The Interstellar Extinction Law in the Near- and Mid-Infrared Based on the APOGEE Spectroscopic Survey

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Collaborators: Mengyao Xue, Jian Gao, Shu Wang, Aigen Li

1. A Precise Determination of the Mid-Infrared Interstellar Extinction Law Based on the APOGEE Spectroscopic Survey
   - Mengyao Xue, B. W. Jiang, Jian Gao, Jiaming Liu, Shu Wang, and Aigen Li
   - 2016, ApJS, in proof
2. Universality of the Near-infrared Extinction Law Based on the Apogee Survey
   - Shu Wang and B. W. Jiang
   - 2014, ApJL 788, L12

Preface

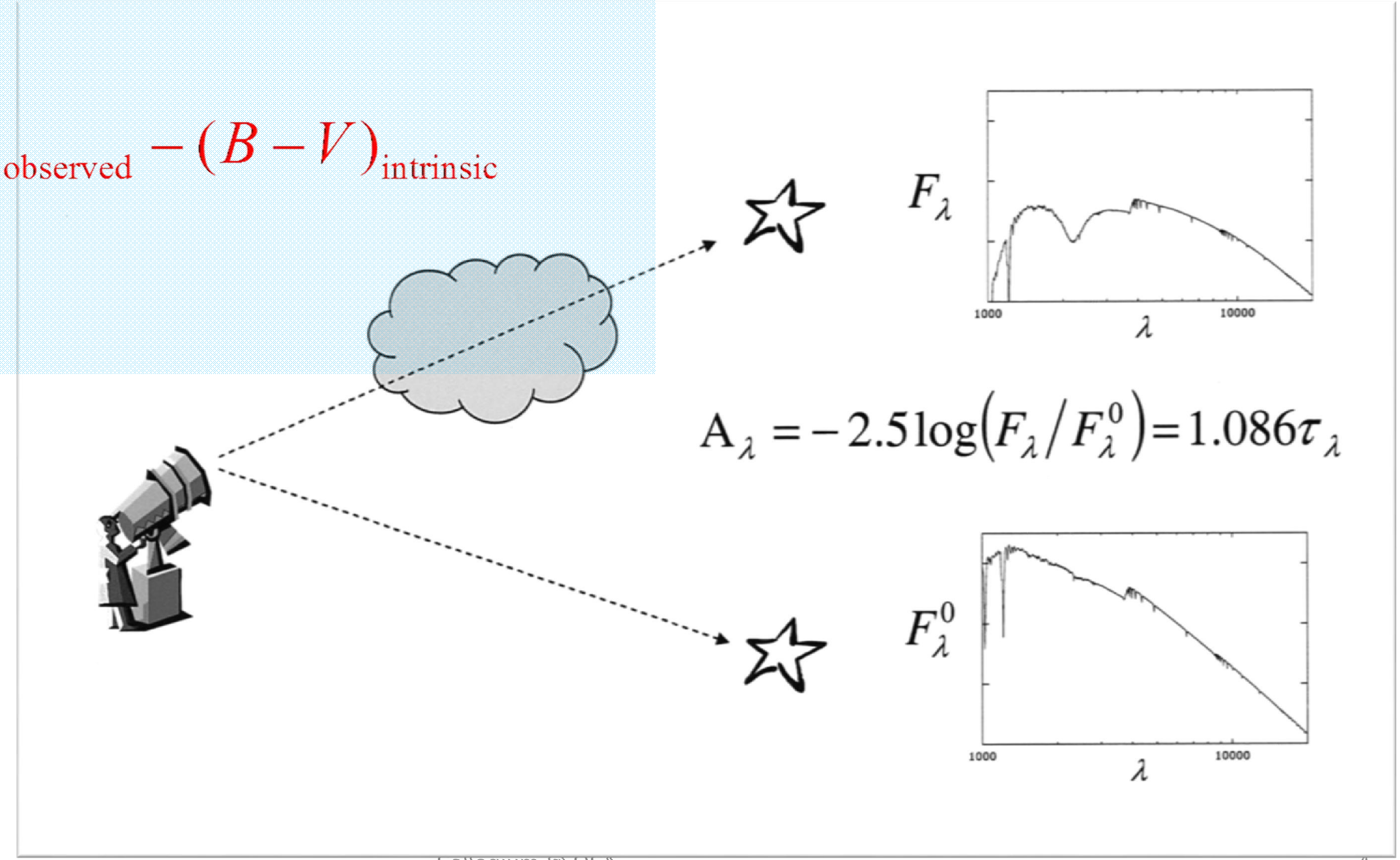
Extinction

$$A_\lambda = -2.5\log\frac{F_\nu}{F_\nu^0} = 1.086 N_\mathrm{d} Q_\mathrm{e}(\lambda, a, \mathrm{shape})\sigma_\mathrm{d}$$

$$N_\mathrm{d} = \int n_\mathrm{d}\, ds$$

$$E(B-V) \equiv (B-V)_\mathrm{observed} - (B-V)_\mathrm{intrinsic}$$

$$R_\mathrm{V} \equiv \frac{A_\mathrm{V}}{E(B-V)}$$



Li et al. 2015, Lessons from the Local Group

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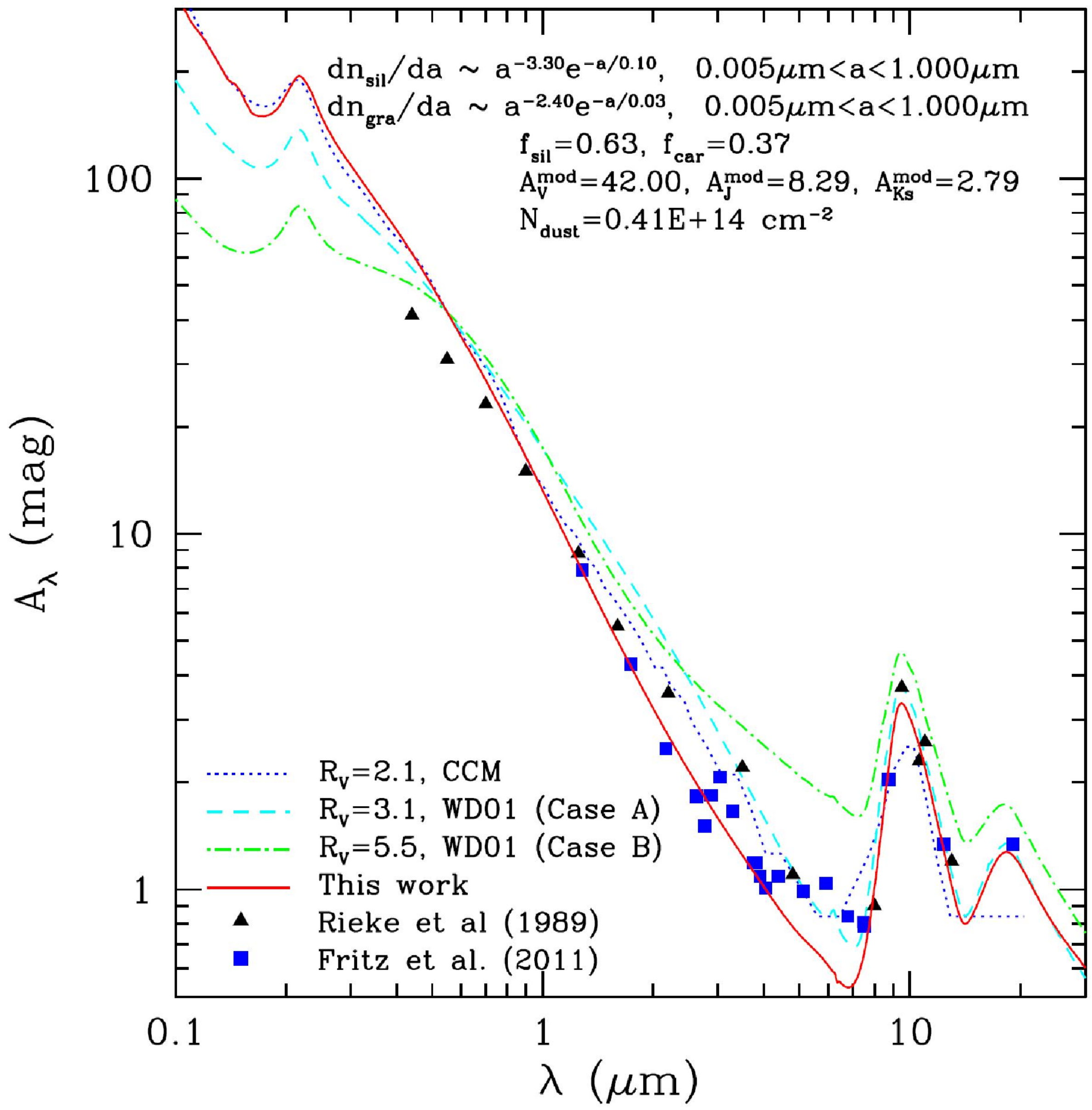
$$R_\mathrm{V} \equiv \frac{A_\mathrm{V}}{E(B-V)}$$

Outline

- Interstellar extinction law in the infrared
- Method based on the APOGEE spectroscopic survey
- Result: mean
  - Near-infrared
  - Mid-infrared
- Result: variation
  - Near-infrared
  - Mid-infrared
- Dust models for the infrared extinction curve

Interstellar Extinction Law

- Variation of interstellar extinction with wavelength
- Continuum extinction
  - Decreasing with wavelength
  - Steep rise to the UV range
- Spectral features
  - 2175A bump
  - 9.7um and 18um silicate features
  - Some DIBs
- In the infrared
  - Much weaker than V/UV



