Extinction law in the range 0.4-4.8 μm and the 8620 Å DIB towards the stellar cluster Westerlund 1

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$$\frac{A_B}{21.43}=\frac{A_V}{14.95}=\frac{A_R}{11.25}=\frac{A_I}{8.72}=\frac{A_Z}{7.23}=\frac{A_Y}{5.10}=\frac{A_J}{3.23}=\frac{A_H}{1.77}=\frac{A_{Ks}}{1}=\frac{A_{W1}}{0.39}=\frac{A_{W2}}{0.26}.$$

Abstract & Introduction

The young stellar cluster Westerlund 1 (Wd 1: $l=339.6°$, $b=-0.4°$) is one of the most massive in the local Universe, but accurate parameters are pending on better determination of its extinction and distance. Based on our photometry and data collected from other sources, we have derived a reddening law for the cluster line–of–sight representative of the Galactic Plane (-5° $<b<$+5°) in the window 0.4-4.8 μm: The power law exponent $\alpha=2.13\pm0.08$ is much steeper than those published a decade ago (1.6–1.8) and our index $R_V=2.50\pm0.04$ also differs from them, but in very good agreement with recent works based on deep surveys in the inner Galaxy. As a consequence, the total extinction $A_{Ks}=0.74\pm0.08$ ($A_V=11.40\pm$ 2.40) is substantially smaller than previous results(0.91–1.13), part of which ($A_{Ks}=0.63$ or $A_V=9.66$) is from the ISM. The extinction in front of the cluster spans a range of ΔA_V ~8.7 with a gradient increasing from SW to NE across the cluster face, following the same general trend of warm dust distribution. The map of the $J-Ks$ colour index also shows a trend of reddening in this direction. We measured the equivalent width of the diffuse interstellar band at 8620 Å (the "GAIA DIB") for Wd 1 cluster members and derived the relation $A_{Ks}=0.612\,EW-0.191\,EW^2$. This extends the Munari et al. (2008) relation, valid for $E_{B-V}<1$, to the non-linear regime ($A_V>4$).

Key words: Galaxy: open clusters and associations: individual: Westerlund 1 - ISM: general - ISM: lines and bands - ISM: dust, extinction:

- 星形成を理解するうえで大質量形成領域の"距離"と"減光量"を精確に知ることは重要
  - 特に銀河中心方向では Rv ~ 3.1 の減光則には従わないことが知られている
  - 減光曲線をきちんと評価することが必要である
- Westerlund1 (Wd1) について B-band から WISE W2-band までの測光観測を実施
  - 視野内の Red Clump stars を減光キャリブレータとして用いる
  - Wd1 のメンバーのうち分光観測からスペクトル型がわかっている天体を解析
  - 赤化量の比較から Wd1 の"減光量"と"減光則"を求めた
  - 減光量はおよそ **AKs ~ 0.7** であり **Rv ~ 2.5** の減光則でよく近似される
- 減光との相関が知られている 8620Å DIB との関係についても調べた
  - この DIB は GAIA によって観測可能なので関係を知っておくことは価値が高い
  - これまで 8620Å DIB との相関は E(B-V)<1 の範囲だけで検証されていた
  - Wd1 のデータをあわせて**広いダイナミックレンジでの関係を確立**した

観測

おもに 4m Blanco Telescope の ISPI camera (JHKs, 10'x10' FOV) を使用.
限界等級はそれぞれ (J,H,Ks) = (21.4, 19.2, 18.2) 程度.

明るい星には CAMIV camera (1.6m & 0.6m OPD/LNA Brazilian telescopes) を使用.

Red Clump stars の ZY-band は VVV サーベイのデータを使用.
可視光の等級はいろいろな論文から引っ張ってきている.

Figure 2 のような図を多波長で作成して Color Excess 比の関係を得る.

減光量の比が Aλ/AKs ~ (λKs/λ)$^\alpha$ という関係に乗ることを仮定すると Color Excess 比について Equation 2 のような関係式が得られる. 多波長の結果を組みあわせて α の値を決定する. Color Excess 比から減光量の比を得る (Figure 4).

