Measuring Dust Properties at Low Metallicity with Color-Magnitude Diagrams of stars in the SMC SW Bar

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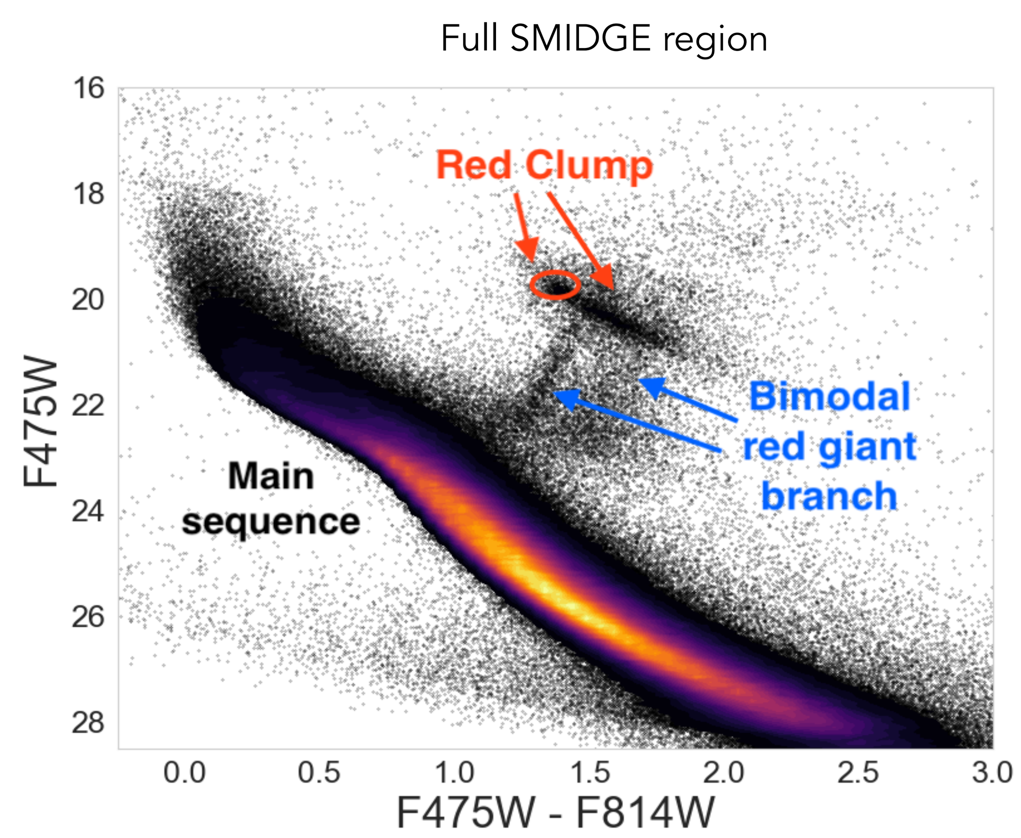
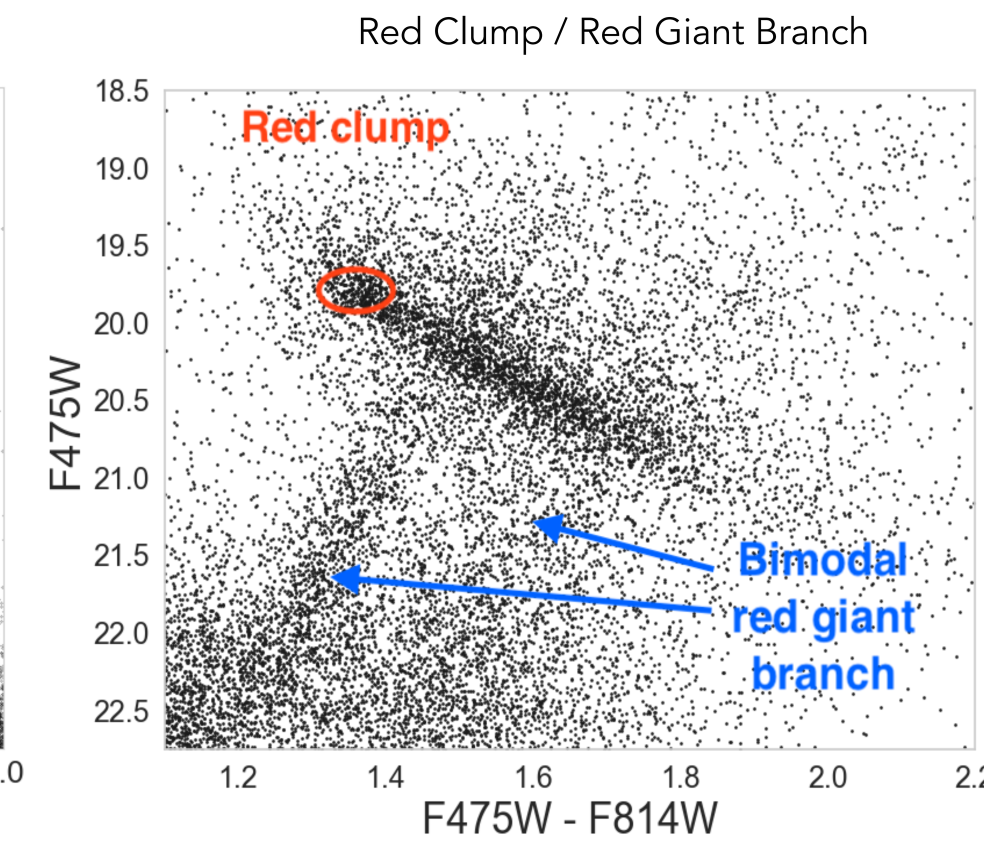
Introduction Dust properties in the Small Magellanic Cloud (SMC) provide insight into the interstellar environment of one of the closest analogs to early-Universe and low-metallicity galaxies. We use eight-band Hubble Space Telescope (HST) observations of reddened red clump and red giant branch stars to constrain the SMC's three-dimensional structure and dust extinction properties.
We model the CMD by taking into account the star formation rate and metallicity evolution, and then simulate the effects of dust extinction and geometry to find the best match to the observations.