Galactic Center

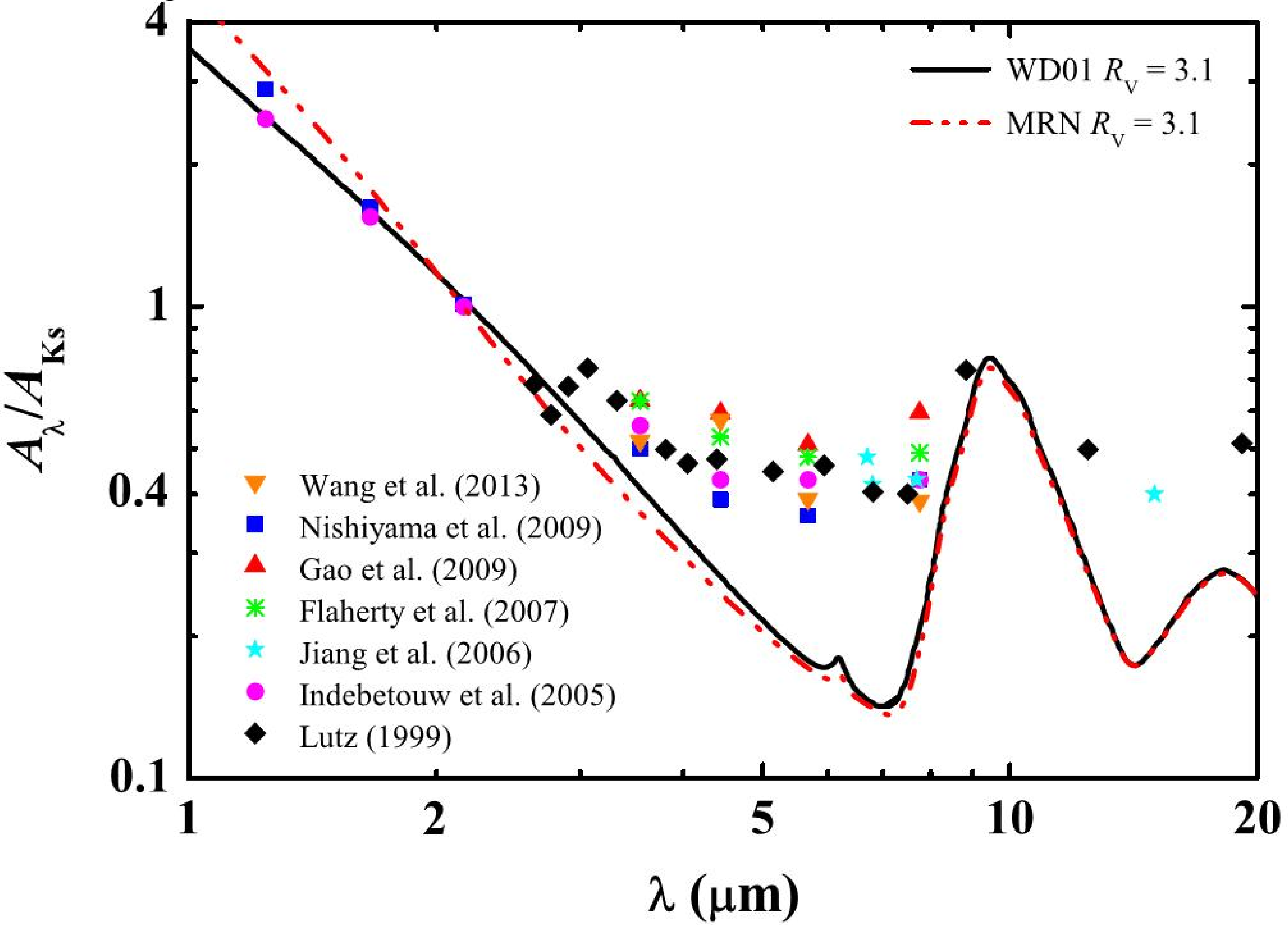
Gao, Li, Jiang, 2013
EPS, 65,1127

Infrared Extinction Law

- Power law, 1-7 μm, $A_\lambda \propto \lambda^{-\alpha}$
  - Index, α~1.7
- Silicate spectral features around 10μm and 20μm

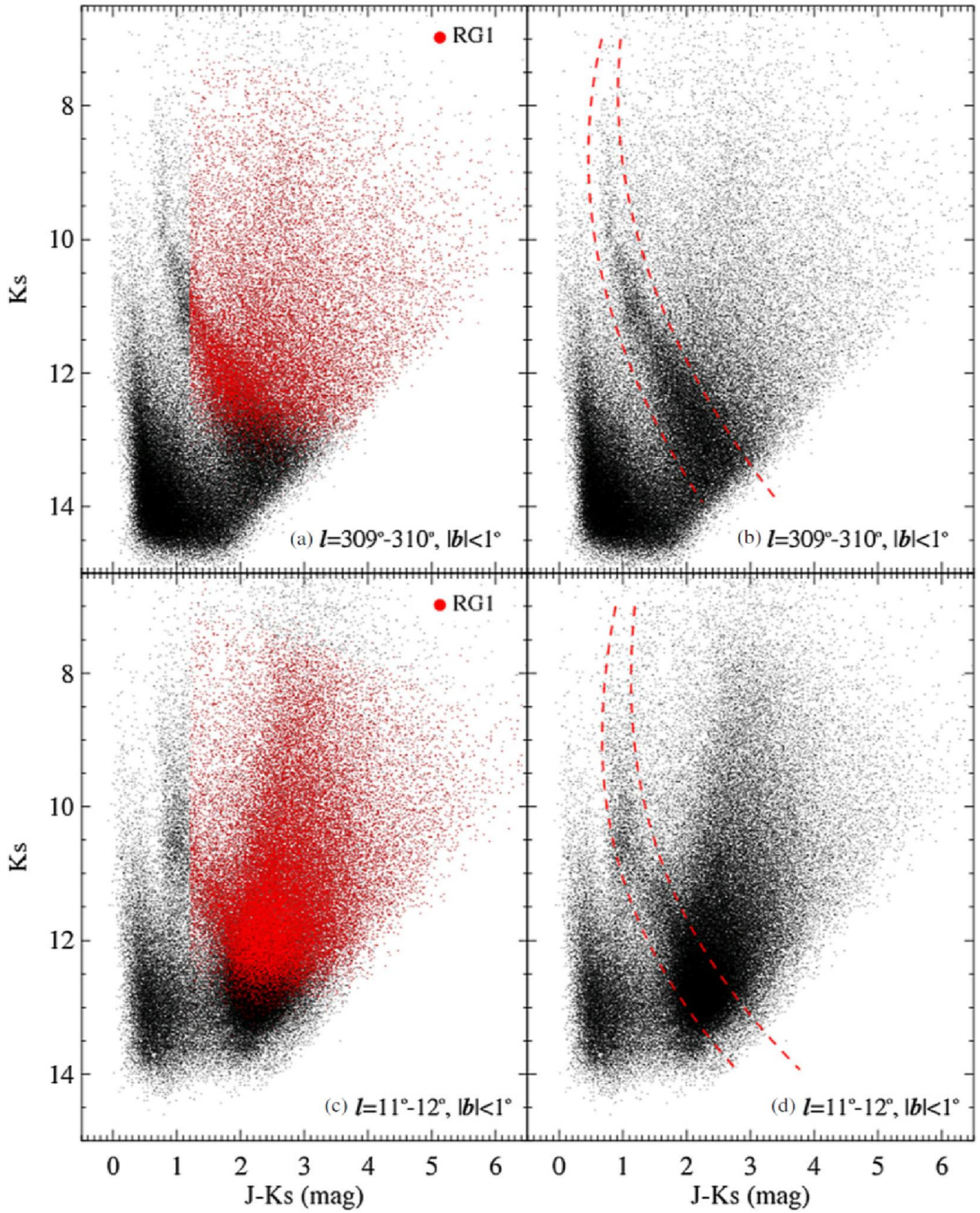
- Much flatter than the model derived from the UV/V extinction law in the 3-8um range
- Lack the dip around 7um predicted by the classical dust model
- Dispersion between works

Wang, Li & Jiang 2014 PSS



Uncertainty from photometric method

- Impurity of the sample
  - Selection of red giants and red clump stars
  - Contamination by AGB stars and YSOs
- Dispersion of the intrinsic colors
  - Red clump stars, $\Delta C_{JKs}^{0} \sim 0.1$ mag
  - Red giants, $\Delta C_{JKs}^{0} \sim 0.2$ mag

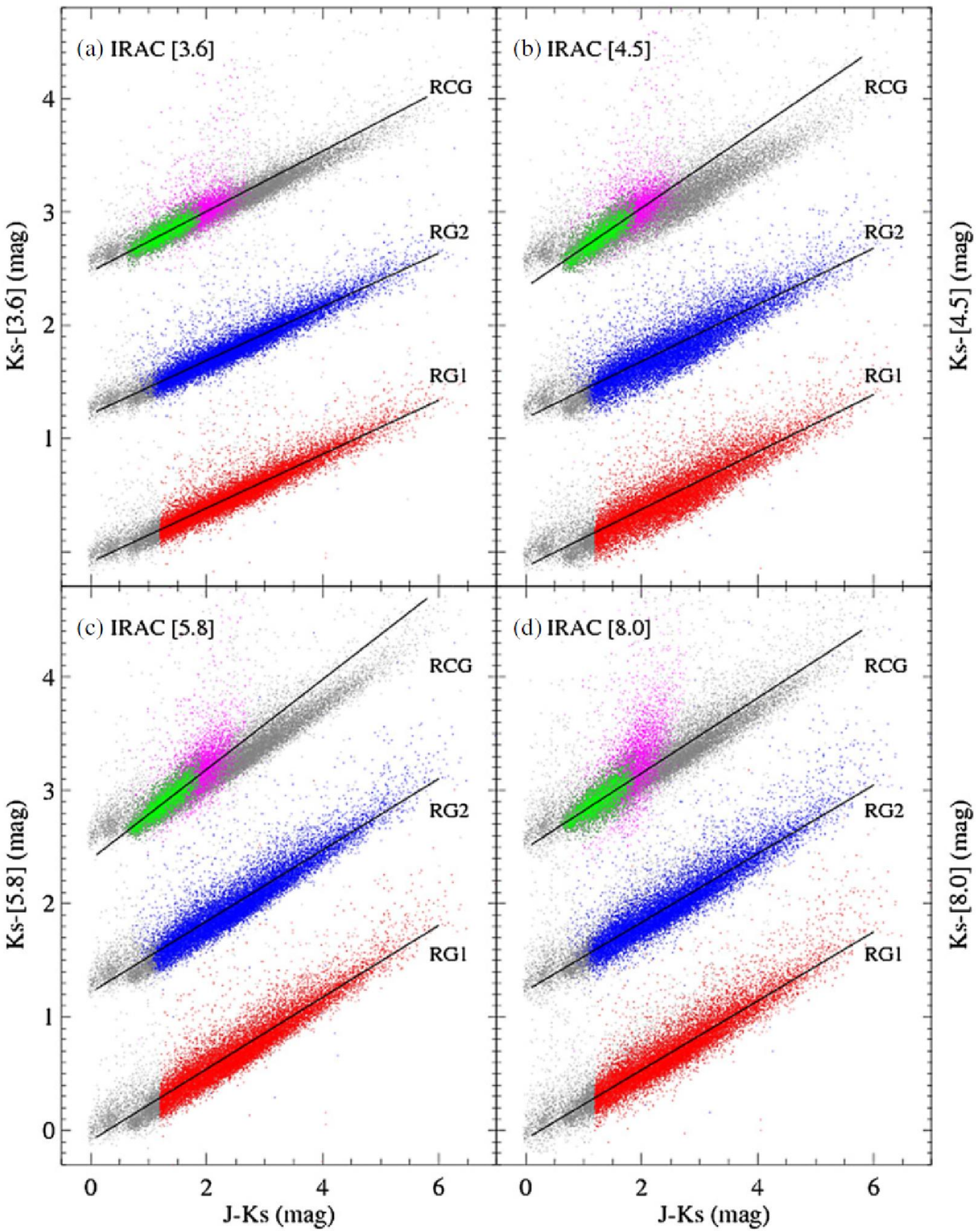


2MASS + Spitzer/GIMPLSE

Source selection

- Color indexes based on photometry
- Red clump
- Red giant

Gao, Jiang & Li 2009



Method

- Linear fitting of observed color respective to J-Ks
- Convert to relative extinction

- Color ratio instead of color-excess ratio

$$k_\lambda = \frac{E(\mathrm{K_S}-\lambda)}{E(\mathrm{J}-\mathrm{K_S})} = \frac{(\mathrm{K_S}-\lambda)-(\mathrm{K_S}-\lambda)_0}{(\mathrm{J}-\mathrm{K_S})-(\mathrm{J}-\mathrm{K_S})_0} = \frac{A_{\mathrm{K_S}}-A_\lambda}{A_\mathrm{J}-A_{\mathrm{K_S}}}$$

$$\frac{A_\lambda}{A_{\mathrm{K_S}}} = 1 + k_\lambda\left(1 - \frac{A_\mathrm{J}}{A_{\mathrm{K_S}}}\right)$$

