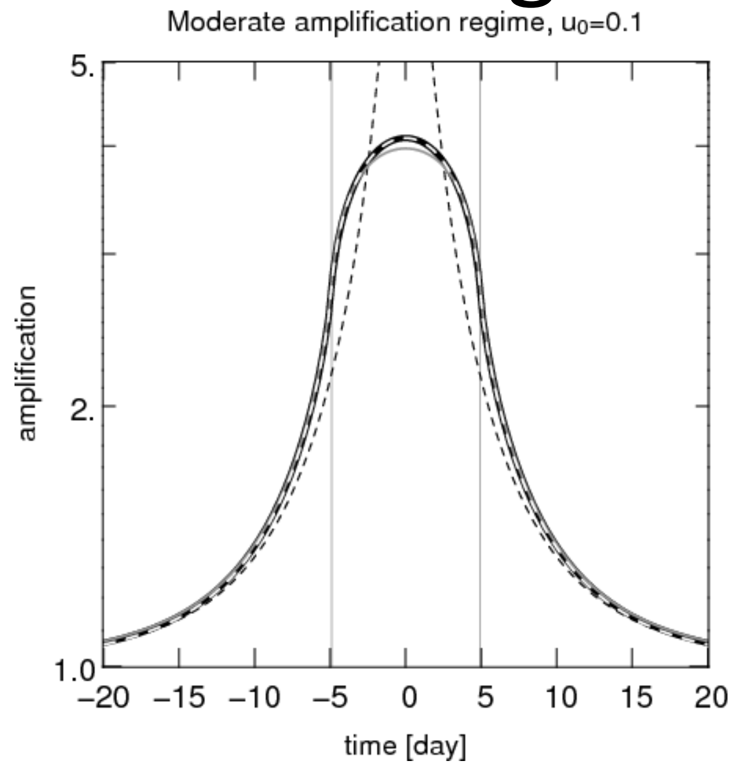


Why reddening and extinction matter

- The extinction toward the WFIRST microlensing window covers the range $0.4 \lesssim A_H \lesssim 3$, or up to $A_V \approx 25$ in the optical. The extinction is large and variable.

Why reddening and extinction matter case study: The Einstein ring

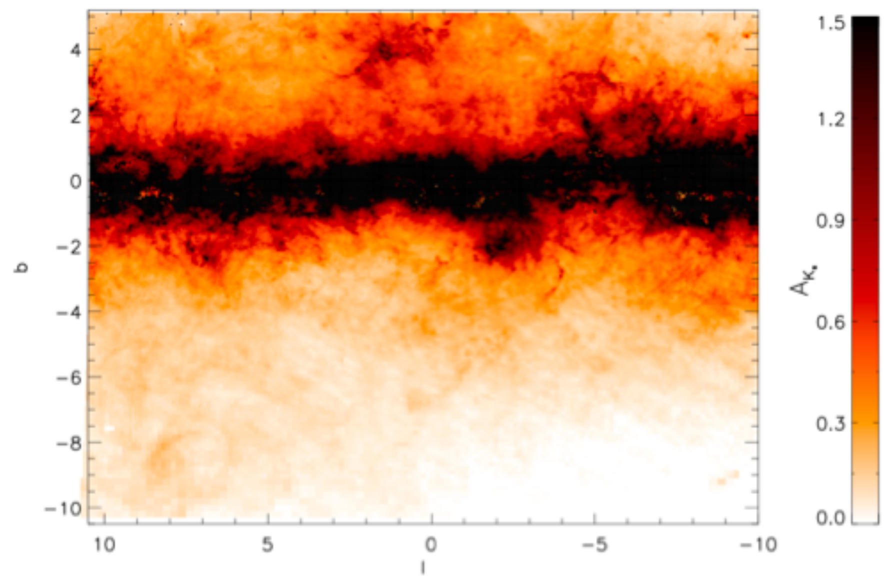
- The einstein ring of a lens, the finite-source effects in the lightcurve (at right, Lee et al. 2009), and the deredenned surface brightness of a source are related by a simple equation. See talk by Henderson for more details.
- Differential reddening in the WFIRST microlensing window regularly exceeds $\boldsymbol{\sigma}_{A\_H}$ = 0.10 mag, which corresponds to a ~5% error on the product of the finite source term and the Einstein ring radius.
- Propagates as a ~10% error in the mass of the lens, if a microlens parallax is available.