SMIDGE optical color-magnitude diagrams

The full SMIDGE region shows the effect of dust:

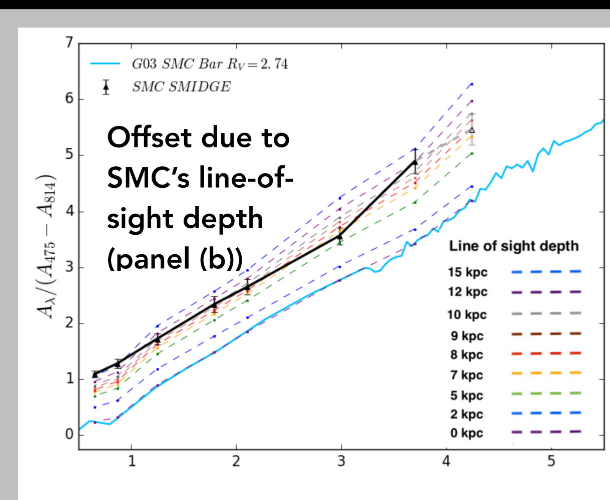
- The red clump is compact and fits inside the red ellipse in the absence of dust but is elongated due to extinction;
- The red giant branch appears bimodal since the stars are not embedded in the thin dust layer.
- The main sequence is wide and also appears bimodal in dusty regions.

Taking Depth Into Account is Critical

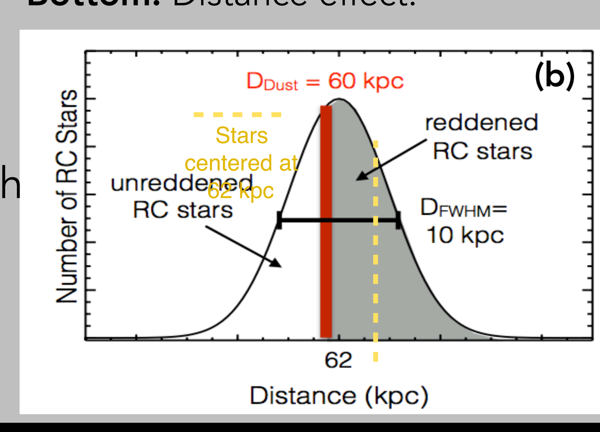
In our 2017 study measuring the shape of the extinction curve from reddened red clump stars we found:

1. An extinction curve shape consistent with Gordon et al. (2003).
2. An offset between our extinction curve using RC stars and previously observed extinction curves due to a **significant line of sight depth.**

A number of observational and theoretical studies show a large depth (see reference in green).



Top: Extinction curve from RC stars. **Bottom:** Distance effect.