Equation 2: Color Excess Ratio

$$\frac{E(\lambda_1-\lambda_2)}{E(\lambda_2-K_s)}=\frac{A_{\lambda_1}-A_{\lambda_2}}{A_{\lambda_2}-A_{K_s}}=\frac{\left(\frac{\lambda_2}{\lambda_1}\right)^{\alpha}-1}{1-\left(\frac{\lambda_2}{\lambda_{K_s}}\right)^{\alpha}}.$$

$$E(\lambda_1-\lambda_2)=(m_{\lambda_1}-m_{\lambda_2})_{\rm obs}-(m_{\lambda_1}-m_{\lambda_2})_0$$

Figure 2: JHKs Color-Color Diagram

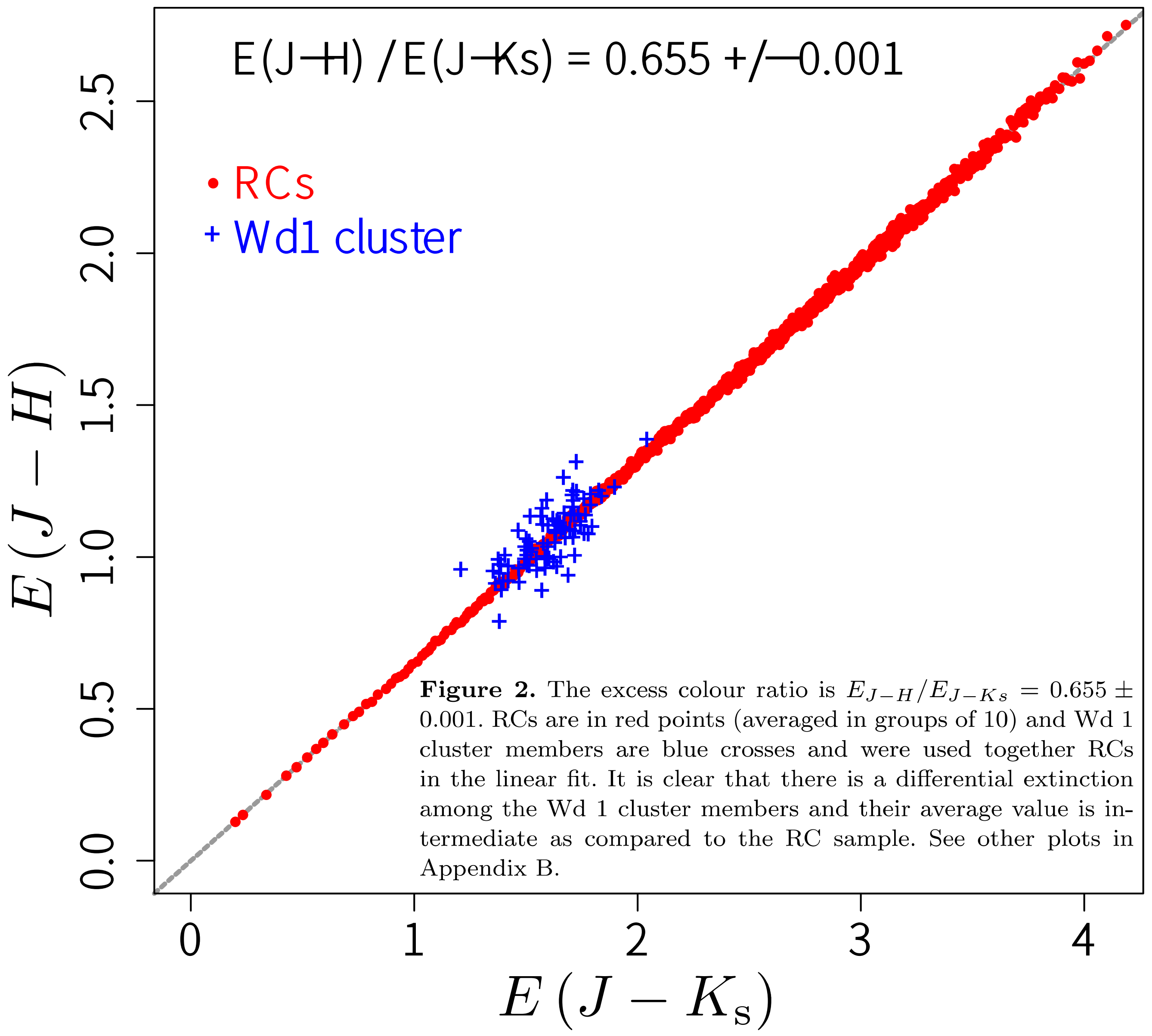

Figure 2. The excess colour ratio is $E_{J-H}/E_{J-Ks}=0.655\pm0.001$. RCs are in red points (averaged in groups of 10) and Wd 1 cluster members are blue crosses and were used together RCs in the linear fit. It is clear that there is a differential extinction among the Wd 1 cluster members and their average value is intermediate as compared to the RC sample. See other plots in Appendix B.