New method: color-excess method with intrinsic color correction

- Selection of G-type and K-type giants by T_{eff}, log g and Z
- Relation of intrinsic color with stellar effective temperature T_{eff}
  - Choosing nearly zero extinction stars
  - Taking the observed color as the intrinsic color
- **Determination of intrinsic color from $\boldsymbol{T_{\mathrm{eff}}}$**
- Statistical linear fitting between **color excesses**

Wang & Jiang, 2014, ApJL 788, L12

$J - K_S$ vs T_{eff} diagram

The bluest envelope

Selection of zero-reddening stars

APOGEE stellar parameters

$\boldsymbol{C^0_{\lambda 1 \lambda 2} - T_{eff}}$

Photometry $\boldsymbol{C_{\lambda 1 \lambda 2}}$

$\boldsymbol{E_{Ks\lambda}, E_{Ks\lambda}/E_{JKs}}$

The APOGEE Spectroscopic Survey

- SDSS/DR12
- >100,000 red giant stars to magnitude H=12.2
- Resolution R=λ/Δλ ~22,500
- Typical S/N > 100
- Stellar parameters: log g**<3.0**, $T_{\rm eff}$, Z **>-1.0**
- Spectral type: A, F, **G, K**
- **J_err <0.05 mag, Ks_err <0.05 mag**
- **VSCATTER < 0.3 km/s**
- 63,330 stars

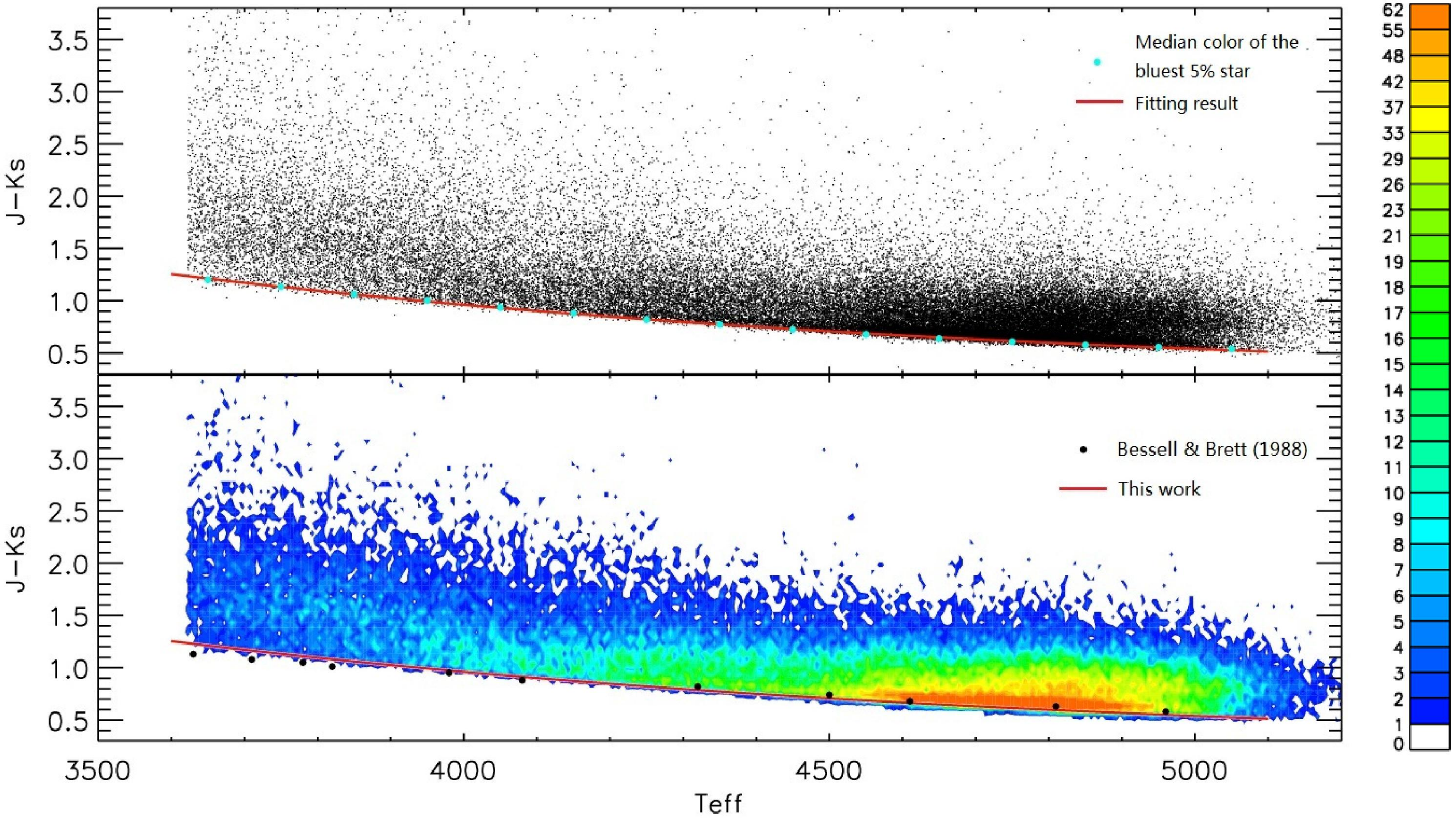
Mid-infrared bands

Survey	AKARI		*WISE*				*Spitzer*/GLIMPSE				*Spitzer*/MIPSGAL
Bands	S9W	~~L18W~~	W1	W2	W3	W4	[3.6]	[4.5]	[5.8]	[8.0]	[24]
$\lambda_{\rm eff}$ (μm)	8.23	17.61	3.35	4.60	11.56	22.09	3.55	4.49	5.73	7.87	23.68
area	All sky		All sky				$-105° < l < 65°$, $\lvert b\rvert < 5°$				$-68° < l < 69°$, $\lvert b\rvert < 3°$
5σ limit (mag)	7.6	5.0	16.9	16.0	11.5	8.0	15.0	14.5	12.5	12.5	7.9
Cross radius	$3''$		$1''$				*				$3''$
No. of sources $\otimes$ APOGEE	4,296	901	154,842	154,845	154,735	154,793	15,058	15,307	15,251	15,071	3,045
σ_λ (mag)	0.2	0.3	0.1				0.1				0.2
No. of sources qualified	1,024	108	61,734	61,935	41,510	2,008	5,411	5,540	5,474	5,502	806

The $C^0_{\lambda1\lambda2} - T_{\mathrm{eff}}$ relation

- (Nearly) zero-reddening sources
  - Blue envelop in the $C_{\lambda1\lambda2} - T_{\mathrm{eff}}$ diagram （Ducati 2001）
    - The least extinction
  - Practice
    - In the $C_{\mathrm{JKs}} - T_{\mathrm{eff}}$ diagram
- The photometric error is taken into account
  - Deviation less than 1 sigma from the blue envelop
- Fitting function
  - Exponential or quadratic

$$C_{\mathrm{JKs}}^{0} = 20.285 \times \exp\left(\frac{-T_{\mathrm{eff}}}{1214\mathrm{K}}\right) + 0.209$$