Modeling the Color-Magnitude Diagram

1. We generate an **unreddened synthetic CMD** incorporating the full ranges of ages & metallicities appropriate for the SMIDGE region using the MATCH software (Dolphin 2002).
2. We then apply a **3D geometry** by distributing the stars along the line of sight and adding a thin layer of dust to determine the reddened fraction.
3. We use the **BEAST** (Bayesian Extinction And Stellar Tool, Gordon+ '16) to model the dust extinction and the photometric noise.
4. We vary the **dust and distance parameters**:

CMD Model Parameters

- Log-normal distribution of **extinction A_V** with width $\sigma(A_V)$.
- **SMC line of sight depth** (distance modulus offset)
- **Stars-dust relative position**
- **Extinction law**

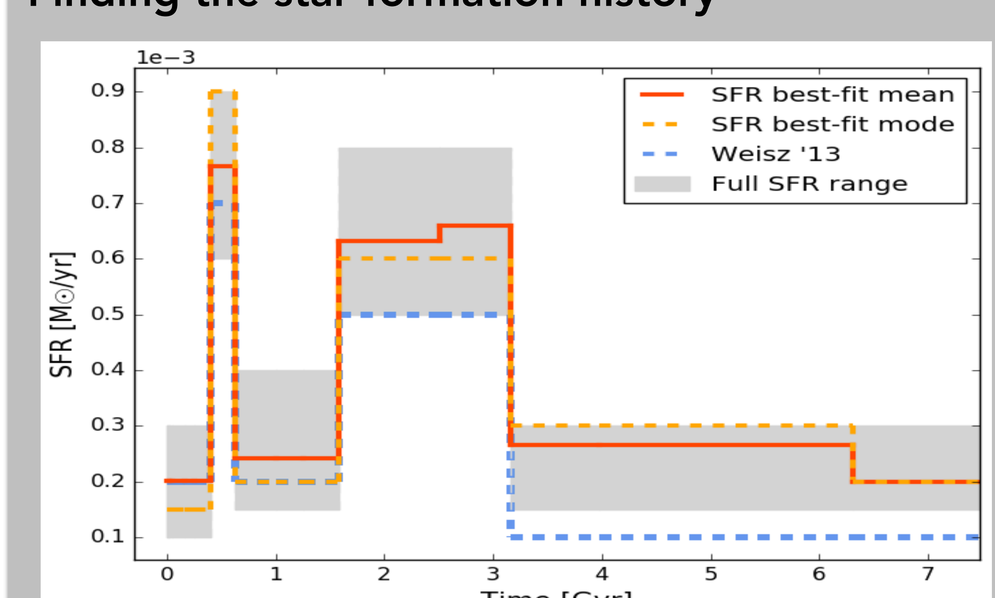
Comparing model and observed CMDs

We use a CMD matching technique employed by studies of SFHs of nearby galaxies (Dolphin 2002, Weisz+ 2013, and others):

1. We create a grid of parameter space (Table 1) from which we extract the 1st order best-fit parameters.
2. We bin the reddened CMD in color and magnitude.
3. For each bin we calculate the **Poisson Likelihood Ratio (PLR)** by comparing stellar counts between the models and the observed SMIDGE CMDs. The PLR is defined below, where m_i is the model CMD value (the number of sources) of bin i, and n_i is the observed value of bin i.
4. The minimum Poisson Likelihood Ratio gives us the best-fit model.