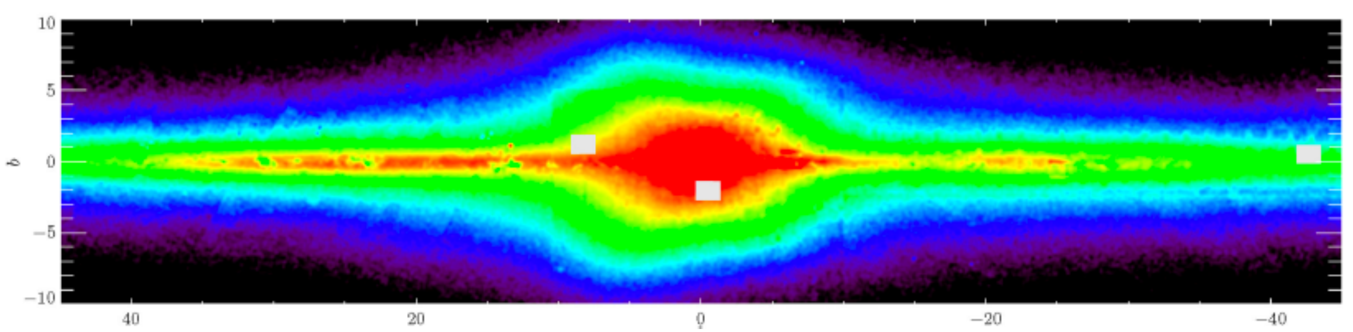


$$\rho\theta_E = \sqrt{\frac{F}{\pi S}}$$

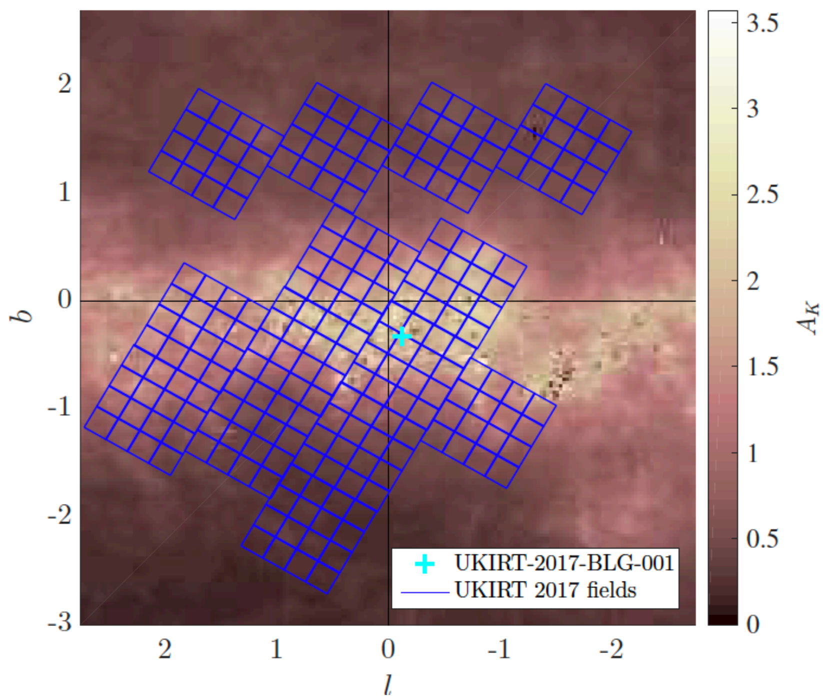
Why reddening and extinction matter Part II: Extinction maps are essential for target/field selection

