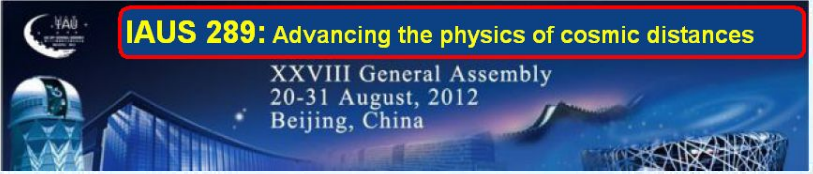


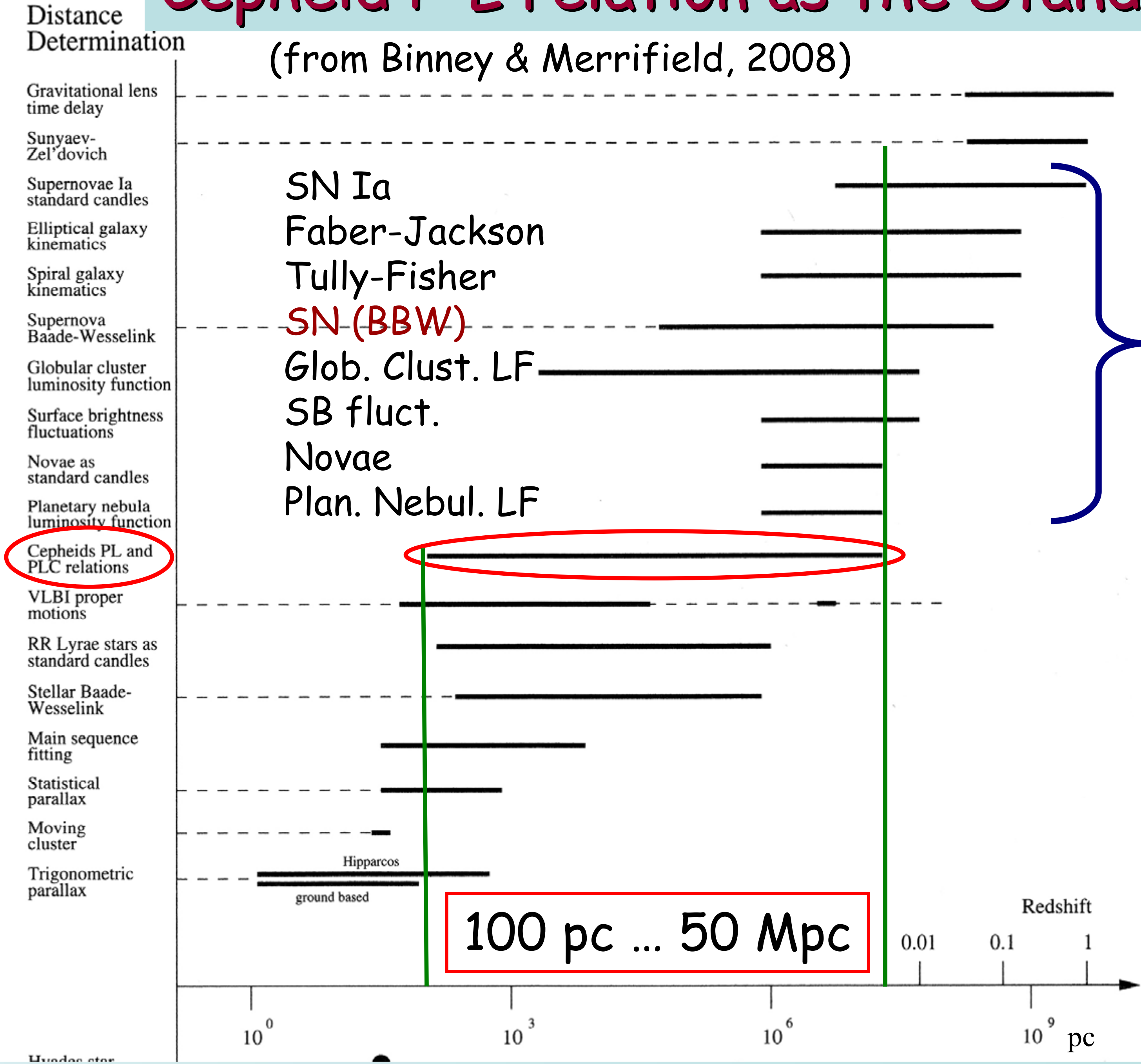
The Baade-Becker-Wesselink technique and the fundamental astrophysical parameters of Cepheids

by Alexey S. Rastorguev
(Lomonosov Moscow State University,
Sternberg Astronomical Institute,
Moscow, Russia)

with Andrey K. Dambis, Marina V. Zabolotskikh,
Leonid N. Berdnikov and Natalia A. Gorynya