$$-2\ln PLR = 2\sum m_i - n_i + n_i \ln\frac{n_i}{m_i}$$

Finding the star formation history



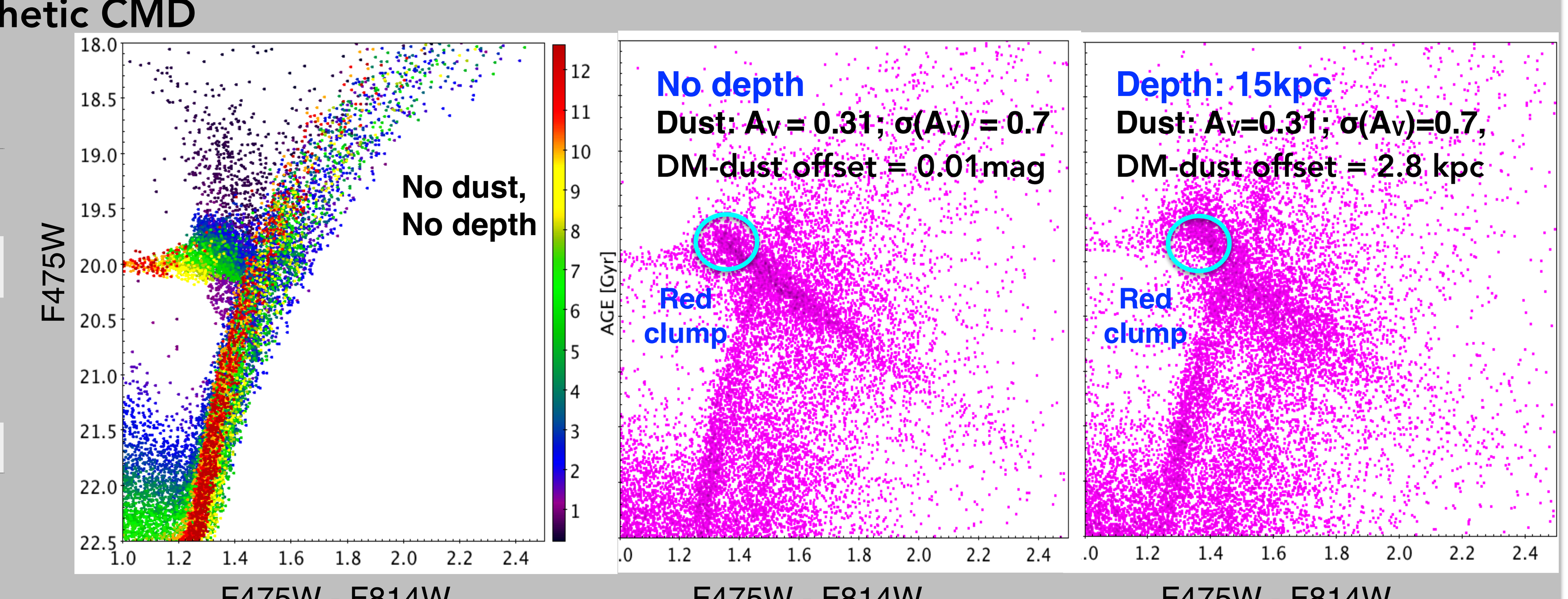
To reproduce the observed number of stars in the RC/RGB region, we vary the SMC SFH based on a nearby region (Weisz et al. 2013). We do this by matching the stellar number count in CMD bins parallel to the extinction vector.