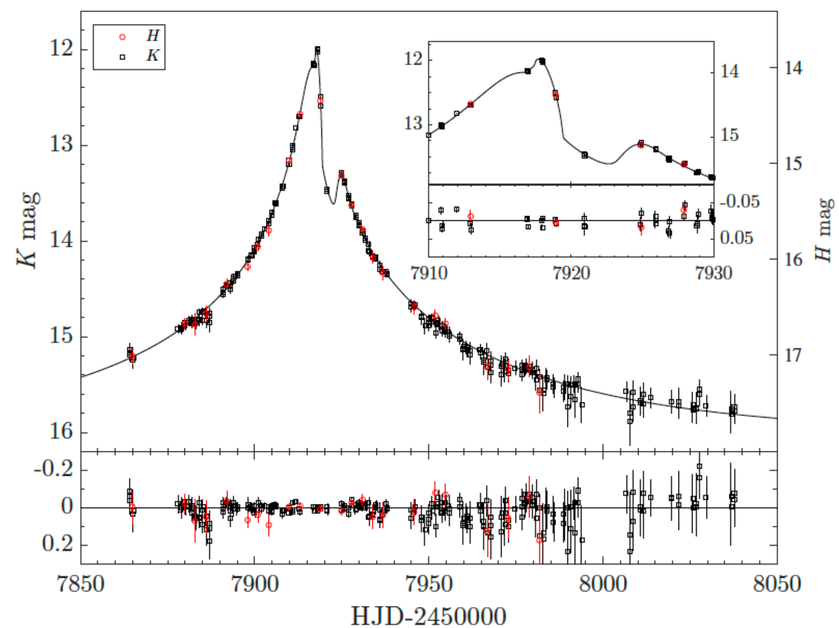
- Sightlines closer to the plane have more sources (Wegg et al. 2015, bottom) but are also more obscured by extinction (Gonzalez et al. 2012, right). It's a tradeoff.





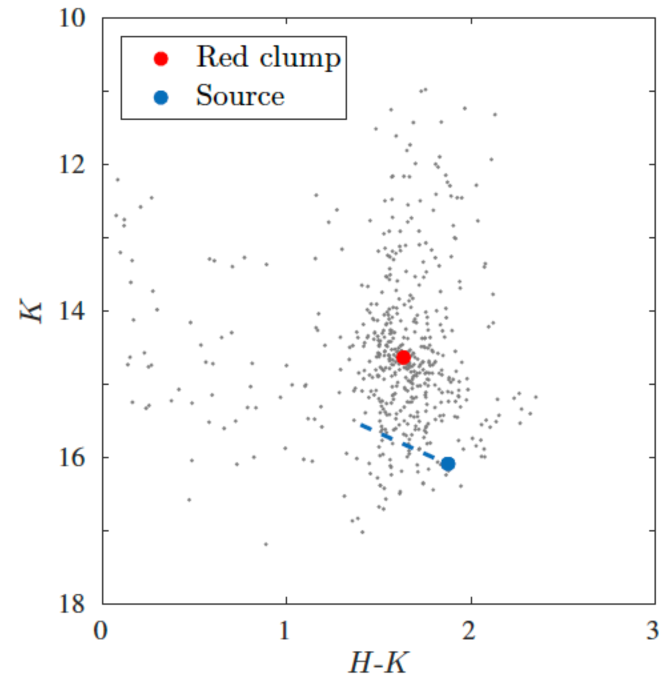
Shvartzvald et al. have set up a UKIRT campaign to investigate this tradeoff





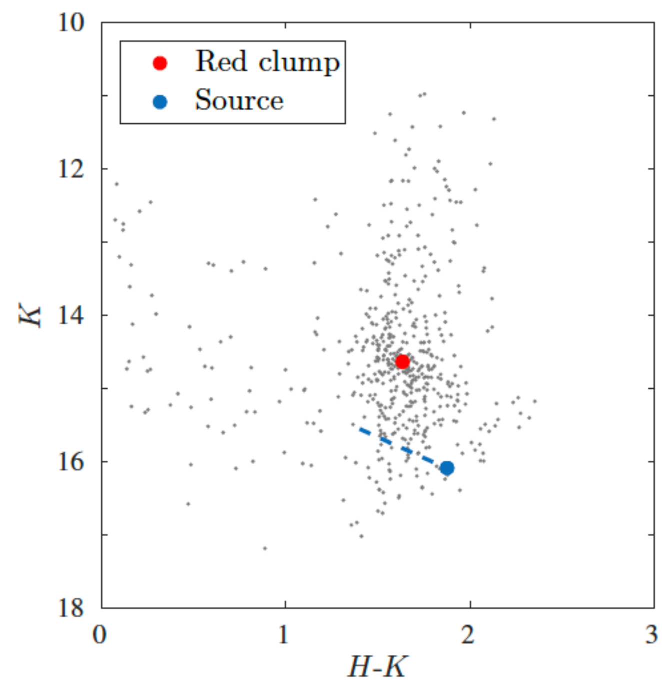
Developments from the UKIRT microlensing campaign

- Tons of microlensing events are being observed, as expected !
- However, the extinction toward events such as UKIRT-2017-BLG-001 (Shvartzvald et al. 2018, in prep) is so high that it's difficult to interpret.