Figure 4: Extinction Curve normalized at Ks-band

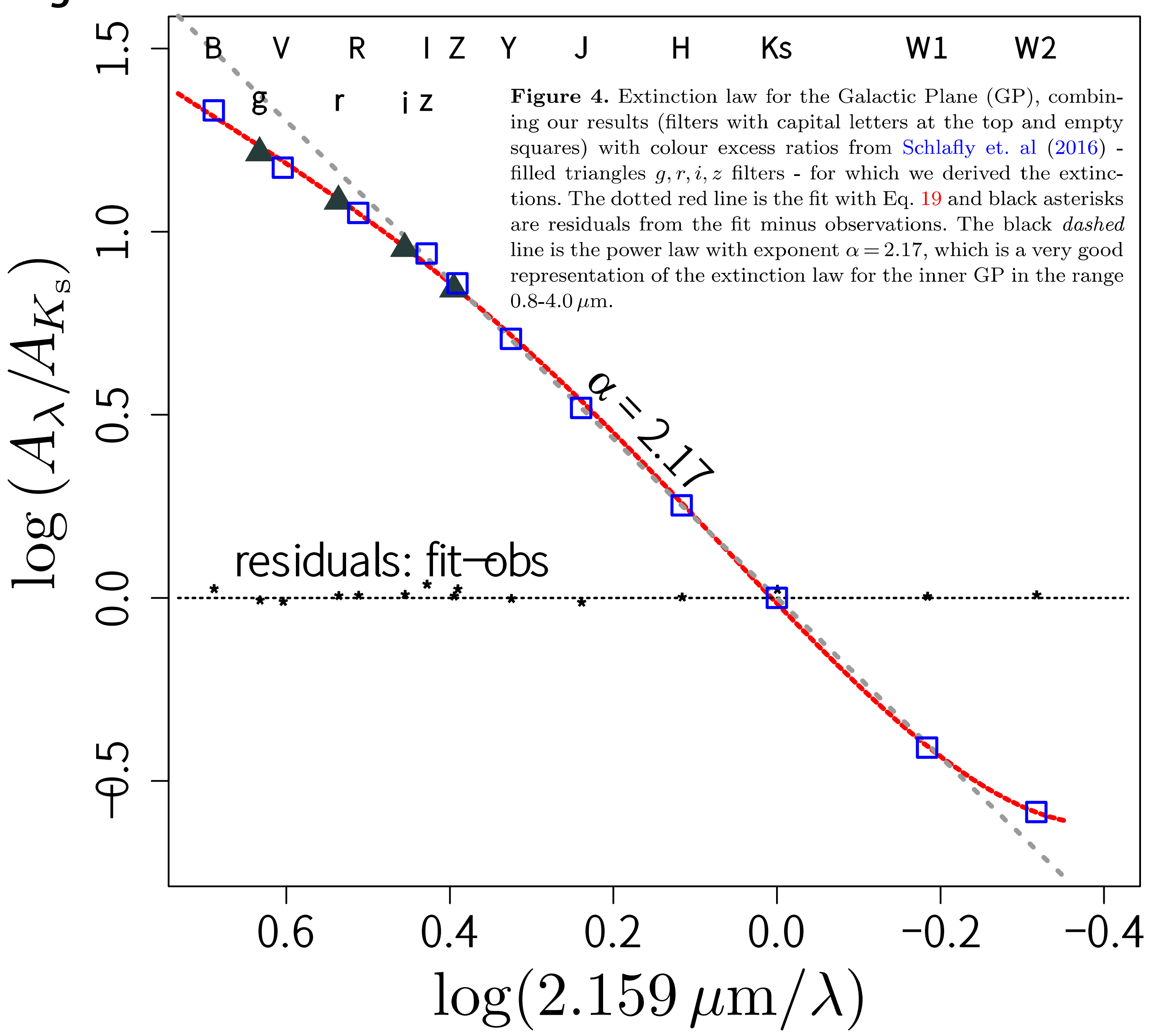

Figure 4. Extinction law for the Galactic Plane (GP), combining our results (filters with capital letters at the top and empty squares) with colour excess ratios from Schlafly et. al (2016) - filled triangles g,r,i,z filters - for which we derived the extinctions. The dotted red line is the fit with Eq. 19 and black asterisks are residuals from the fit minus observations. The black *dashed* line is the power law with exponent $\alpha=2.17$, which is a very good representation of the extinction law for the inner GP in the range 0.8-4.0 μm.