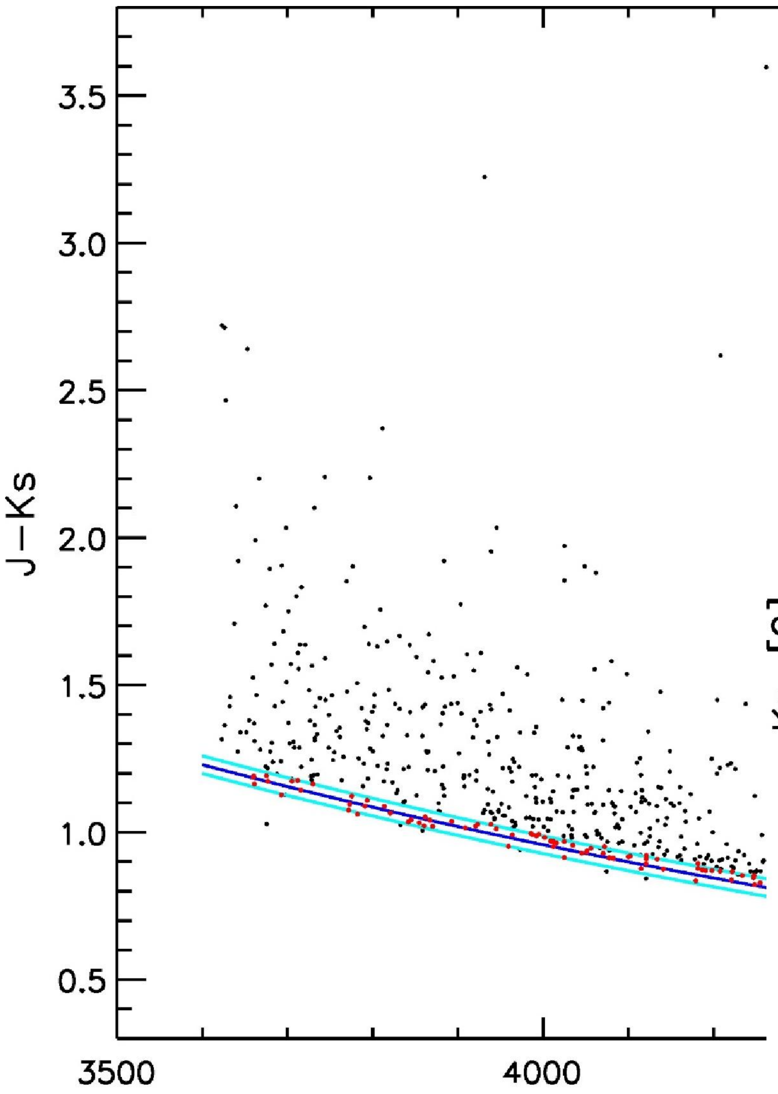
Comparison of C^0_{JKs}

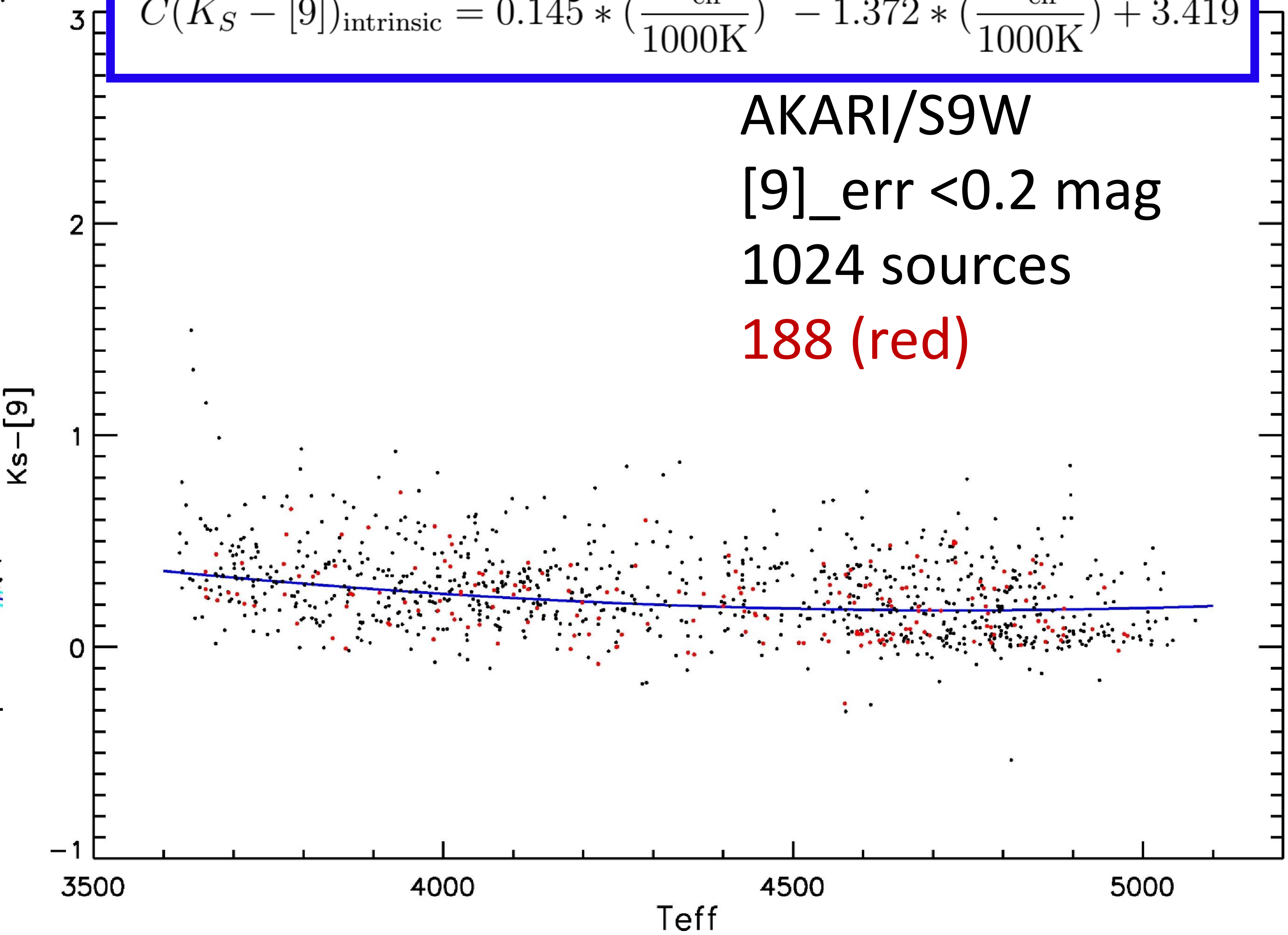
e 2: Comparison of $C^0_{\mathrm{JK_S}}$ in this work, Bessell & Brett (1988) and Wang & Jiang (2014)

T_{eff}	3630K	3710K	3780K	3820K	3980K	4080K
This work	1.21	1.15	1.10	1.07	0.97	0.91
Bessell & Brett (1988)	1.13	1.08	1.05	1.01	0.95	0.88
Wang & Jiang (2014)	1.43	1.35	1.28	1.25	1.11	1.03

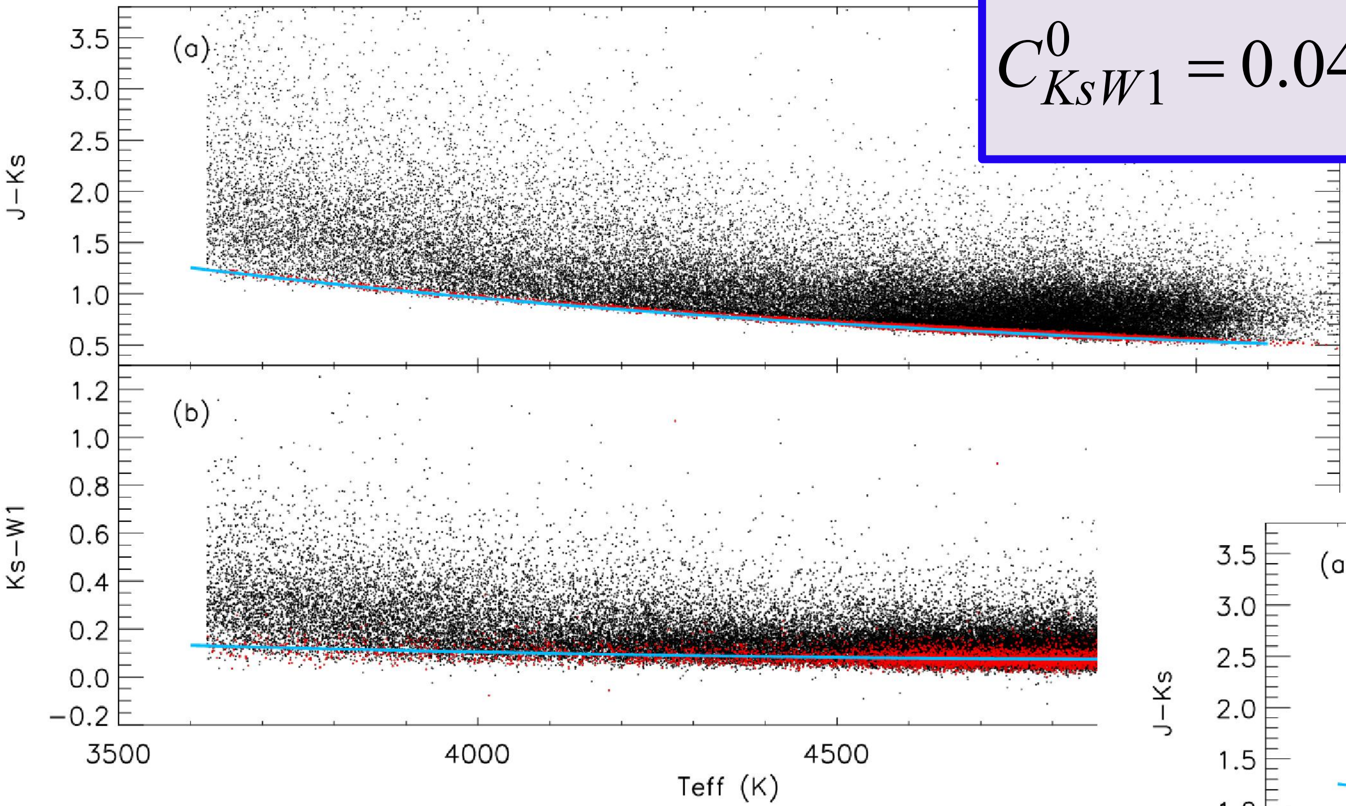
T_{eff}	4320K	4500K	4610K	4810K	4960K
This work	0.78	0.70	0.65	0.57	0.52
Bessell & Brett (1988)	0.82	0.74	0.68	0.63	0.58
Wang & Jiang (2014)	0.87	0.78	0.73	0.66	0.62

$$C(K_S - [9])_{\mathrm{intrinsic}} = 0.145 * (\frac{\mathrm{T_{eff}}}{1000\mathrm{K}})^2 - 1.372 * (\frac{\mathrm{T_{eff}}}{1000\mathrm{K}}) + 3.419$$

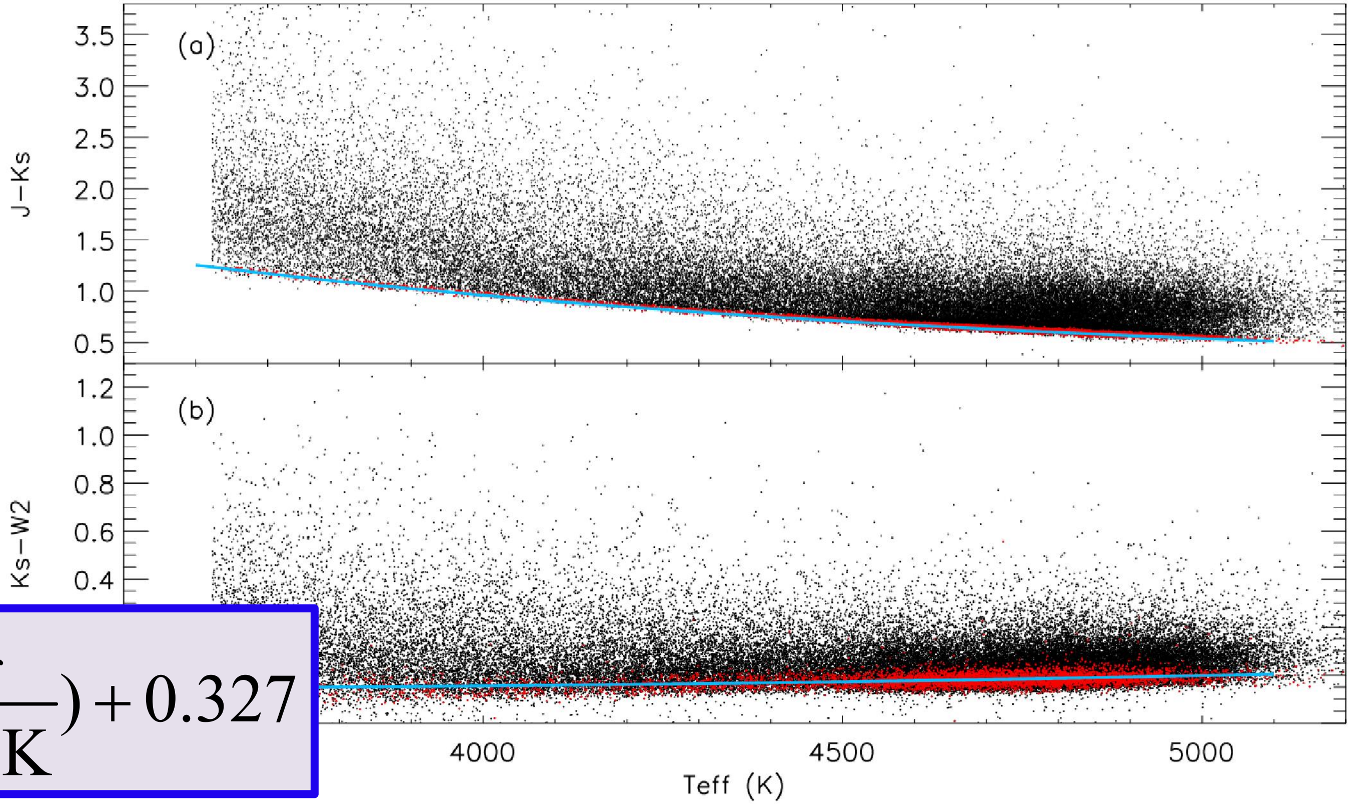




AKARI/S9W
[9]_err <0.2 mag
1024 sources
188 (red)