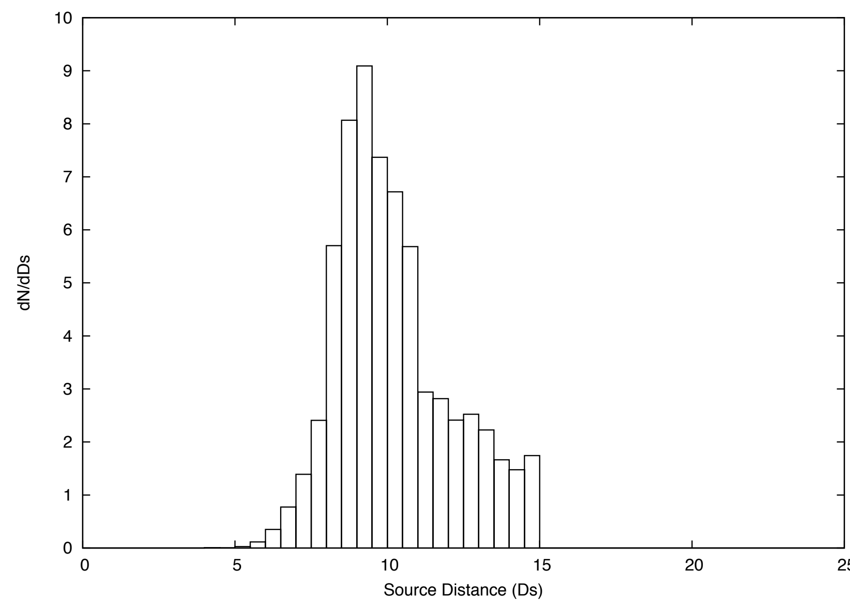
High extinction and other challenges toward UKIRT-2017-BLG-001 continued

- $A_{Ks} \approx 1.70$ ($A_V \approx 28$) toward the field – no information, no constraints from VIZY or even J band.
- Differential reddening is $E(H\text{-}K_s) \approx 0.15$ mag !
- Extinction curve is highly non-standard, $A_{Ks}/E(H\text{-}K_s)$ is shifted by 18% or 0.35 mag.
- Crowding is too high for Spitzer photometry.



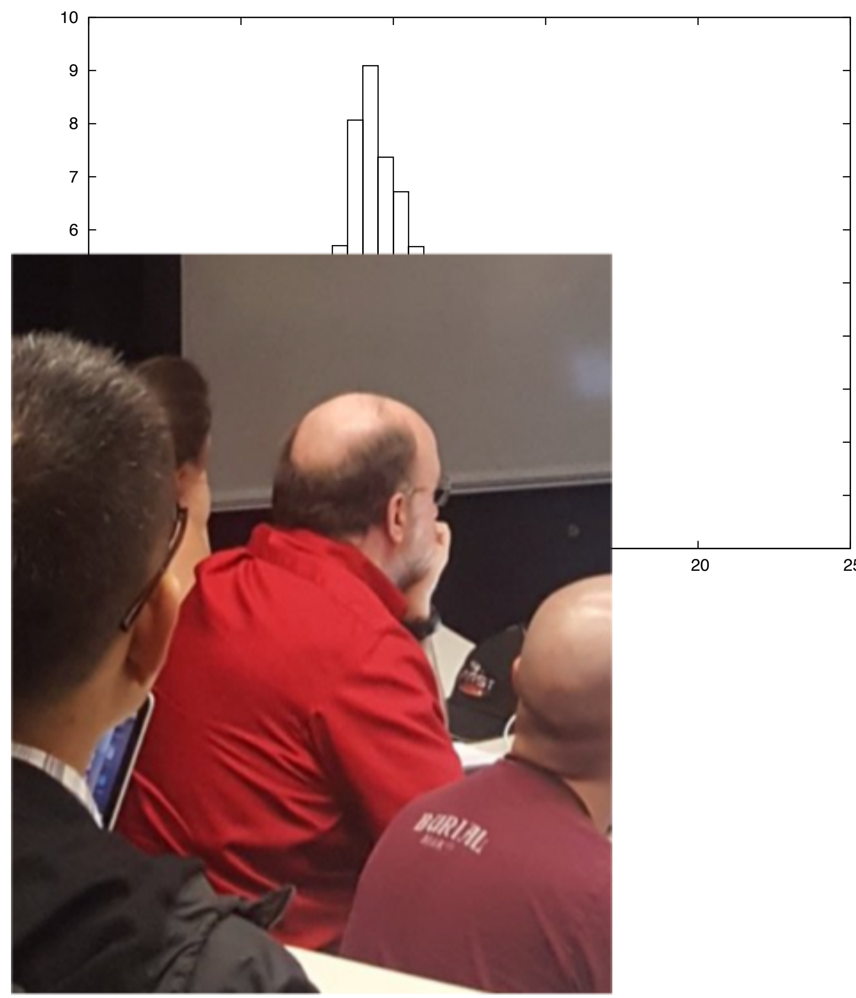
Challenges toward UKIRT-2017-BLG-001 continued