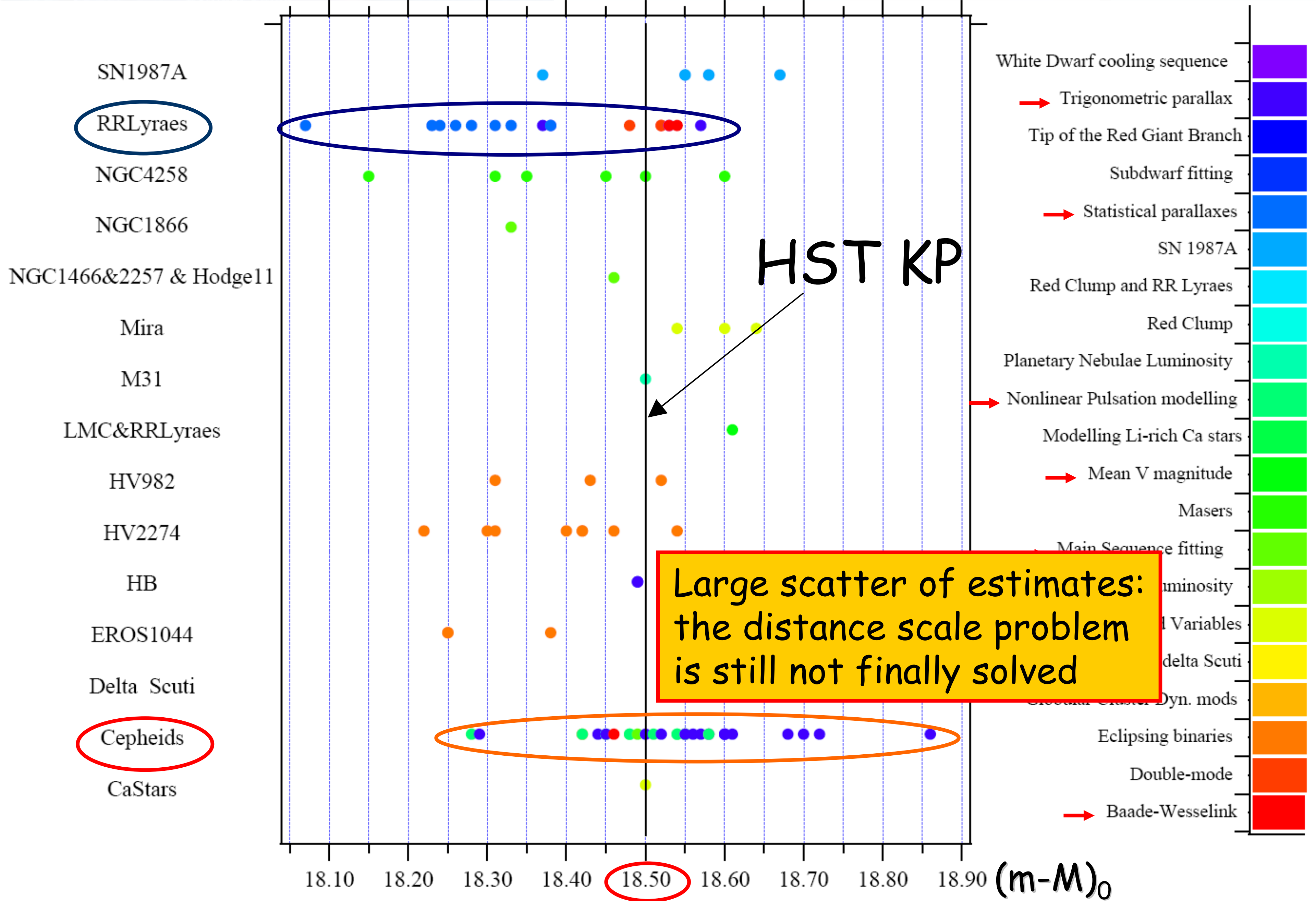
Cepheid P-L relation as the Standard Candle

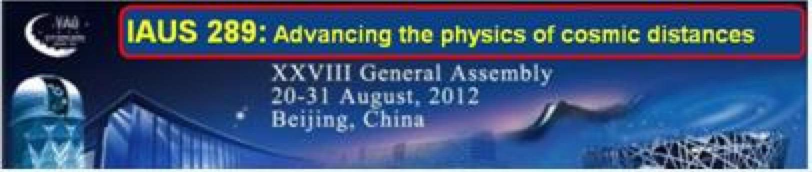
(from Binney & Merrifield, 2008)



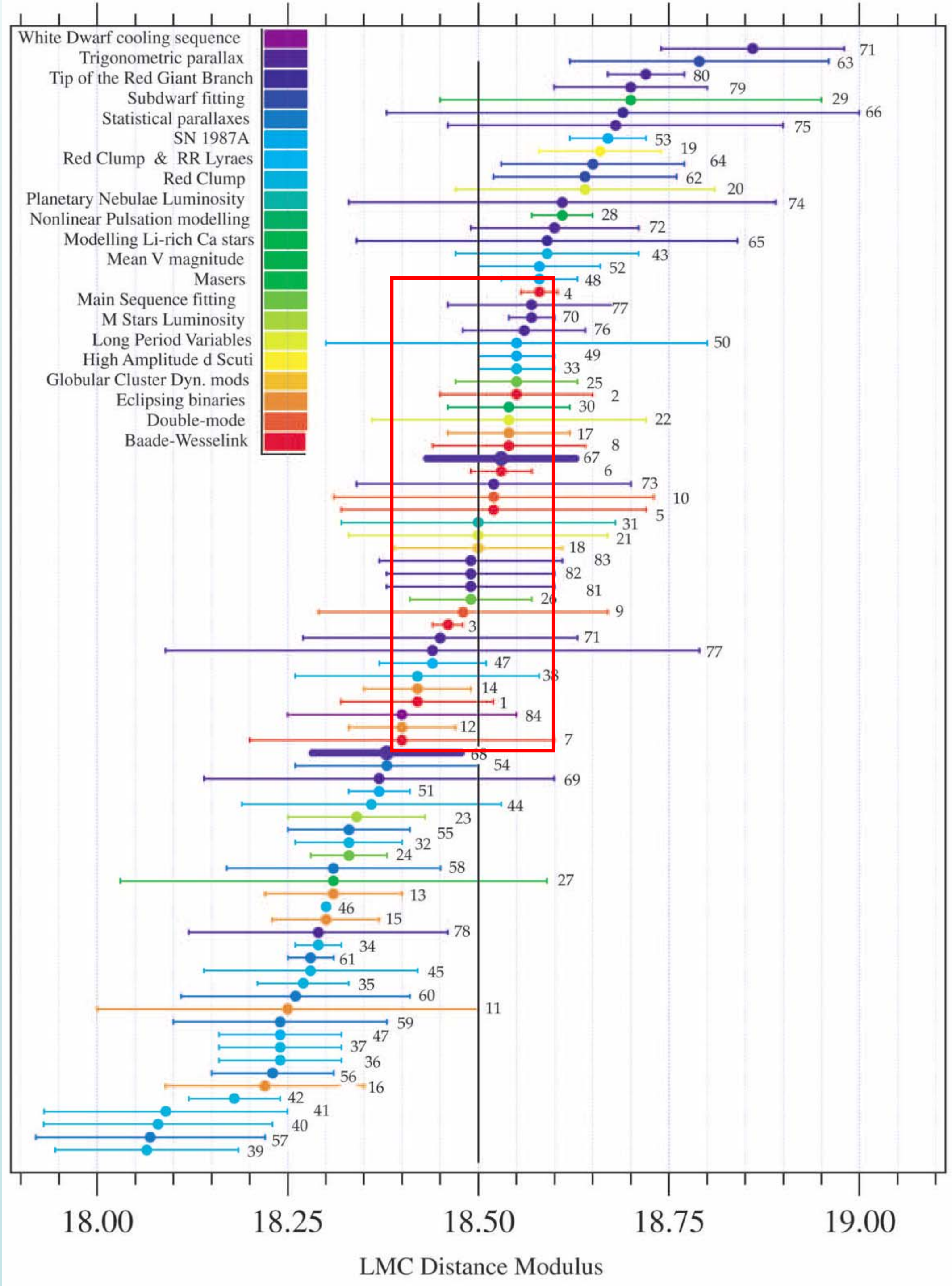
Cepheids are still used for calibration of these secondary methods