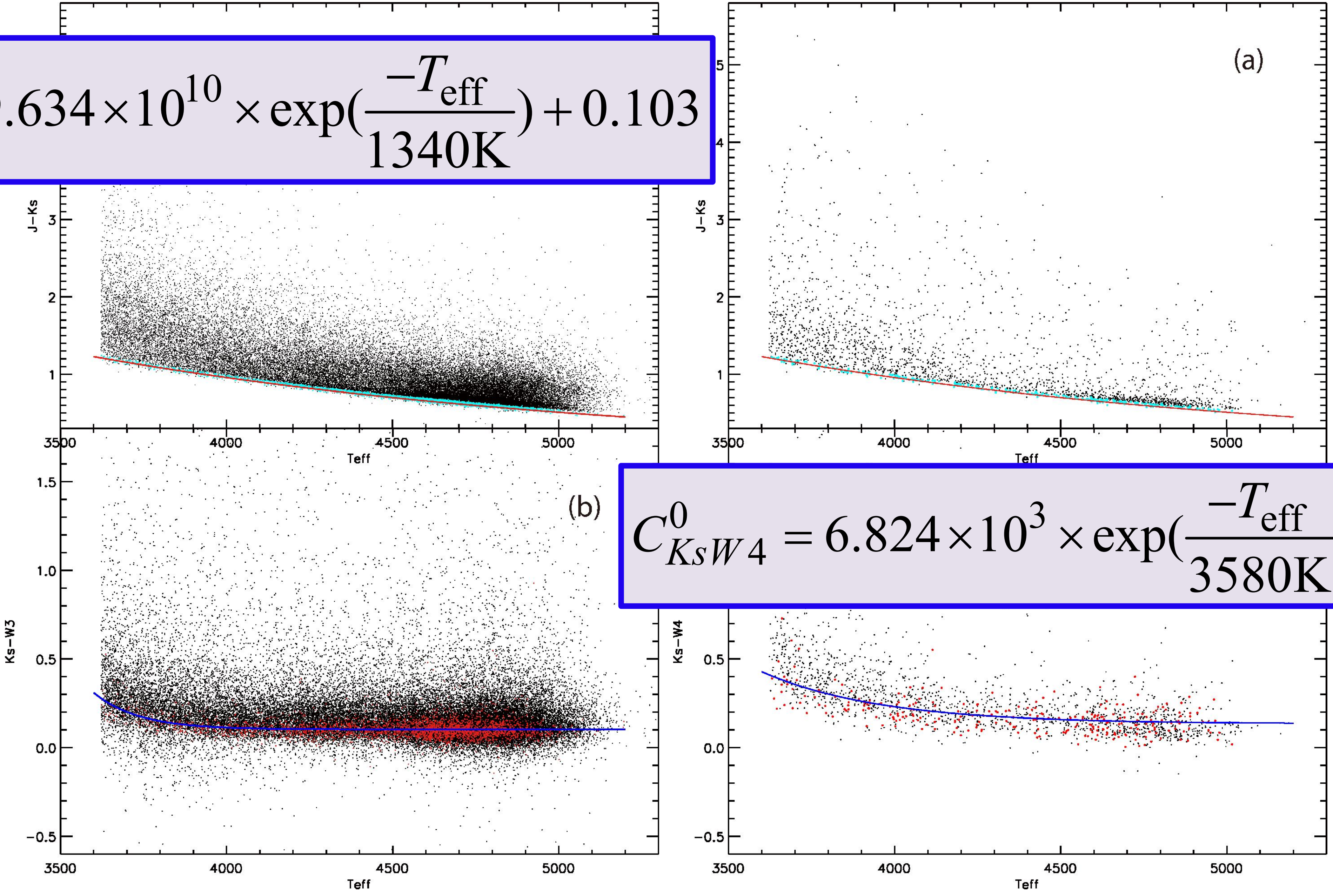


$$C_{KsW1}^{0} = 0.041 \times \left(\frac{T_{\rm eff}}{1000\mathrm{K}}\right)^{2} - 0.388 \times \left(\frac{T_{\rm eff}}{1000\mathrm{K}}\right) + 1.006$$



$$C_{KsW2}^{0} = 0.029 \times \left(\frac{T_{\rm eff}}{1000\mathrm{K}}\right)^{2} - 0.208 \times \left(\frac{T_{\rm eff}}{1000\mathrm{K}}\right) + 0.327$$

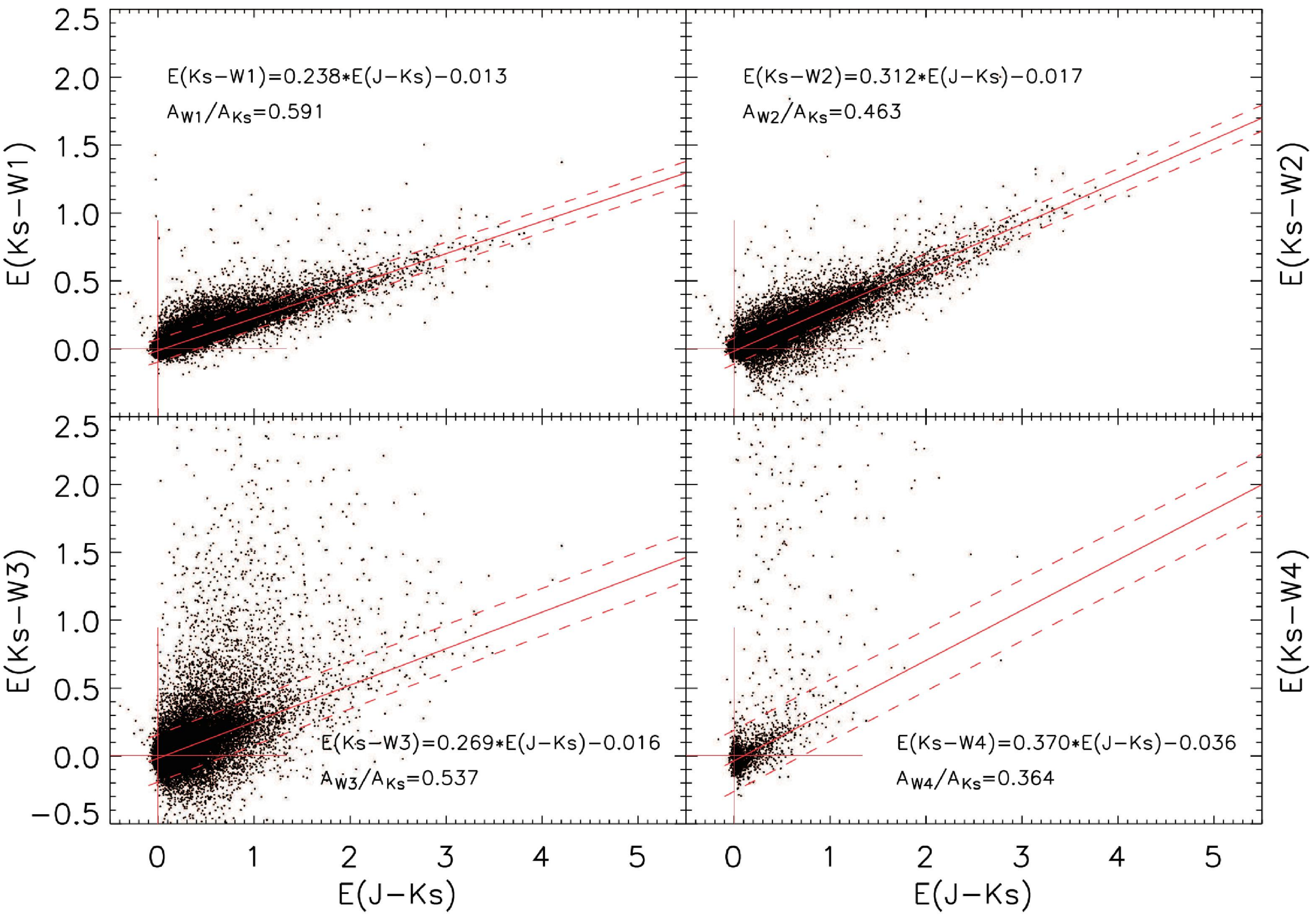
$$C_{KsW3}^{0} = 9.634 \times 10^{10} \times \exp(\frac{-T_{\mathrm{eff}}}{1340\mathrm{K}}) + 0.103$$



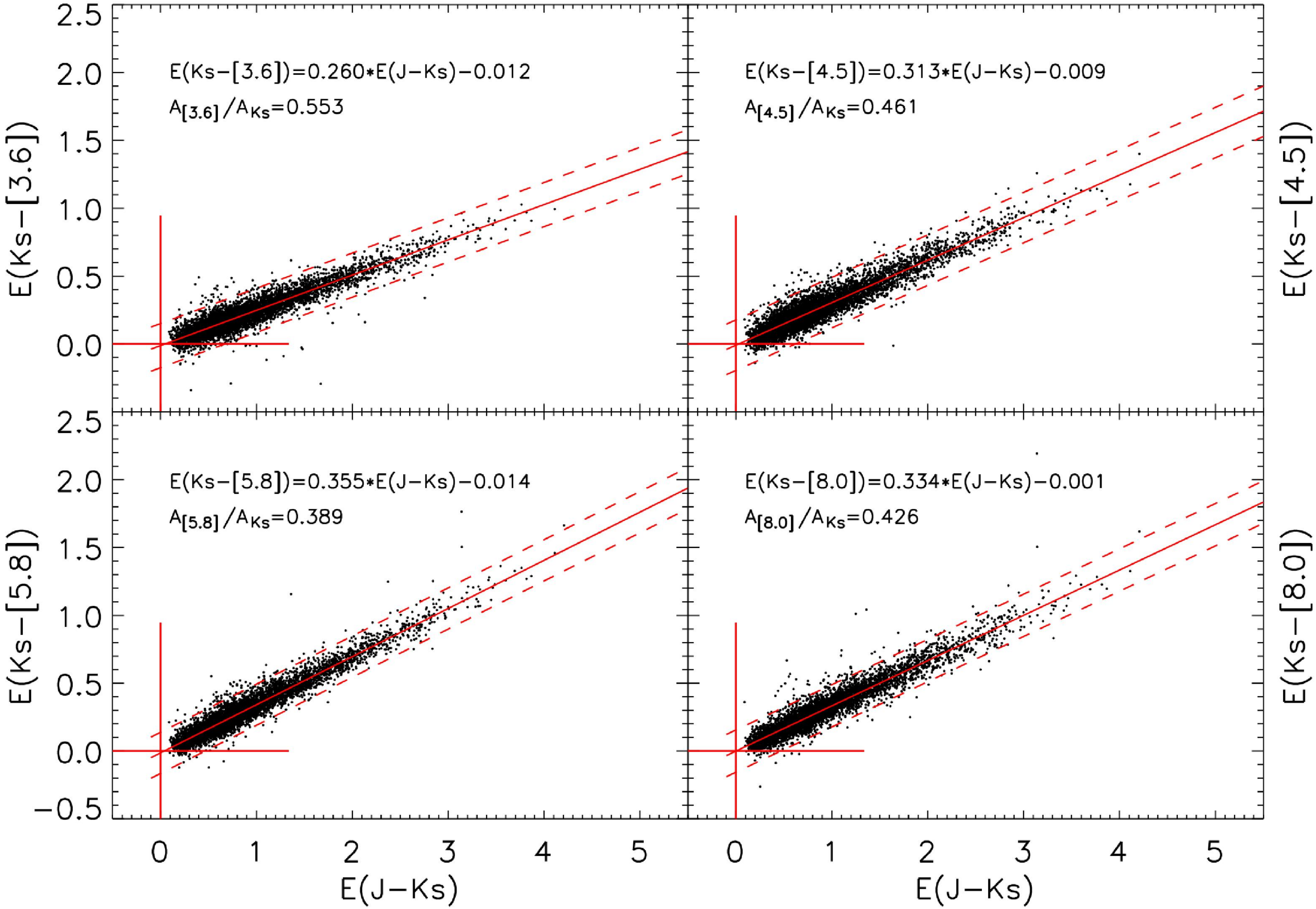
$$C_{KsW4}^{0} = 6.824 \times 10^{3} \times \exp(\frac{-T_{\mathrm{eff}}}{3580\mathrm{K}}) + 0.135$$