Figure 3: Extinction Curve compared with vdH#16

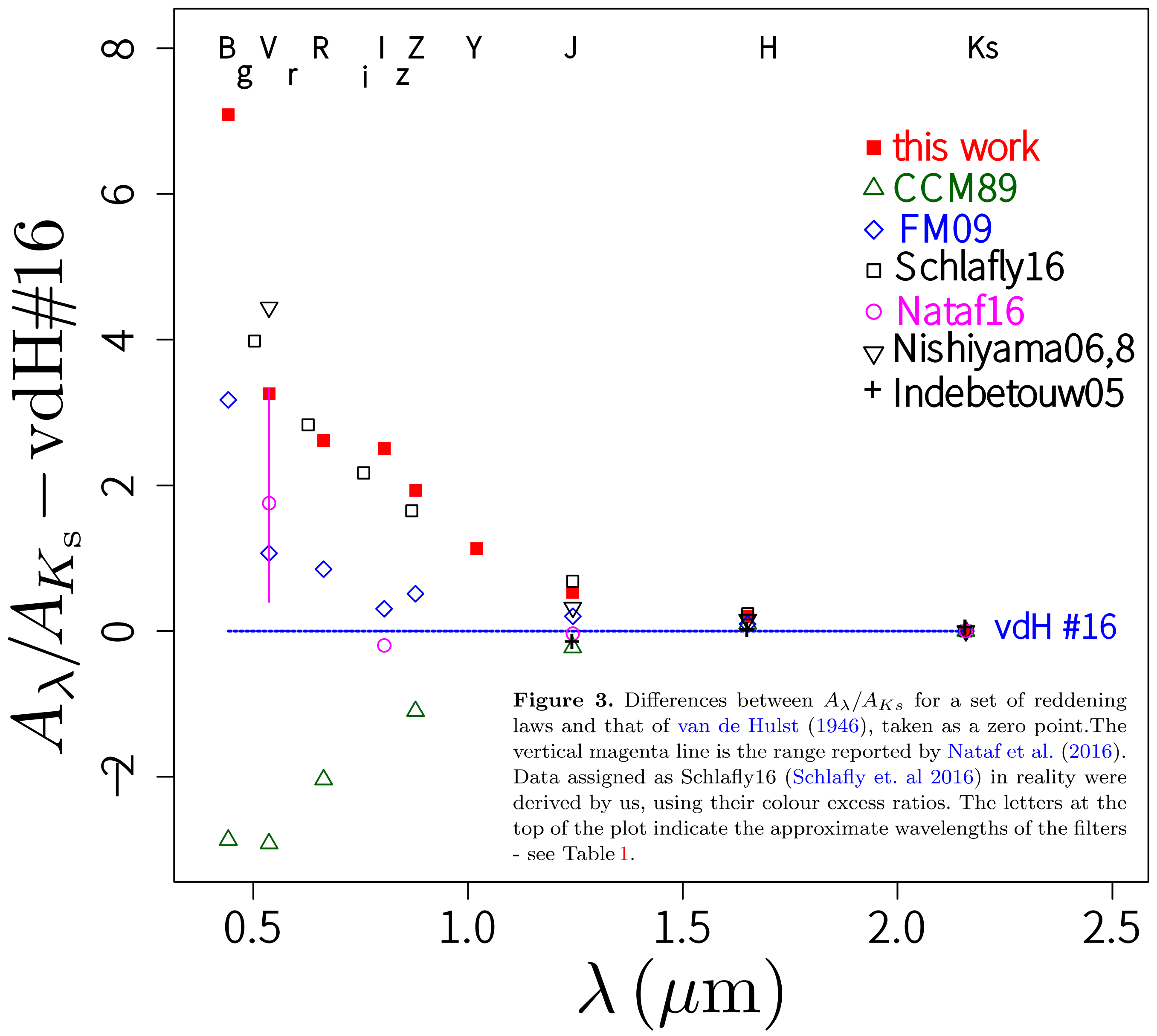

Figure 3. Differences between A_λ/A_{Ks} for a set of reddening laws and that of van de Hulst (1946), taken as a zero point.The vertical magenta line is the range reported by Nataf et al. (2016). Data assigned as Schlafly16 (Schlafly et. al 2016) in reality were derived by us, using their colour excess ratios. The letters at the top of the plot indicate the approximate wavelengths of the filters - see Table 1.