Applying dust and distance to the synthetic CMD

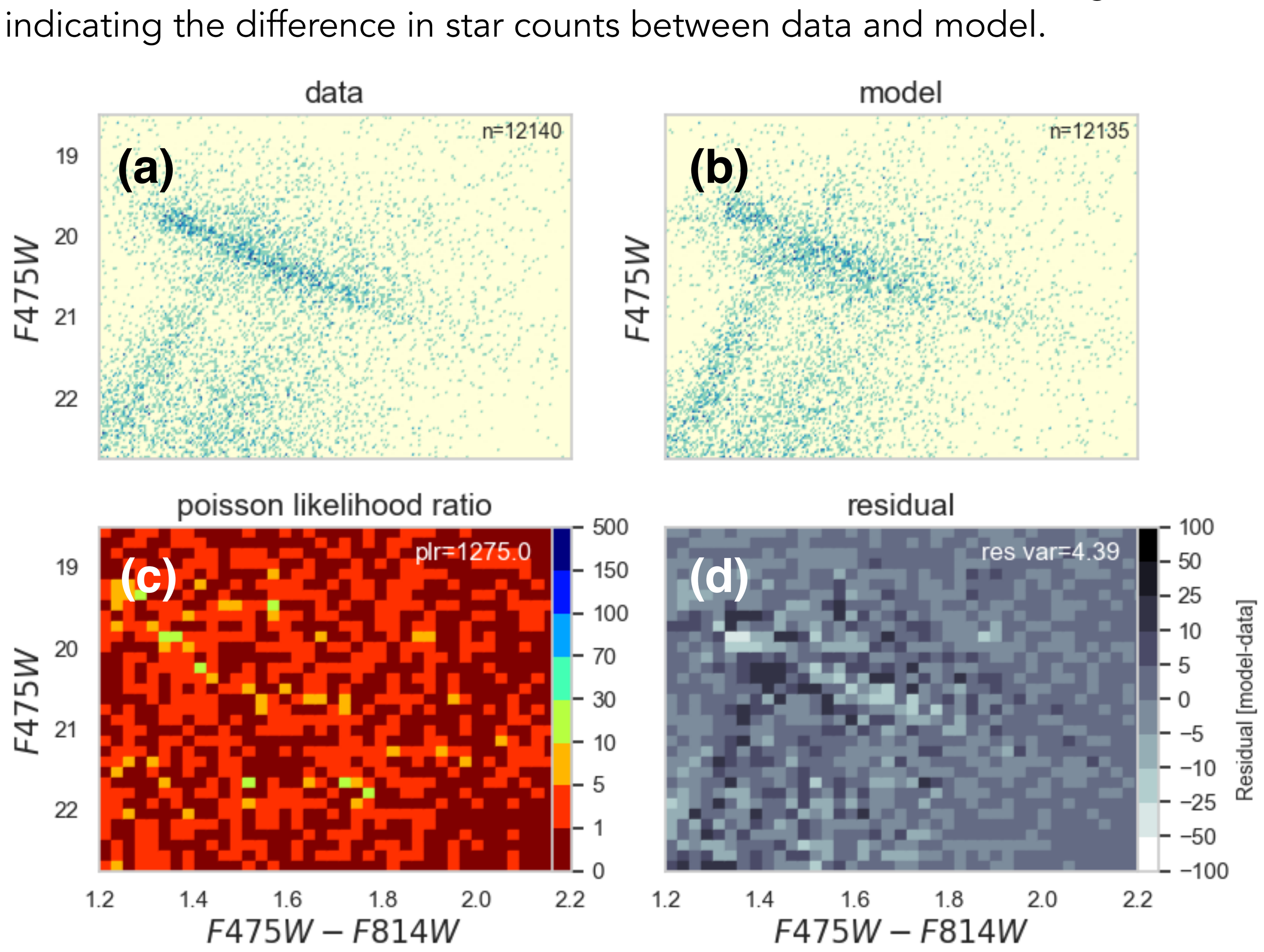
Table 1. Parameter Grid Ranges

	Min	Max
Log-normal extinction Av	0.2 mag	0.425 mag
Extinction width $\sigma(A_V)$	0.4 mag	1.0 mag
σ (dist. mod. (DM) FWHM relative to DM_{MEAN} = 18.96)	0.05 mag FWHM=1.7kpc	0.225 mag FWHM=15kpc
Star - Dust offset	-0.025* mag	-0.2 mag
Extinction Law**	G03*, F99*, G16 (f_A=0.5)*	

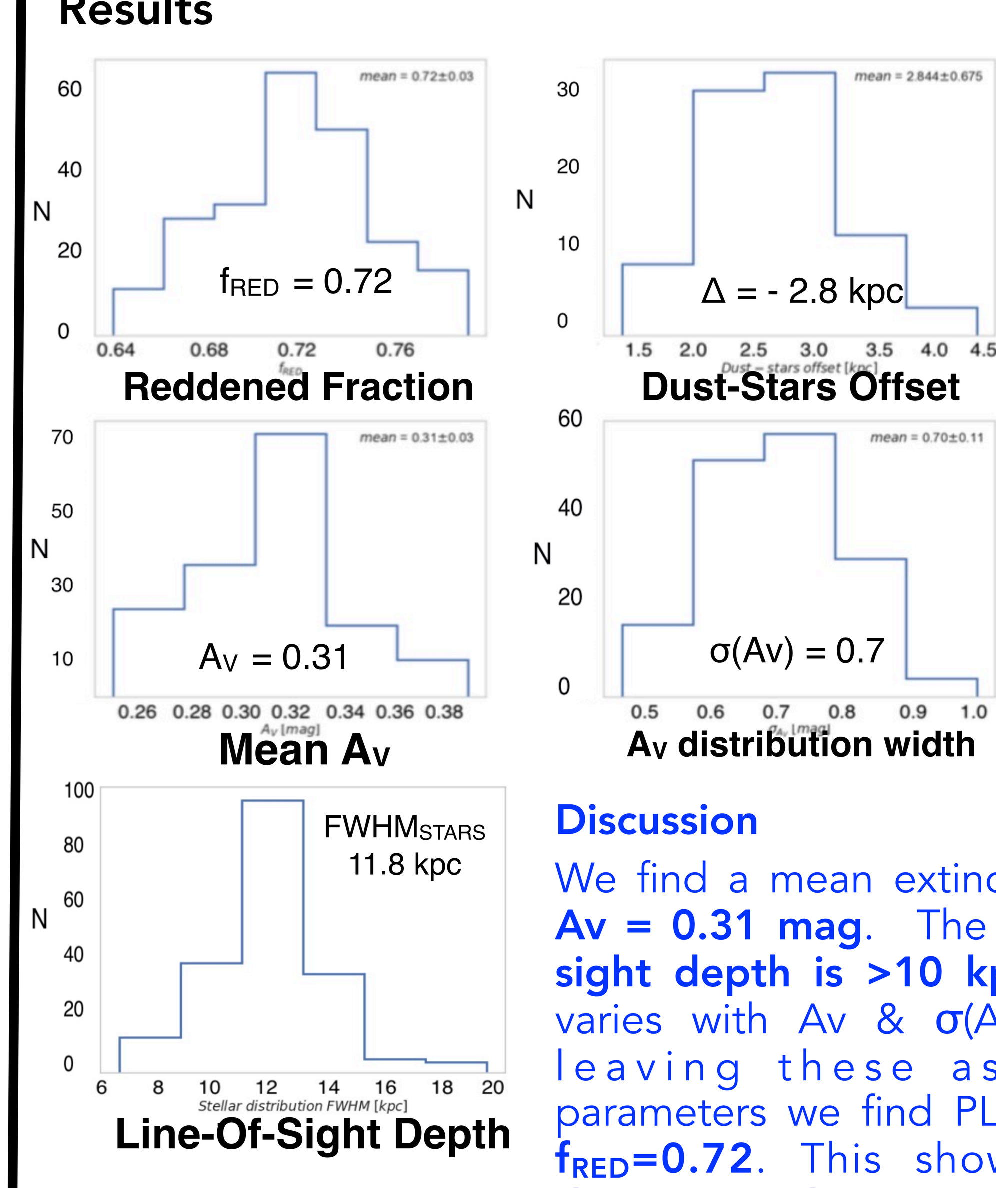
* A negative offset places the dust in front of stars; ** G03=SMC Bar (Rv=2.74); F99=MW Fitzpatrick '99; G16=Gordon '16 MW/SMC mix