Linear fitting of color excesses

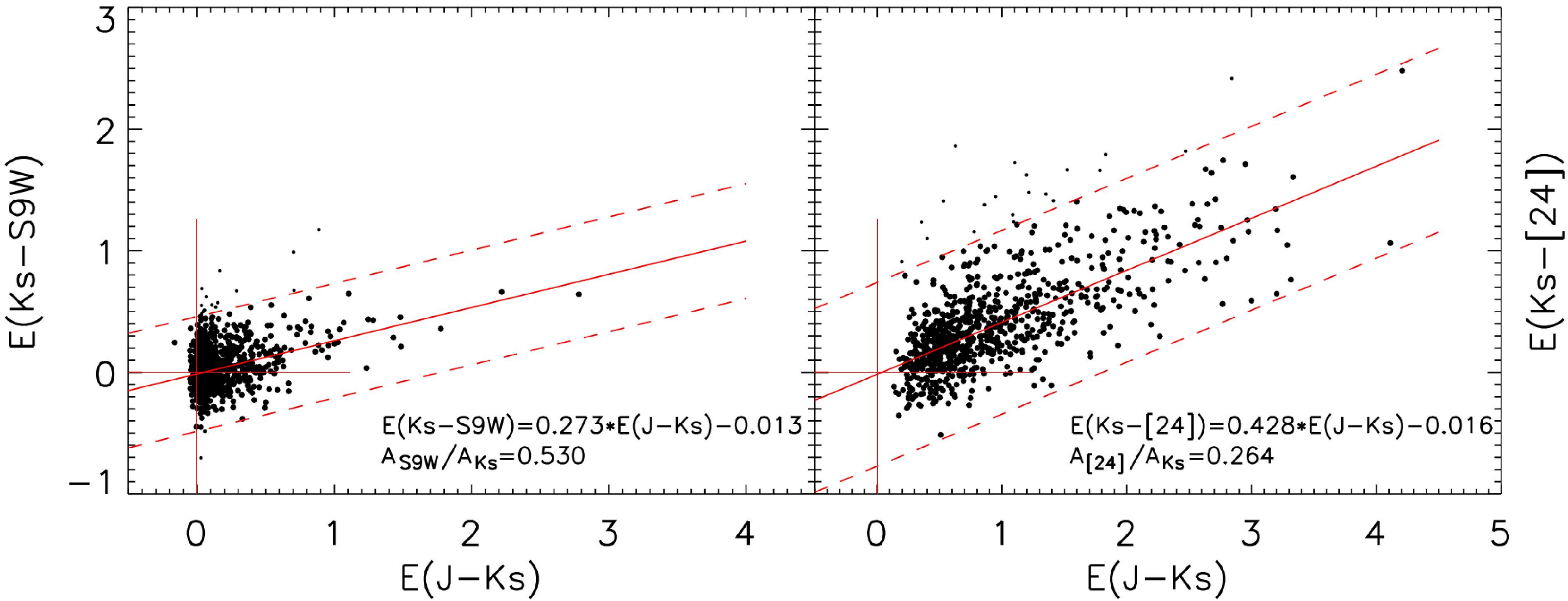
- Subtraction of the intrinsic color indexes
- Linear fitting of the color excesses $E(Ks - \lambda)$ and $E(J - Ks)$
- Exclusion of outliers by 3 sigma criterion
  - Important for sources with silicate features
- Intercept
  - Nearly zero
- Conversion to A_λ / A_{Ks} given $\frac{A_J}{A_{Ks}} = 2.72$ from $\frac{E(Ks-\lambda)}{E(J-Ks)}$



E(Ks−W1)=0.238*E(J−Ks)−0.013
A_W1/A_Ks=0.591
E(Ks−W2)=0.312*E(J−Ks)−0.017
A_W2/A_Ks=0.463
E(Ks−W3)=0.269*E(J−Ks)−0.016
A_W3/A_Ks=0.537
E(Ks−W4)=0.370*E(J−Ks)−0.036
A_W4/A_Ks=0.364
E(Ks−W1)
E(Ks−W2)
E(Ks−W3)
E(Ks−W4)
E(J−Ks)
E(J−Ks)

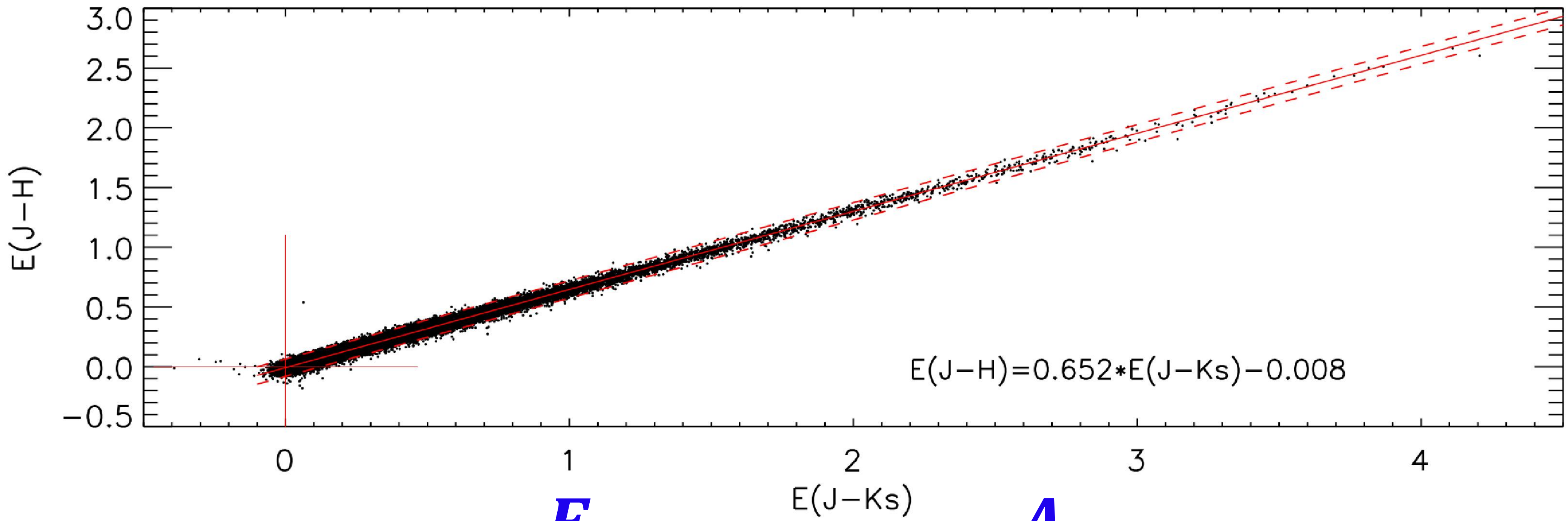


E(Ks−[3.6])=0.260*E(J−Ks)−0.012
A[3.6]/AKs=0.553
E(Ks−[4.5])=0.313*E(J−Ks)−0.009
A[4.5]/AKs=0.461
E(Ks−[5.8])=0.355*E(J−Ks)−0.014
A[5.8]/AKs=0.389
E(Ks−[8.0])=0.334*E(J−Ks)−0.001
A[8.0]/AKs=0.426
E(Ks−[3.6])
E(Ks−[4.5])
E(Ks−[5.8])
E(Ks−[8.0])
E(J−Ks)
E(J−Ks)



E(Ks−S9W)
E(Ks−[24])
E(J−Ks)
E(J−Ks)
E(Ks−S9W)=0.273*E(J−Ks)−0.013
A S9W/A Ks=0.530
E(Ks−[24])=0.428*E(J−Ks)−0.016
A [24]/A Ks=0.264

Result-1: Near-IR



$$\frac{E_{JH}}{E_{JKs}} = 0.652, \frac{A_J}{A_{Ks}} = 2.72, \alpha = 1.79$$

Result-2: Mid-IR

Table 4: The relative extinction in the mid-infrared bands and comparison with other work

	$E_{K_S\lambda}/E_{JK_S}$	A_λ/A_{K_S} ($A_J/A_{K_S}=2.72$)	A_λ/A_{K_S} ($A_J/A_{K_S}=2.52$)	A_λ/A_{K_S} (1)*	A_λ/A_{K_S} (2)*	A_λ/A_{K_S} (3)*	A_λ/A_{K_S} (4)*
WISE/W1	0.238	0.591	0.638			0.621	0.600
WISE/W2	0.312	0.463	0.526			0.500	0.333
WISE/W3	0.269	0.537	0.591				0.867
WISE/W4	0.370	0.364	0.438				
AKARI/S9W	0.273	0.530	0.585				
Spitzer/[3.6]	0.260	0.553	0.605	0.63	0.56		
Spitzer/[4.5]	0.313	0.461	0.524	0.57	0.43		
Spitzer/[5.8]	0.355	0.389	0.460	0.49	0.43		
Spitzer/[8.0]	0.334	0.426	0.492	0.55	0.43		
Spitzer/[24]	0.428	0.264	0.349				

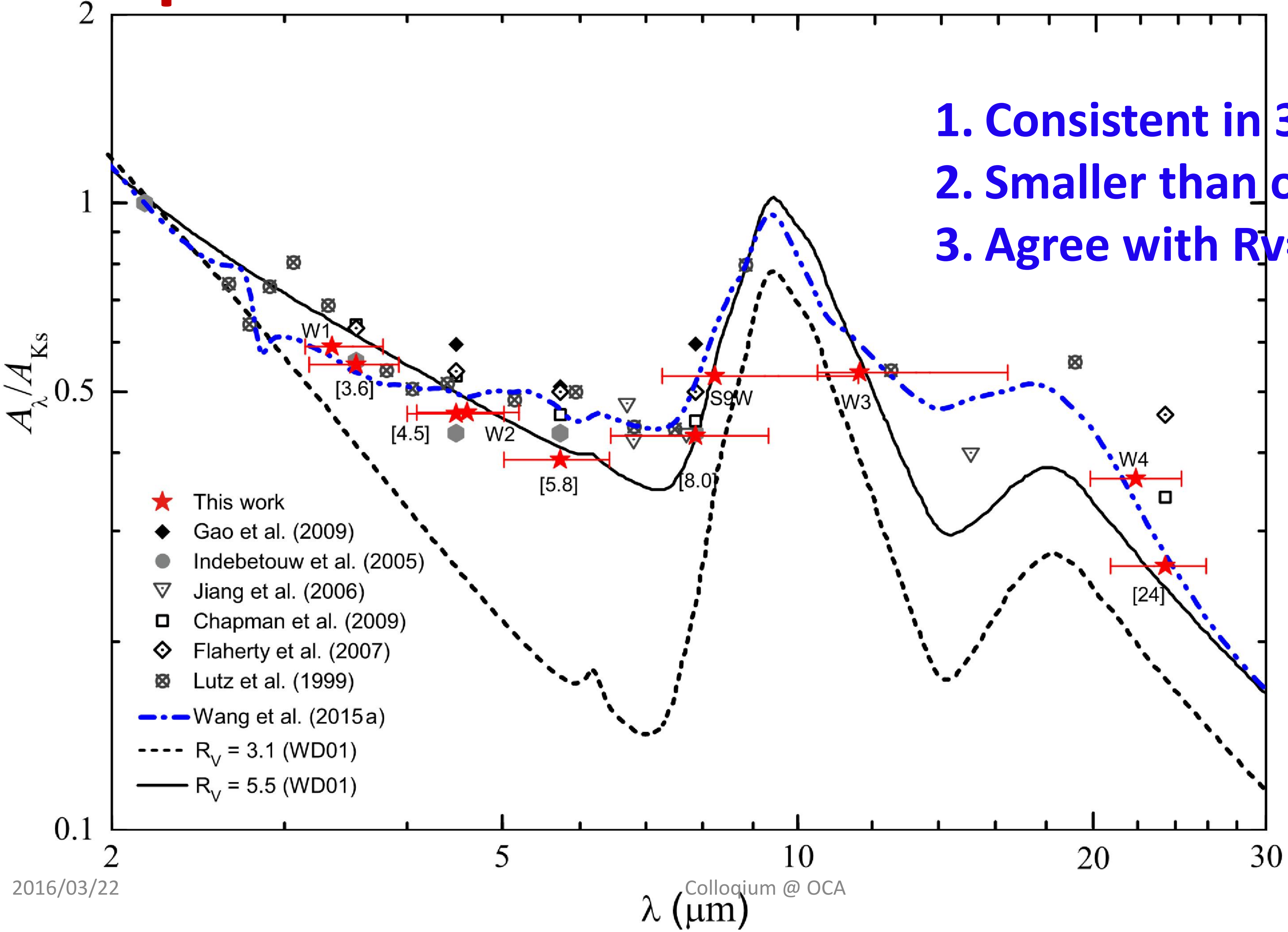
*References: (1) GJL2009; (2)Indebetouw et al. (2005); (3)Yuan et al. (2013); (4)Davenport et al. (2014).