Figure 10: Extinction versus EW of DIB8620

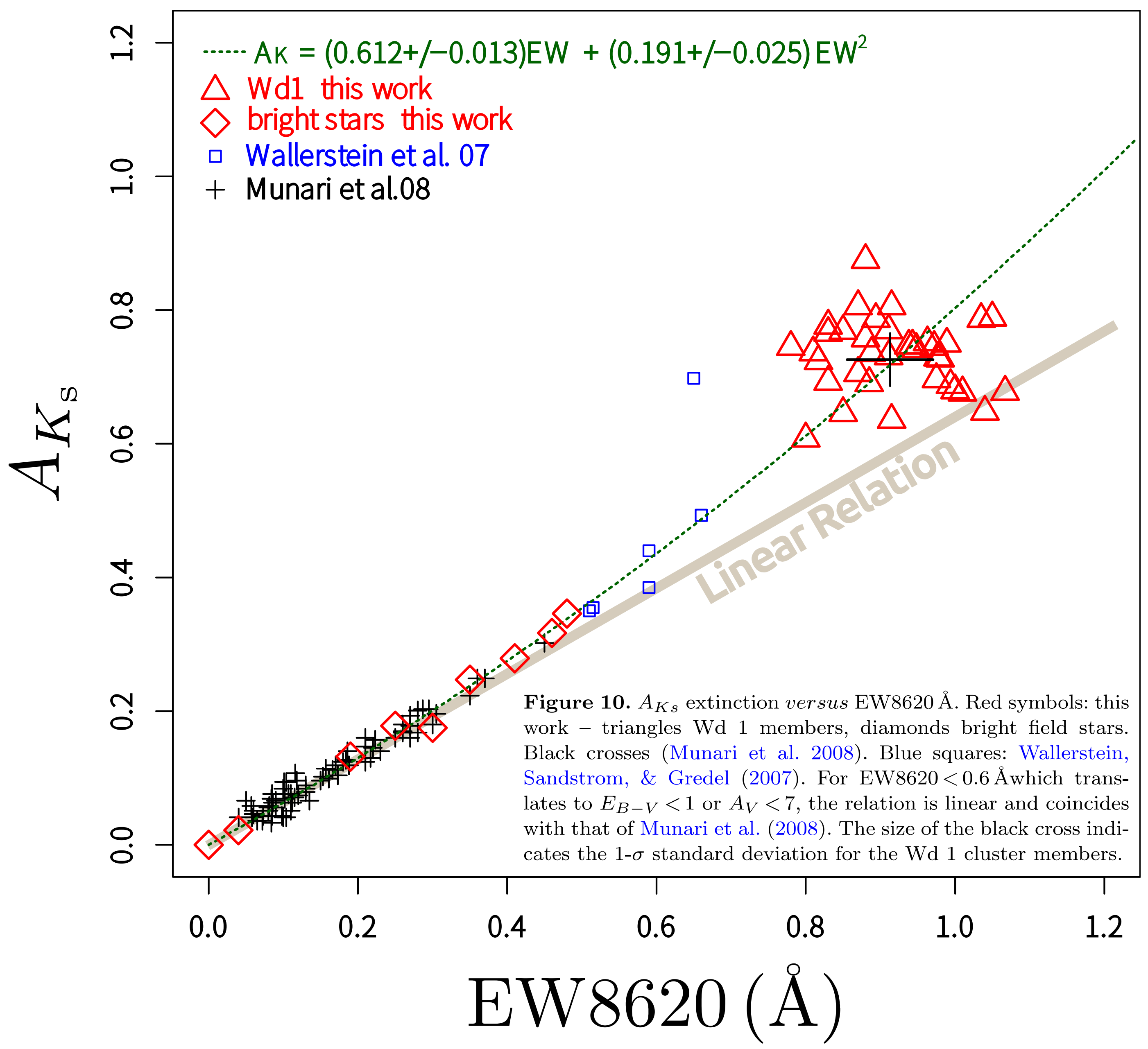

Figure 10. A_{Ks} extinction *versus* EW8620 Å. Red symbols: this work – triangles Wd 1 members, diamonds bright field stars. Black crosses (Munari et al. 2008). Blue squares: Wallerstein, Sandstrom, & Gredel (2007). For EW8620 < 0.6 Åwhich translates to $E_{B-V}<1$ or $A_V<7$, the relation is linear and coincides with that of Munari et al. (2008). The size of the black cross indicates the 1-σ standard deviation for the Wd 1 cluster members.