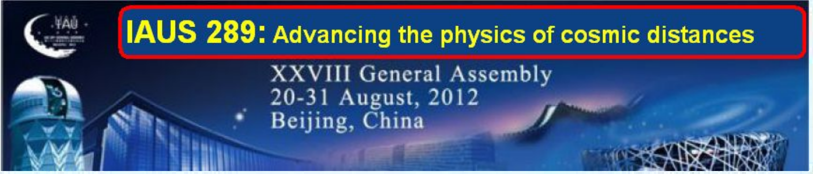
Distance scale testing: LMC





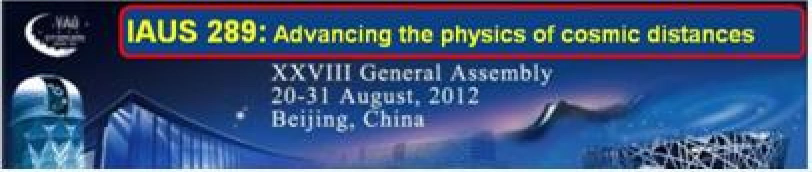
- G.Fritz Benedict et al., 2002): a summary of all the distance measurements to LMC galaxy, performed by 21 different methods, with "mean" value close to $(m-M)_0 \approx 18.50^m$
- Ranking by value
- **BBW method (red) gives closest estimates !**





- Cepheids: most “popular” Standard Candles

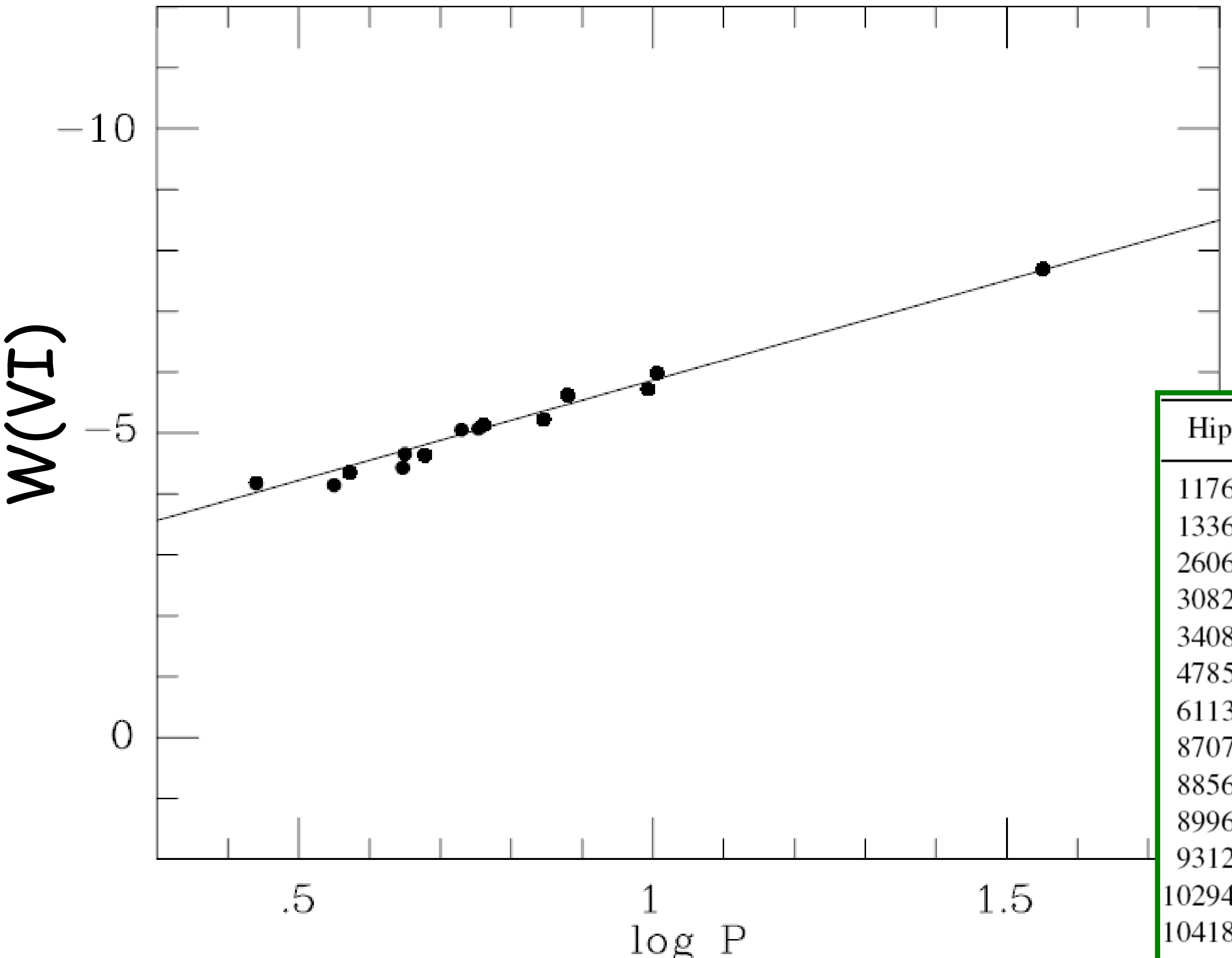
- Aims of this talk: to discuss
  - Cepheid’s **reddenings** and **intrinsic colors** and the problems with calibration of Cepheid’s luminosities
  - the methods used to derive main Cepheid’s **astrophysical parameters**
  - **new facilities** of the BBW technique



I. Wesenheit index

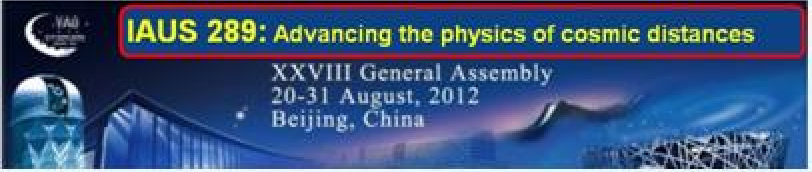
$$W(VI) = \alpha \cdot \lg P + \beta = M_V - \gamma \cdot (V-I)_0$$

Road to P-L relation



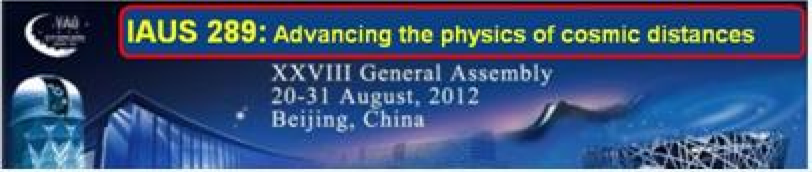
F. Van Leeuwen et al. (2007): W(VI) for 14 Cepheids with most reliable parallaxes from HIPPARCOS and HST FGS3:

Hipp	Name	π	W(VI)	M_W
11767	α UMi	7.72 ± 0.12	0.754	-5.08 ± 0.03
13367	SU Cas	2.57 ± 0.33	0.440	-4.18 ± 0.28
26069	β Dor	3.26 ± 0.14	0.993	-5.72 ± 0.09
30827	RT Aur	2.31 ± 0.19	0.572	-4.35 ± 0.18
34088	ζ Gem	2.74 ± 0.12	1.006	-5.98 ± 0.10
47854	l Car	2.03 ± 0.16	1.551	-7.70 ± 0.17
61136	BG Cru	2.23 ± 0.30	0.678	-4.63 ± 0.29
87072	X Sgr	3.17 ± 0.14	0.846	-5.22 ± 0.10
88567	W Sgr	2.30 ± 0.19	0.880	-5.62 ± 0.18
89968	Y Sgr	2.13 ± 0.29	0.761	-5.13 ± 0.30
93124	FF Aql	2.64 ± 0.16	0.650	-4.66 ± 0.13
102949	T Vul	2.06 ± 0.22	0.647	-4.43 ± 0.23
104185	DT Cyg	2.19 ± 0.33	0.550	-4.15 ± 0.33
110991	δ Cep	3.71 ± 0.12	0.730	-5.05 ± 0.07



- Cepheid's normal colors should be used to convert Wesenheit index, like W_{VI}, to the absolute magnitude:
- $$M_V = W_{VI} + \gamma \cdot (V-I)_0$$
- The use of "mean" *Period – Color* relation instead of individual normal colors may affect P-L-C slope and zero-point

- (M.Groenewegen & R.Oudmaijer, "Multi-colour *PL*-relations of Cepheids in the HIPPARCOS catalogue and the distance to the LMC", A&A V.356, P.849, 2000;
- A.Sandage et al. "The Hubble constant: a summary of the HST program for the luminosity calibration of type Ia SuperNovae by means of Cepheids", ApJ V.653, P.843, 2006;
- F.van Leeuwen et al. "Cepheid parallaxes and the Hubble constant", MNRAS V.379, P.723, 2007)

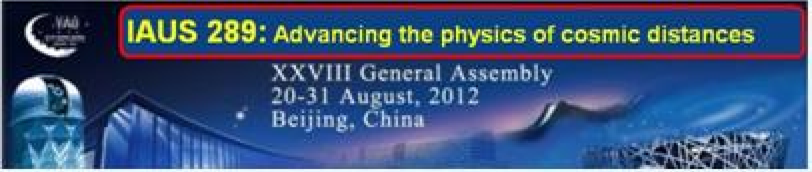


II. Absorption law

- Cepheid's reddenings found from multicolor photometric data: independent tool to derive absorption law in different directions (Fitzpatrick, Massa 2007) on the sky through color excess ratios like

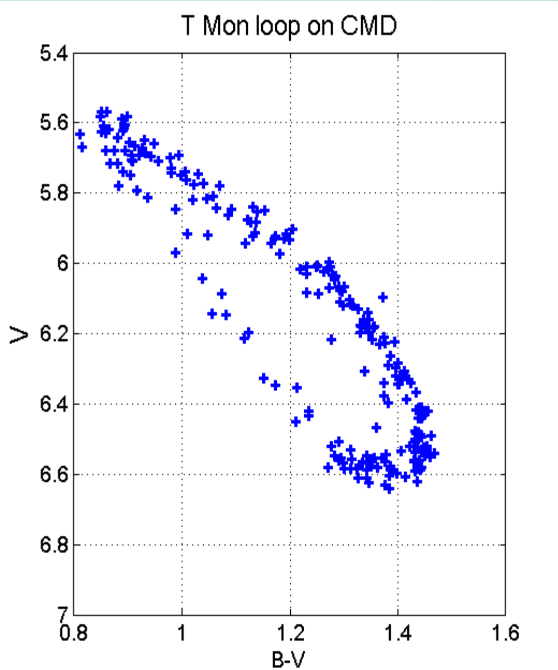
$$\frac{E(\lambda_1-\lambda_2)}{E(B-V)}: \quad \frac{E(V-I)}{E(B-V)}, \quad \frac{E(V-K)}{E(B-V)} \text{ etc.} \Rightarrow \mathrm{A}(\lambda)$$

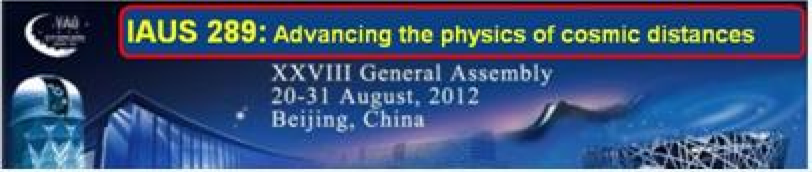
- Can affect $E(\lambda_1-\lambda_2) \Rightarrow E(B-V)$ transformation
- Can affect the ratio $R_V = A_V / E(B-V)$ accepted and Cepheid distance and luminosity estimates
- Color excess – critical Cepheid's parameter



BBW technique: effective tool for PLC calibration

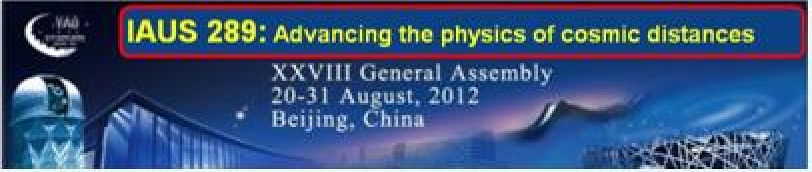
- Early BBW history:
- W.Baade (Mittel.Hamburg.Sternw. V.6, P.85, 1931);
- W.Becker (ZAph V.19, P.289, 1940);
- A.Wesselink (Bull.Astr.Inst.Netherl. V.10, P.468, 1946)
- Used radii difference and ratios derived from Cepheid's radial velocities and loop on CMD:





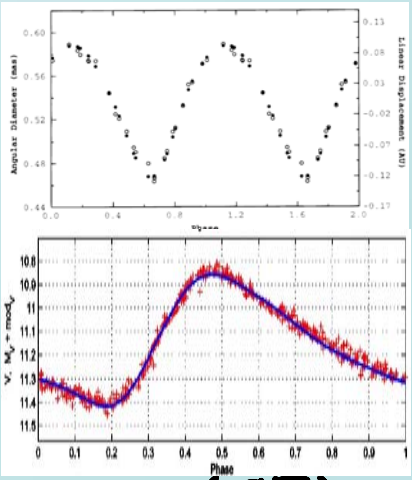
Modern BBW history

- SB (Surface Brightness): pulsation radii variations + (F_λ-CI_0) calibrations + Color Excess (Barnes, Evans, 1976; Turner & Burke, 2002; Sandage et al., 2004) – most popular so far
- ML (Maximum Likelihood, or Light Curve Modelling): pulsation radii variations + (T_{eff} – BC - CI_0) linear presentation (Balona, 1977)
- CORS (Caccin, Onnembo, Russo, Sollazzo, 1980): SB variant with variable (CI_0 - F_λ) calibrations
  - CORS modification: (Molinaro et al., 2011) – uses theoretical (CI_0 – F_λ) calibrations