Best-fit Model (a) Observed SMIDGE CMD. (b) Best-fit model with parameters to the right. (c) Best-fit model binned CMD space with Poisson Likelihood Ratio which we find to be about 1000 . (d) Residual significance indicating the difference in star counts between data and model.



Results



Discussion

We find a mean extinction of **Av = 0.31 mag**. The **line of sight depth is >10 kpc**. f_{RED} varies with Av & $\sigma(A_V)$, but leaving these as free parameters we find PLR_{MIN} at f_{RED}**=0.72**. This shows the **dust is on the near side of the stars offset by ~3kpc.**

Conclusions

- In the **Magellanic Clouds** when using stars as a background to map the dust, it is necessary to take into account both the **dust extinction and the 3D structure** of the galaxy.
- The SMC shows a **significant line-of-sigh depth** and **dust positioned in front of the stars.**

Future Work:

- We will examine how, and if, the extinction curve in the SMC varies as a function of H_2 fraction and average ISM density by using CMD matching inside and outside molecular gas regions.
- We will use BEAST with bright stars to look at the UV part of the extinction curve to find out about the strength of the 2175A bump and the steep UV rise.

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References: • Dolphin, 2002, *MNRAS* • Gordon et al. 2003, *ApJ* • Gordon et al., 2016, *ApJ* • Fitzpatrick, 1999, PASP • Harris & Zaritsky, 2004, *AJ* • Besla et al. 2007, 2012, 2016 • Haschke et al., 2012, *AJ* • Florsch et al., 1981, A&A • Gardiner et al., 1991, 1992, MNRAS • Hatzidimitriou et al., 1989, MNRAS • Jacyszyn-Dobrzeniecka et al., 2016 + 2017, *AA* • Schruba et al. 2011, *AJ*, 142, 37 • Kapakos & Hatzidimitriou, 2012, MNRAS • Nidever et al., 2013, ApJ • Scowcroft et al., 2016, ApJ • Subramanian et al., 2009 (ApJ & A&A) & 2017 (MNRAS) • CMD matching: Dolphin, 2002, *MNRAS* • Dolphin et al., 2003, *AJ* • Harris & Zaritsky, 2004 & 2009, *AJ* • Weisz et al., 2013, MNRAS + others SFH works • Skillman 2002, 2003 • Tolstoy et al. (2009) • Yanchulova Merica-Jones et al., 2017, ApJ • Foster et al., 2013, MNRAS • Dalcanton et al., 2015, ApJ • Rubele et al. 2018, MNRAS