- Given that the sightline is so close to the plane, the source can either be in the bulge or in the background disk (prior probability histogram at right from Matthew Penny).
- Tradeoff: The same effect that adds *so many events* also adds a degree of freedom that needs to be modeled.



Challenges toward UKIRT-2017-BLG-001 continued

- Given that the sightline is so close to the plane, the source can either be in the bulge or in the background disk (prior probability histogram at right from Matthew Penny).
- Tradeoff: The same effect that adds *so many events* also adds a degree of freedom that needs to be modeled.
- **David Bennett is probably concerned.**



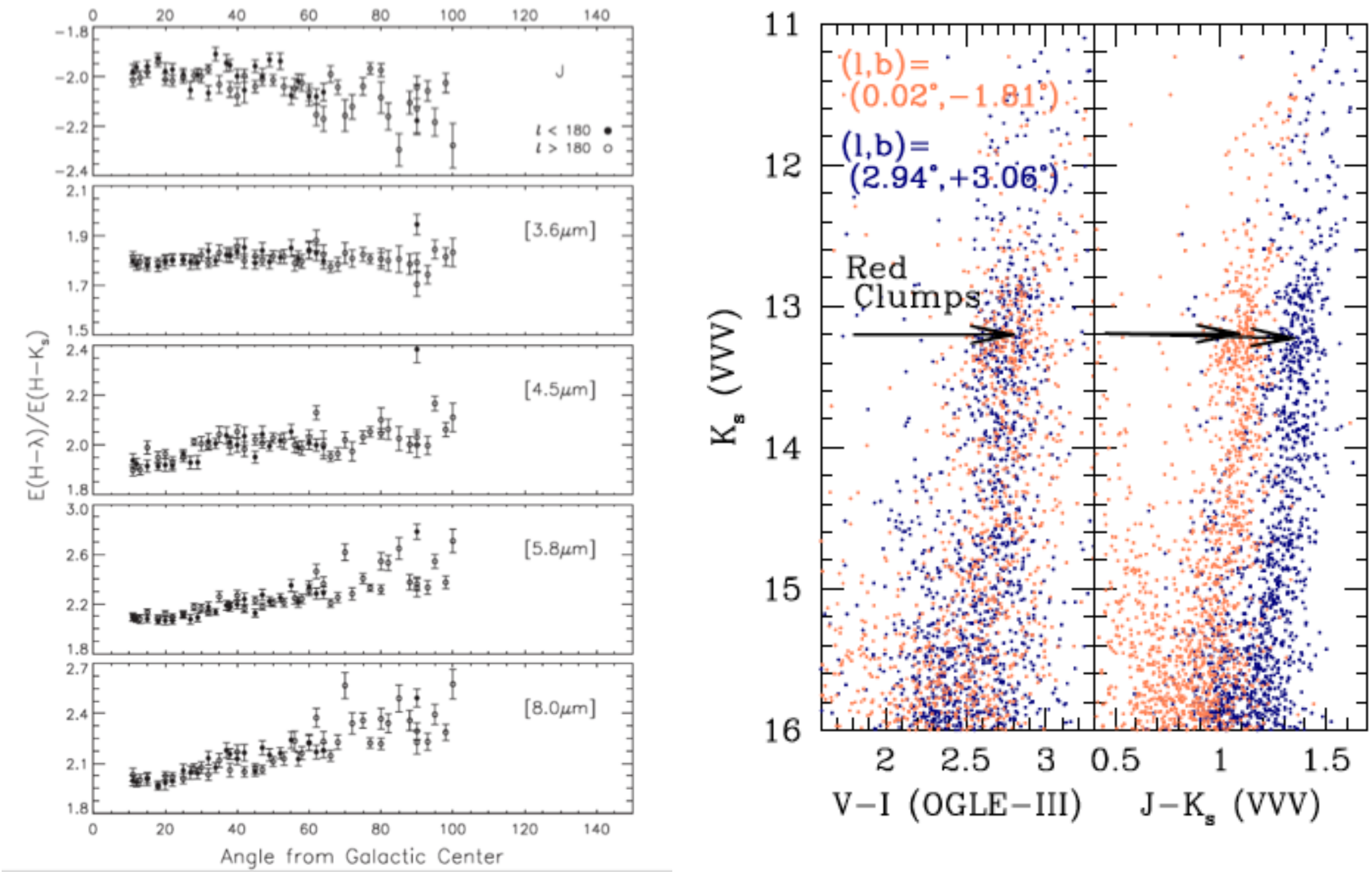
Summary of considerations already elucidated by ongoing UKIRT campaign