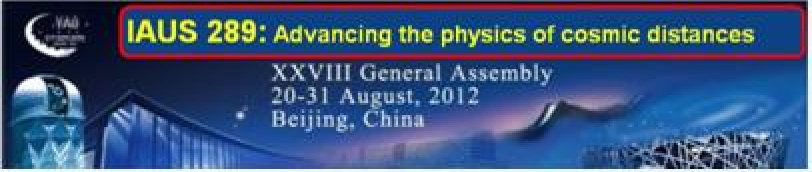


Common physical base of SB and ML

- Stefan-Boltzmann law: $L_{bol} \sim R_{pls}^{2} \cdot T_{eff}^{4}$
- SB: "surface brightness parameter"– normal color relation (F_{λ} - CI_0)
- ML: effective temperature – bolometric correction – normal color relations (T_{eff} – BC - CI_0)
- **Differences:**
- SB: fitting ΔR (radius change calculated by the integration of the radial velocity curve) and the angular size
- ML: light curve modelling

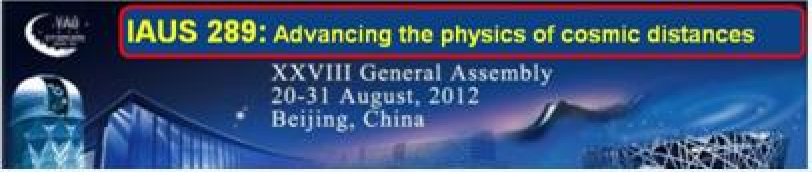


- Common practice: prior data on Color Excess (CE) taken from multicolor photometry, spectra or Period-Color relations



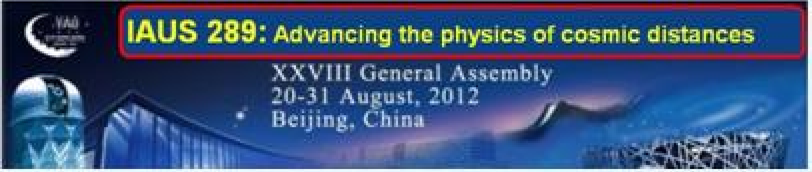
Reddening data:

- Dean, Warren, Cousins (1978) - BVI_C
- Fernie (1987, 1990) – uvbyβ, BVI_C
- Fernie (1994) – the same color at maximum light
- Fernie et al. (1995) – database on CE (17 sources) http://www.astro.utoronto.ca/DDO/research/cepheids/table_colourexcess.html
- Berdnikov et al. (1996, 2000) – P-C relations derived from multicolor ($BVR_CI_CJHK_S$) P-L relations
- Andrievsky et al. (2002a, b) – spectroscopy (T_{eff})
- Laney, Caldwell (2007) – BVI_C, with differences in [Fe/H]
- Kovtyukh et al. (2008) - spectroscopy (T_{eff})
- Kim, Moon, Yushchenko (2011) – uvbyβ + photosphere models
- **All estimates use proper (native) calibrations**

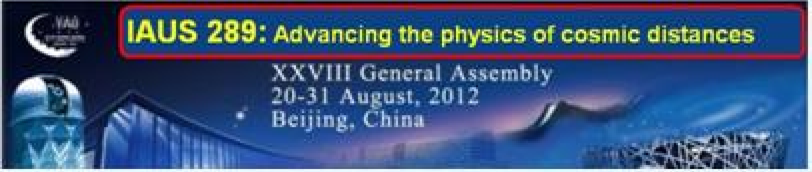


Problems with reddenings found by different methods:

- Large (up to 0.2^m) scatter in individual CE estimates
- Large width of the Instability Strip
- Different P-L-C relations for different IS crossings
- Differences in metallicity
- Unrecognized first-overtone pulsators



- Madore & Freedman (1991) – HST Key Project #1 (Hubble constant and Universal distance scale):
- "... any attempt to disentangle the effects of differential reddening and true color deviations within the instability strip must rely first on a precise and *thoroughly independent* determination of the intrinsic structure of the period-luminosity-color relation.
- ... **independent reddenings and distances to individual calibrator Cepheids must be available**".
- The search for new ideas on CE estimates is still actual, and **this was our primary aim**



BBW new version: an extension of L. Balona's (1977) ML technique - Rastorguev A.S., Dambis A.K.

"Classical Cepheids: Yet another version of the Baade-Becker-Wesselink method", Astrophysical Bulletin, V.66, pp.47-53, 2011

$$L_{bol} = 4\pi\sigma T_{eff}^{4} R^{2}$$

$$R = \langle R \rangle + \Delta R$$

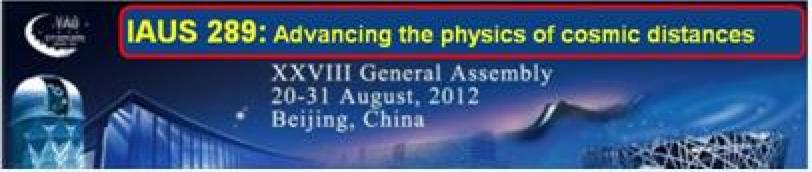
$$\frac{L_{bol}}{L_{bol}^{0}} = \frac{T_{eff}^{4}}{T_{0}^{4}} \left(\frac{R}{R_{0}} \right)^{2}$$

$$M_{bol} - M_{bol}^{0} = -2.5 \log \frac{L_{bol}}{L_{bol}^{0}} =$$

$$= -10 \log T_{eff} + 10 \log T_{0} - 5 \log \frac{R}{R_{0}}$$

Substitute for $M_{bol} = M_{V} + BC(V)$

and $M_{V} = V - 5 \cdot \lg D(pc) + 5 - A_{V}$



After simple conversion built the Light Curve Model:

Apparent distance modulus

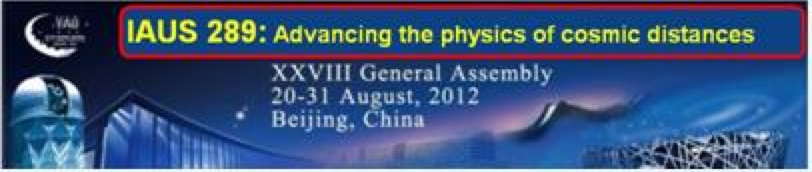
$$V = -5 \cdot \log \frac{\langle R \rangle + \Delta R}{R_0} - \Psi(CI_0) + Y,$$

where constant $Y = 10 \cdot \log T_{eff}^{0} + M_{bol}^{0} + A_V + (m - M)_0$

$\Psi(CI_0)$ - (known) calibration for

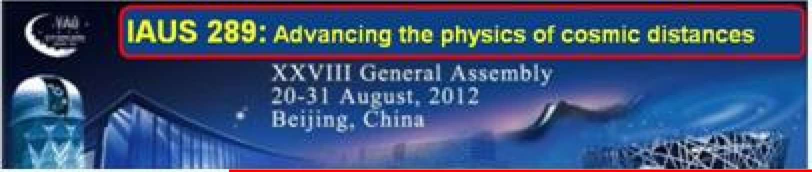
$\Psi = 10 \cdot \log T_{eff} + BC(V)$ on normal color,

$CI_0 = CI - CE$



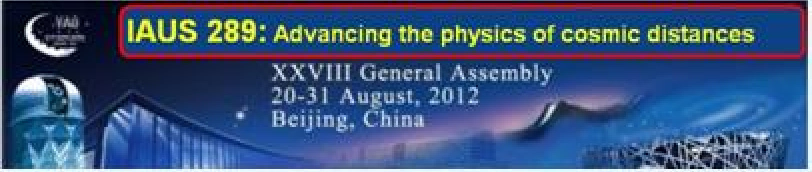
Key point of dereddening:

- Use of modern multicolor calibrations CI_0 – $\log T_{eff}$ – BC(V), for (known) function $\Psi(CI_0) = 10 \log T_{eff} + BC(V)$, taken as power series on normal color, CI_0 (with [Fe/H] and lg g terms included, if possible)
- Advantages:
  - Needs only one calibration (very small, < 1-3%, contribution of BC(V) to $\Psi(CI_0)$ value), whereas SB technique is based on two calibrations (SB parameter + normal color calibration)
  - Self-consistent and independent estimate of CE



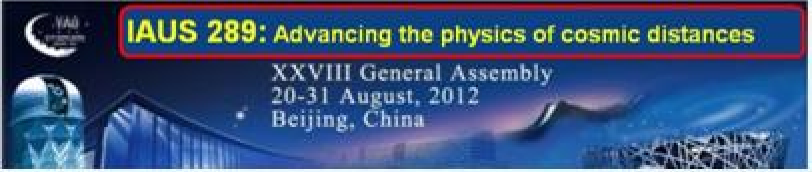
$$V = -5 \cdot \log \frac{\langle R \rangle + \Delta R}{R_0} - \Psi(CI - CE) + Y$$

- Our new light curve model includes <R>, CE, and constant Y (it includes known Sun parameters and unknown apparent distance modulus) as unknown parameters
- Color Excess can be found independently, along with other astrophysical parameters, like mean radius <R>, distance D, weighted mean absolute magnitude $\langle M_V \rangle_I$, weighted mean effective temperature $\langle T_{eff} \rangle_I$ and mean normal color, say $\langle B_0 - V_0 \rangle_I$ (or any other)



Observational data used:

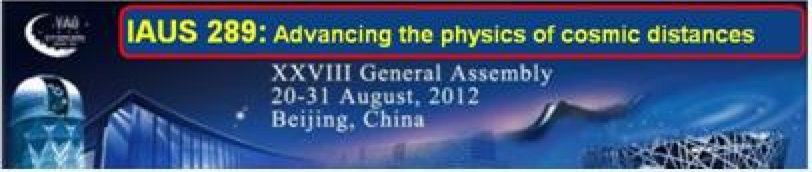
- **Multicolor ($UBVR_CI_C$) photometric observations** of Cepheids (Berdnikov et al. 1982-2011; ~200000 measurements) + $UBVR_CI_CJHK_S$ database of SAI MSU (Moscow)
- **Radial velocity measurements**, taken with CORAVEL-type spectrograph by Moscow team (Gorynya et al. 1987-2012; ~11000 measurements of 170 northern Cepheids) with characteristic accuracy from 0.3 to 1 km/s
- **Key point:** Our photometric and radial velocity measurements are nearly synchronous, thus preventing any phase shifts, due to evolutionary period changes, which can lead to large (up to 30%) systematical errors in calculated radii. Period changes were taken into account by special investigation.



log T_{eff} - BC calibrations checked:

- Flower (1996): I-II, III-V, empirical + radii
- Bessel, Castelli, Plez (1998): theoretical energy distribution for different lg g
- Alonso, Arribas, Martinez-Roger (1999): [Fe/H], lg g, IRFM + radii
- Sekiguchi, Fukugita (2000): [Fe/H], lg g, IRFM
- Ramirez, Melendez (2005): III, [Fe/H], IRFM
- Biazzo, Frasca, Catalano, Marilli (2007): IRFM
- Gonzalez Hernandez, Bonifacio (2009): IRFM
- Worthey, Lee (2011): empirical UBVRIJHK

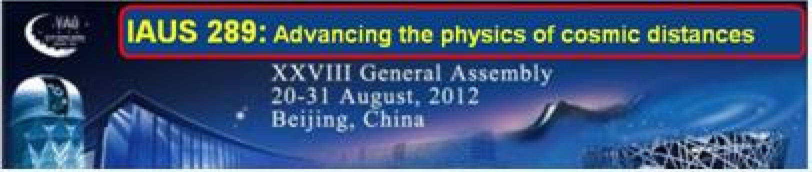
- For BC(V)-$(B-V)_0$, only Flower (1996) calibration was used
- IRFM = InfraRed Flux Method