Error analysis: Bootstrap and Monte Carlo: 20000

Table 5: Results of linear fitting (LF), Bootstrap Re-sampling (BR) and Monte Carlo (MC) simulation

	W1	[3.6]	[4.5]	W2	[5.8]	[8.0]	S9W	W3	W4	[24]
$E_{K_S\lambda}/E_{JK_S}$	0.238	0.260	0.313	0.312	0.355	0.334	0.273	0.269	0.370	0.428
σ (LF)	2.260E-04	0.001	0.002	2.560E-04	0.001	0.001	0.009	0.001	0.004	0.016
Mean (BR)	0.238	0.260	0.313	0.312	0.355	0.334	0.274	0.269	0.371	0.428
σ (BR)	5.015E-04	0.001	0.001	5.956E-04	0.001	0.001	0.020	0.002	0.012	0.020
Mean (MC)	0.236	0.259	0.312	0.310	0.354	0.332	0.268	0.265	0.360	0.426
σ (MC)	4.592E-04	0.001	0.001	4.518E-04	0.001	0.001	0.015	0.001	0.010	0.007
Intercept	-0.013	-0.012	-0.009	-0.017	-0.014	-0.001	-0.013	-0.016	-0.036	-0.017
σ (LF)	3.660E-04	0.001	0.001	4.170E-04	0.001	0.001	0.021	0.001	0.010	0.014
Mean (BR)	-0.013	-0.012	-0.009	-0.017	-0.014	-0.001	-0.013	-0.016	-0.036	-0.017
σ (BR)	1.596E-04	0.001	0.002	1.808E-04	0.001	0.001	0.006	3.873E-04	0.002	0.018
Mean (MC)	-0.012	-0.011	-0.007	-0.031	-0.012	0.001	-0.012	-0.015	-0.034	-0.015
σ (MC)	1.889E-04	0.001	0.001	1.897E-04	0.001	0.001	0.004	3.619E-04	0.003	0.008

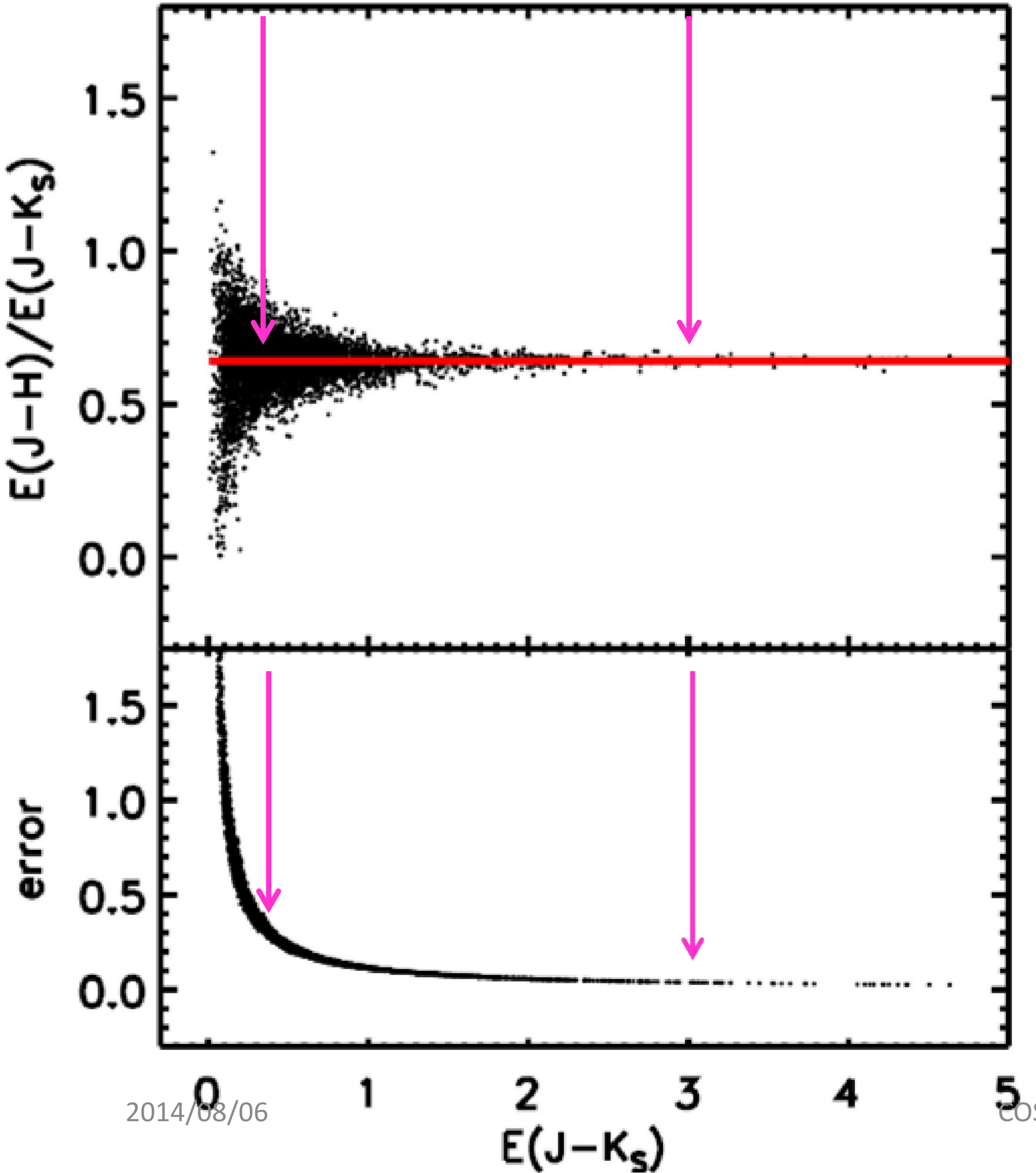
Comparison with other results



1. **Consistent in 3-8um, flat**
2. **Smaller than others**
3. **Agree with Rv=5.5 (WD01)**

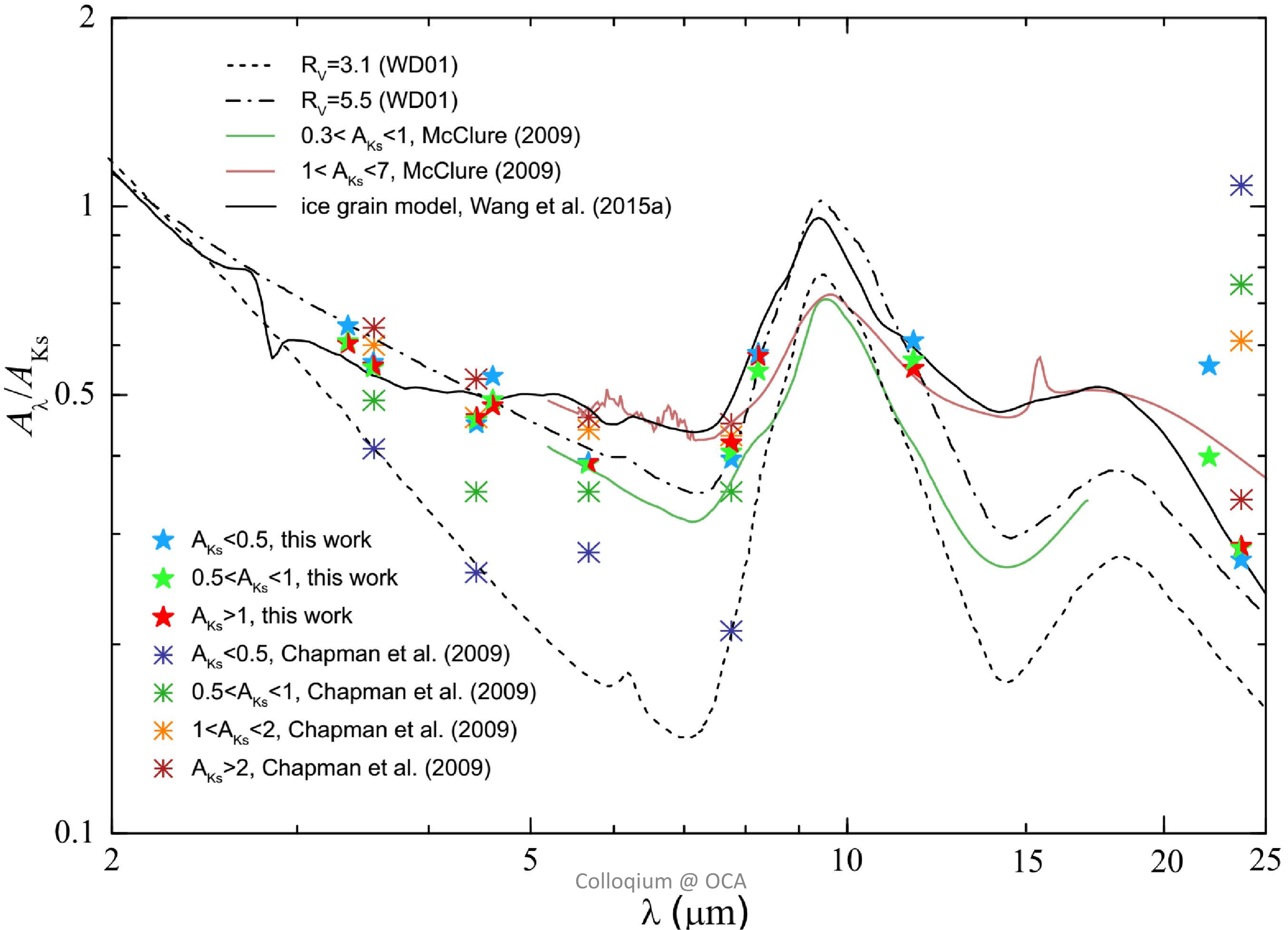
Variation or not?