- Sightlines closer to the plane yield more events, largely due to configurations with the background disk as sources.
- Errors from differential extinction and a variable shape to the extinction curve are much higher and will need to be modeled.
- The extinction is high enough that we will never have complementary data blueward of 1 micron.
- The crowding is high enough that we will not have assistance from Spitzer.
- Microsit will submit a JWST proposal (PI: Nataf) to further investigate UKIRT-2017-BLG-001.

Question: Who cares about a variable extinction curve? WFIRST is a near-IR mission !

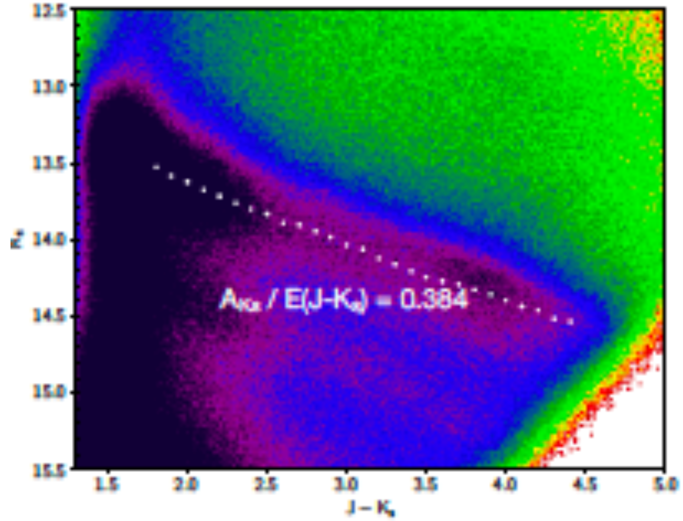
- “The results are thus consistent with an invariant IR extinction curve. At wavelengths greater than ≥≈ 1 μm, the extinction curve roughly resembles a power law with an index of ≈ 1.5.” – Fitzpatrick (1999);

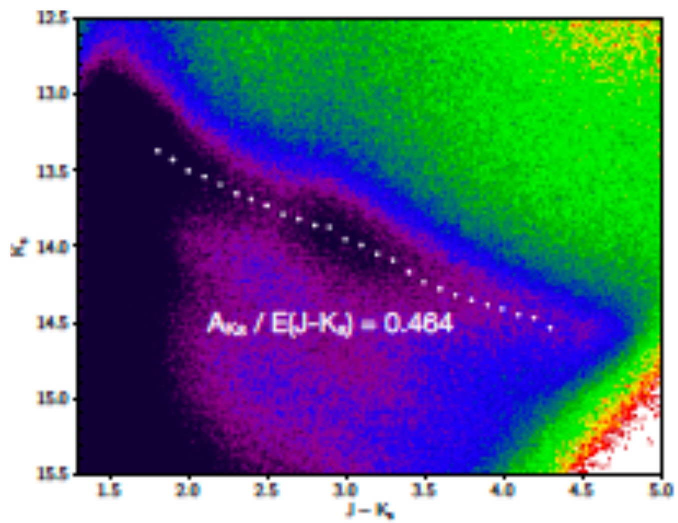
Infrared extinction curve is in fact variable Spitzer-2MASS study from Zasowski et al. (2009, left), OGLE-VVV study from Nataf et al. (2016, right)