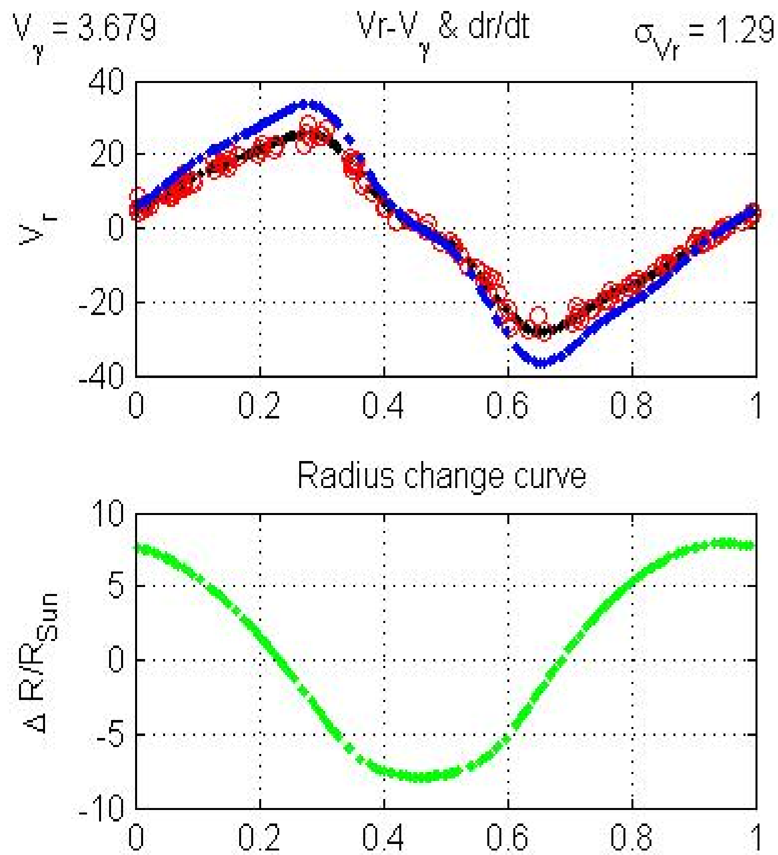
Method's testing

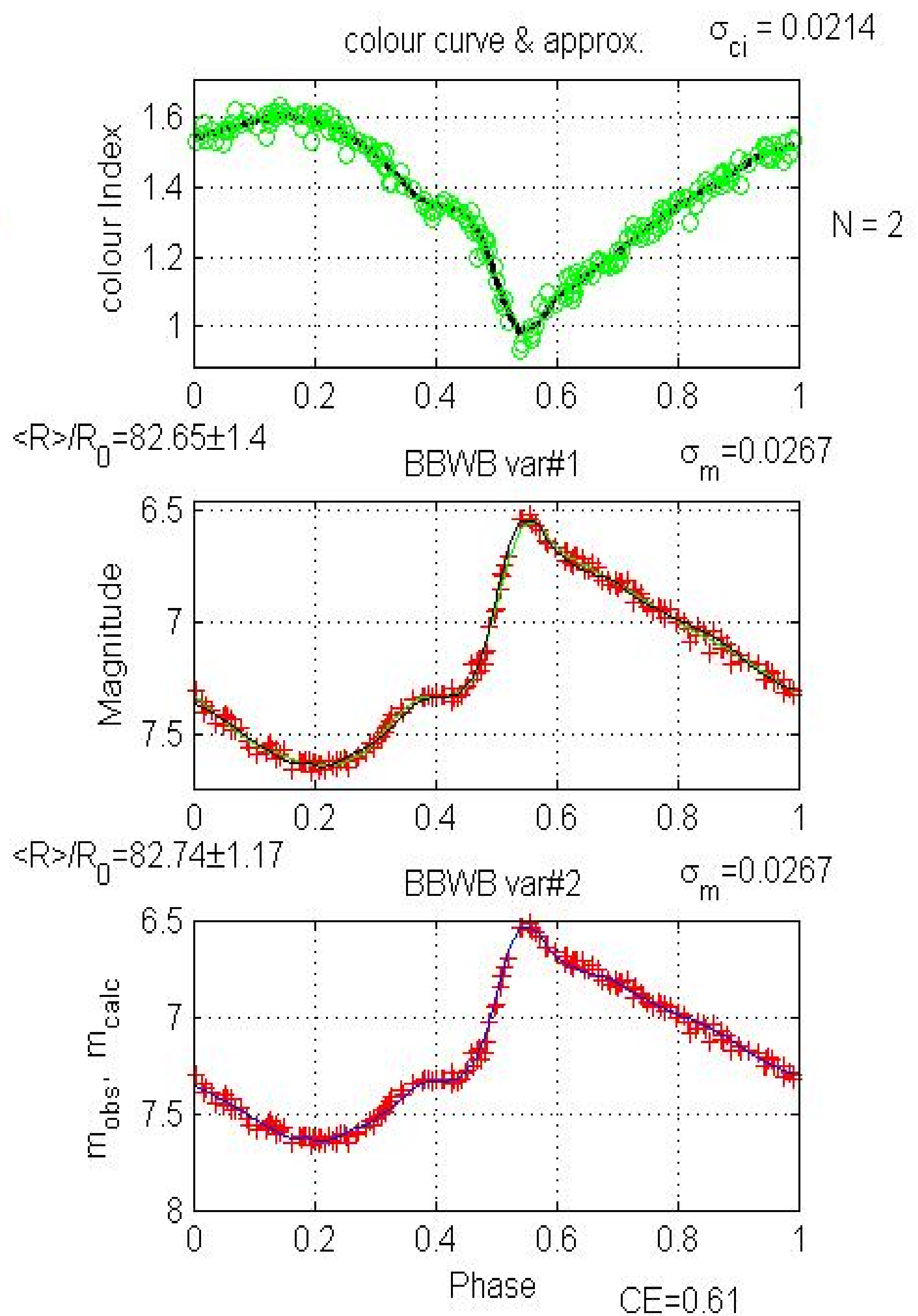
- Cepheids – known members of some open star clusters, with E(B-V) found by isochrone fitting technique: SZ Tau, CF Cas, U Sgr, DL Cas, GY Sge; and some bright single Cepheids with most reliable CEs: general agreement found

Cepheid	*Cluster*	E_{B-V}	E_{B-V}(WEBDA)	$<R>/R_\odot$	M_V
SZ Tau	NGC 1647	0.40±0.02	0.370	57.0±7.0	−4.32±0.25
CF Cas	NGC 7790	0.54±0.02	0.531	46.7±0.9	−3.41±0.05
U Sgr	IC 4725	0.50±0.03	0.475	54.2±1.8	−3.90±0.08
DL Cas	NGC 129	0.47±0.05	0.548	69.3±1.6	−4.12±0.06
GY Sge	Anon OB	1.44±0.05	1.29±0.06 (*)	208±11	−6.27±0.15