Universality of the Near-IR Extinction Law



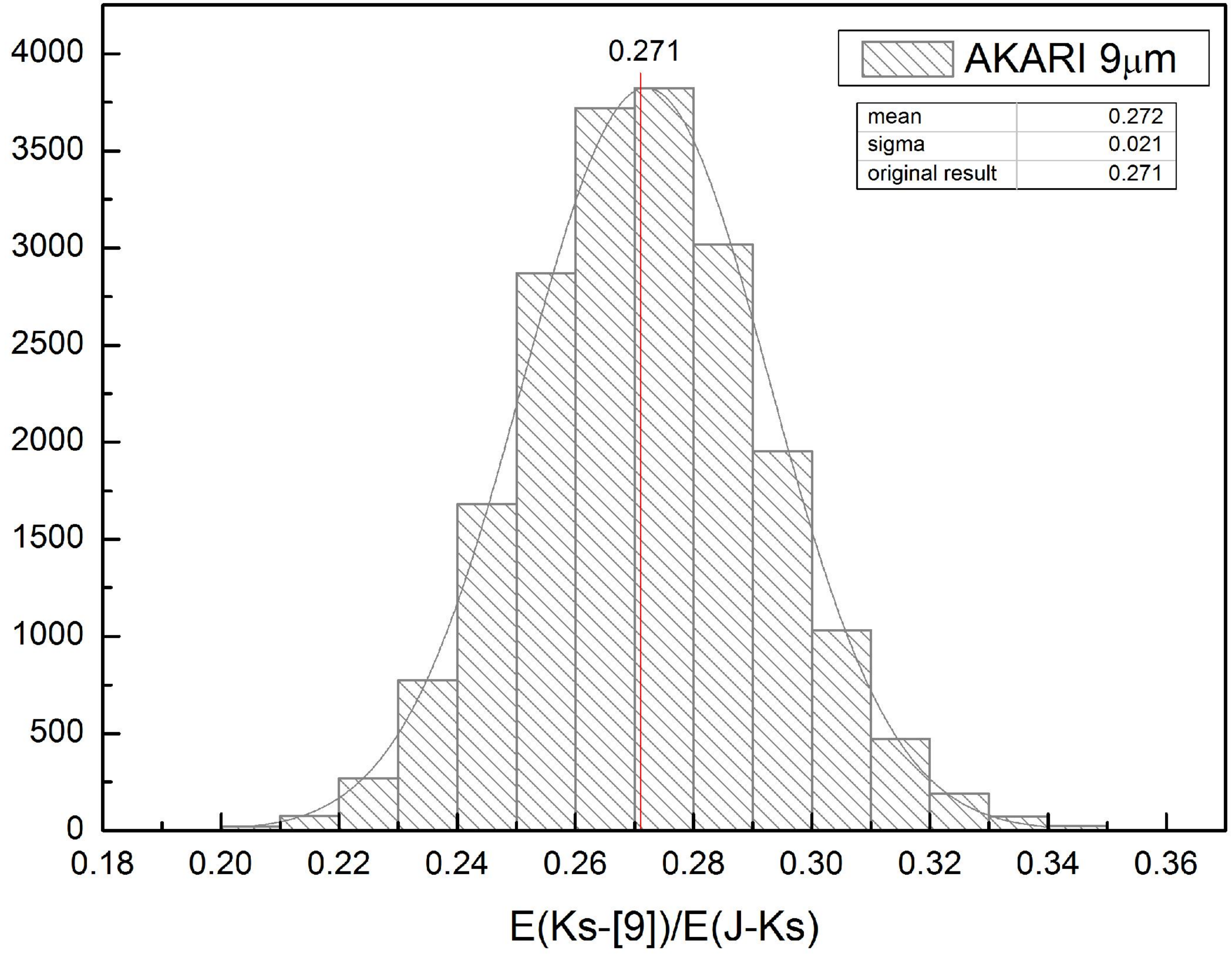
- $E(J-H)/E(J-K_S)$=0.652
- If a star have $E(J-K_S)$=0.3
  - $[E(J-H)/E(J-K_S)]$err = 0.38
- If a star have $E(J-K_S)$=3
  - $[E(J-H)/E(J-K_S)]$err = 0.038
- At $E(J-K_S)$=0.1
  - the error reaches 1.14
- **The dispersion can be fully explained by the error**
- **Pearson correlation coefficient of 0.03**

No apparent variation in the mid-IR with the extinction depth A_{K_S}



Error Analysis

- Bootstrap resampling test
  - Introduced by Efron (1979)
  - Generates a large number of datasets, each with N data points randomly drawn from the original data.
  - 20000 times Bootstrap for each pair of color excess
- Monte-Carlo simulation
  - To investigate the influence of photometric error
  - A sample is selected within the photometric error of each source
  - 20000 times for each band.



The slope distribution of 20000 times Bootstrap resample test of $E(K_S\text{-}[9])/\ E(J\text{-}K_S)$.
The red line indicates the linear fitting result

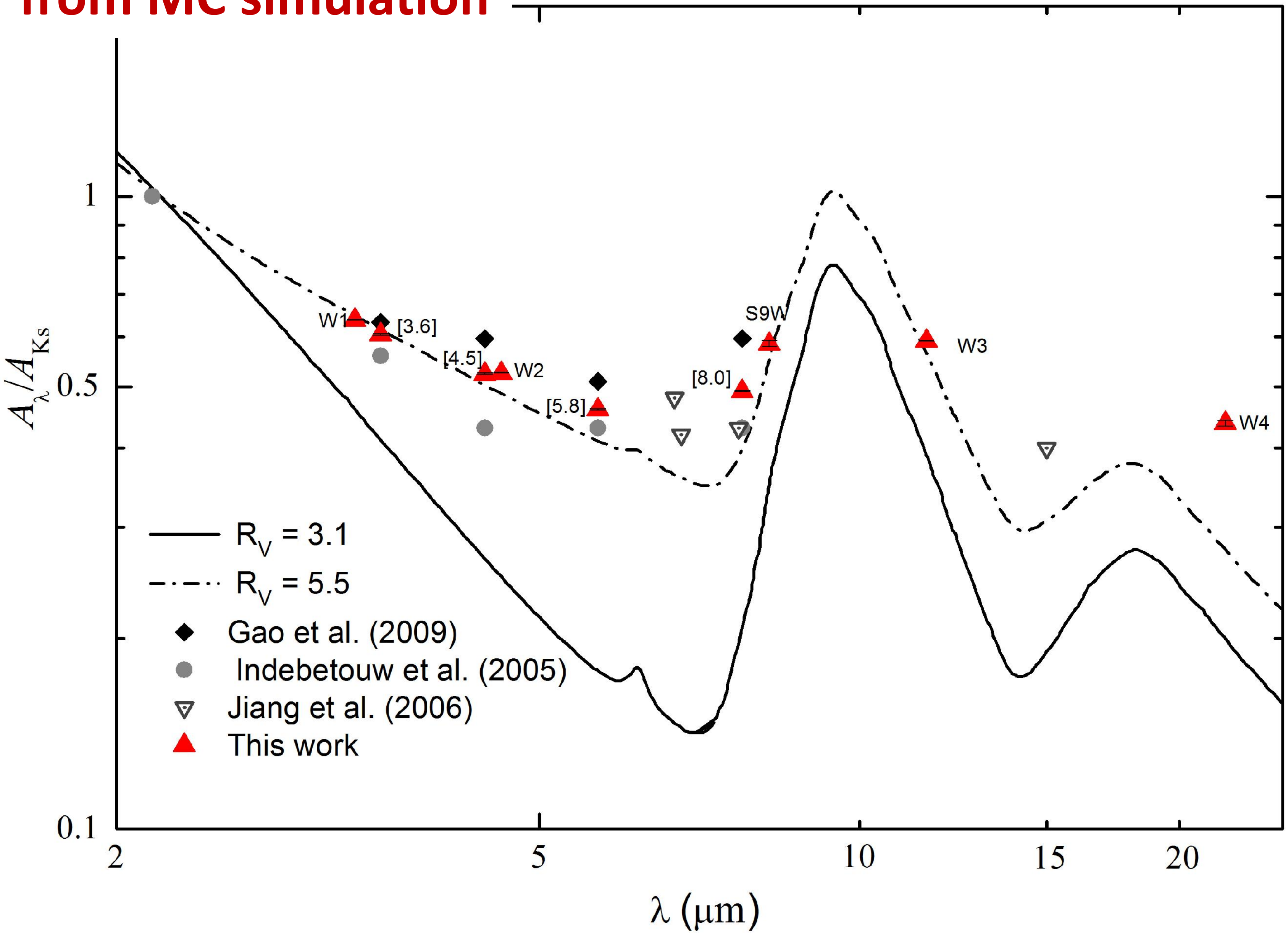
The slope $E(K_S\text{-}\lambda)/ E(J\text{-}K_S)$

	W1	W2	[8.0]	[9]	W3	W4
	3.4μm	*4.6μm*	*8.0μm*	*9μm*	*12μm*	*22μm*
$E(K_S\text{-}\lambda)/ E(J\text{-}K_S)$	0.240	0.313	0.335	0.271	0.277	0.388
Bootstrap Mean	0.240	0.313	0.335	0.272	0.270	0.371
Bootstrap σ	5.253E-04	5.929E-04	0.001	0.021	0.002	0.012
Monte-Carlo Mean	0.238	0.310	0.333	0.266	0.265	0.359
Monte-Carlo σ	4.580E-04	4.518E-04	0.001	0.013	0.001	0.010
Linear fitting σ	0.030	0.033	0.051	0.159	0.060	0.075

The intercept

	W1	W2	[8.0]	[9]	W3	W4
	3.4μm	*4.6μm*	*8.0μm*	*9μm*	*12μm*	*22μm*
Intercept	-0.028	-0.031	-0.003	-0.019	-0.021	-0.040
Bootstrap Mean	-0.028	-0.031	-0.003	-0.019	-0.021	-0.038
Bootstrap σ	1.739E-04	1.897E-04	0.001	0.006	4.031E-04	0.002
Monte-Carlo Mean	-0.028	-0.031	-0.002	-0.017	-0.019	-0.036
Monte-Carlo σ	1.936E-04	1.897E-04	0.001	0.004	3.720E-04	0.003
Linear fitting σ	0.030	0.033	0.051	0.159	0.060	0.075

With error from MC simulation



Summary

- With the stellar parameters of G- and K-type giants from the APOGEE spectroscopic survey, we precisely determined the relative extinction in the 2MASS, AKARI, WISE and Spitzer/IRAC photometric bands, consistent with the *R*v=5.5 curve except in the W4 band.
- A quite complete mid-Infrared extinction Law of the MW is derived, with the extinction at 9μm, 12μm, and 22μm for the first time to characterize the silicate extinction profile.
- No apparent variation is found of the infrared extinction law.

- The relations between infrared intrinsic colors and T_{eff} are derived for G- and K-type giants.

Dust modelling: very large grains

- Wang, Li & Jiang 2015, ApJ 811, 38
  Very large interstellar grains as evidenced by the mid-infrared extinction
- Wang, Li & Jiang 2015, MNRAS 454, 569
  The interstellar oxygen crisis, or where have all the oxygen atoms gone?
- Wang, Li & Jiang 2014, PSS 100, 32
  Modeling the infrared interstellar extinction

Post-Doctoral Position

- https://jobregister.aas.org/node/53477
- Interstellar/Circumstellar Dust
- Deadline to Apply for Job: June 1, 2016

Merci Beaucoup