More on infra-red extinction curve variations: Alonso-Garcia et al. (2017)

- Comined ZYJHKs photometry for 30 million objects, measured $A_\lambda \propto \lambda^{-2.47}$ in the mean with variations, contrasts sharply to the “universal” value of $A_\lambda \propto \lambda^{-1.61}$.
- Arguably the most precise study of the near-infrared extinction curve: they have 5 bandpasses, 30 million objects, all at high reddening.





The extinction curve has never been measured in the WFIRST filter

- The WFIRST filters (orange) include photons from wavelengths not accessible by ground-based filters (blue) due to the Earth's atmosphere.
- Interpolation uncertainty adds a small error, but it's solvable with HST/WFC3 … or JWST/NIRcam for that matter.

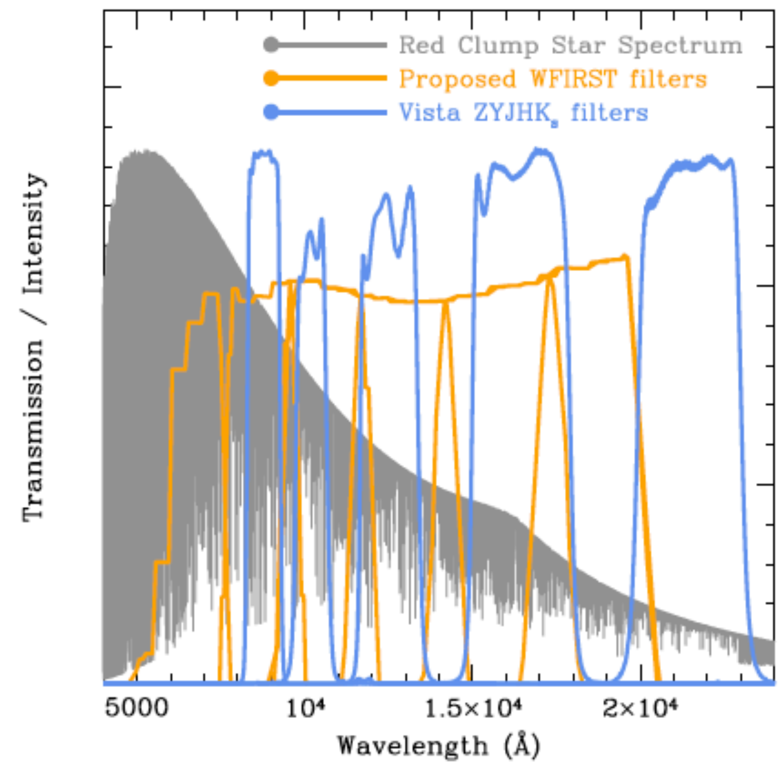


Figure 1: A synthetic spectrum of a red clump giant star (gray), standard ground-based NIR filter transmission curves (blue) and the proposed *WFIRST* filters (orange).

Extinction problem is solvable, and will be solved by WFIRST's launch

- Photometry from *VVV* and *OGLE* are now both expanded relative to when the current reddening maps were made. We also have the *DECam Galactic plane* survey (Schlafly et al. 2017) and *Blanco DECam Bulge Survey* (Rich, Clarkson, et al).
- Complementary photometry has been acquired using Subaru (PI: Suzuki, PI: Henderson).
- Further options include using red giant spectra as standard crayons (APOGEE, Majewski et al. 2017) and measurements of diffuse interstellar bands (Zasowski et al. 2015). There will eventually be a far higher density of crayons available.

Conclusions

- Further extinction studies are needed to both calibrate the field selection, and to eventually understand the measured events.
- Current precision in bulge extinction maps is $\sim$10%, the road to $\sim$1% is perfectly transversable with a combination of improved data (OGLE, VVV, Subaru, DECam, Apogee, HST? JWST?) and hierarchical Bayesian methods (see talks by Angie Wolfgang and Sanjib Sharma for more information).
- Please email me (david.nataf@gmail.com) if you have reliable Bulge photometry in interesting bandpasses. I'm willing to exchange co-authorship, cute dog videos, and citations for data.