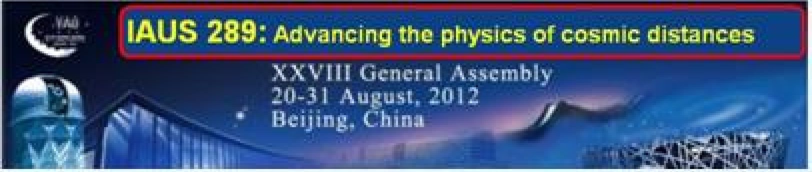


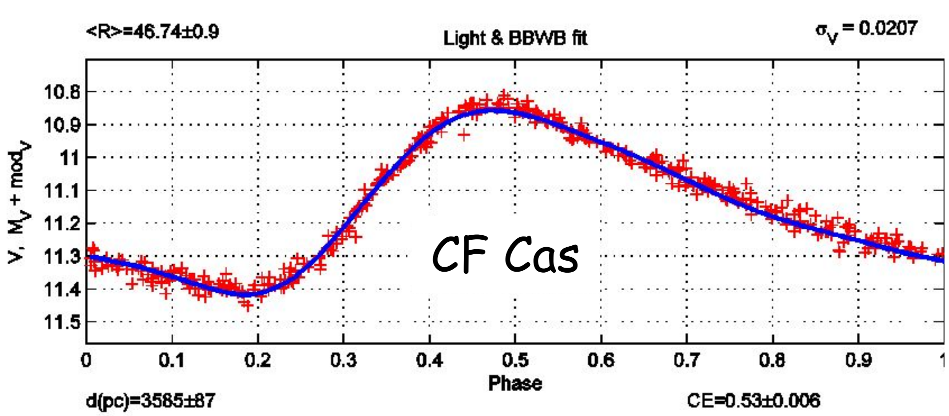
- High stability of calculated E(B-V) (in weak dependence on Projection Factor value, data smoothing technique and solution method) was revealed: internal accuracy σ_{CE}~0.01^m for best calibrations used
- The explanation: high sensitivity of model light curve amplitude to color shift by CE to high temperatures: $\Delta V \sim 10 \log T_{eff}$
- External accuracy (comparing different calibrations) estimated as $\sigma_{CE} \sim 0.03 \ldots 0.05^m$

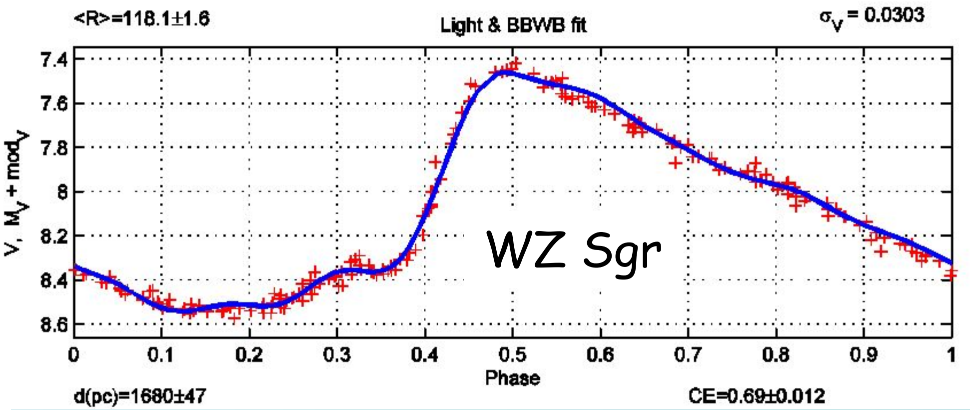


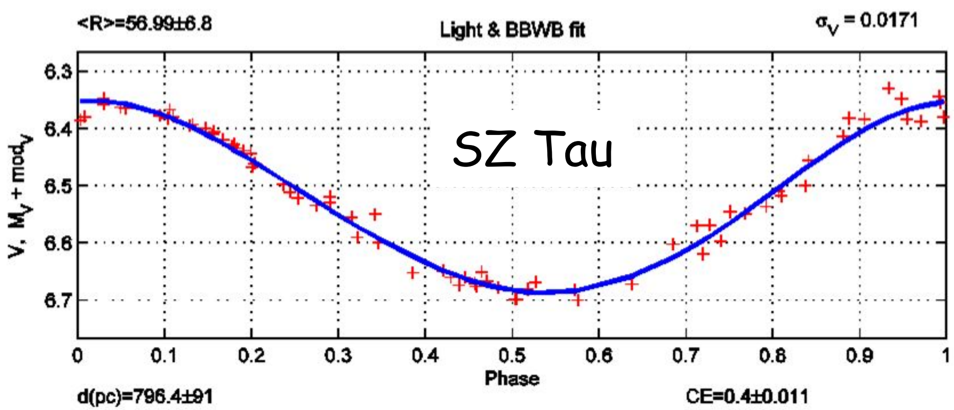


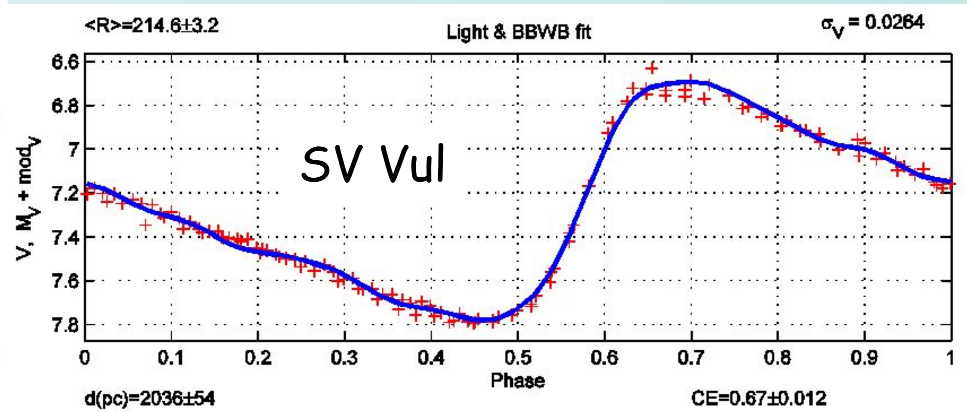
Example of light curve modelling for TT Aql Cepheid: very good fit

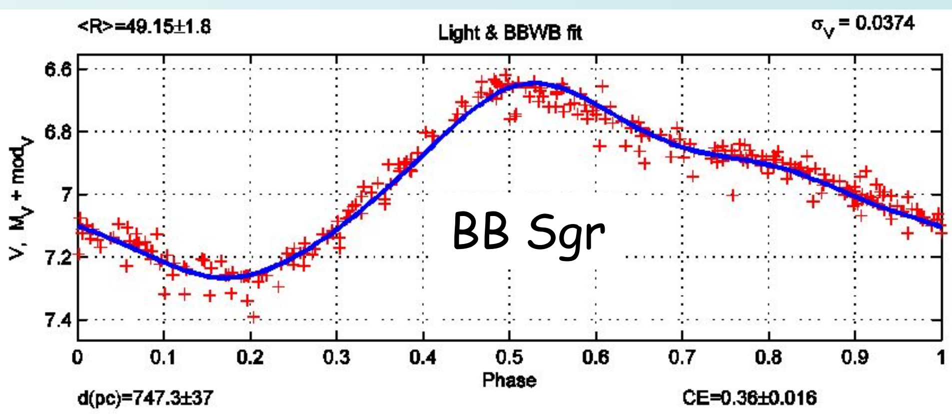




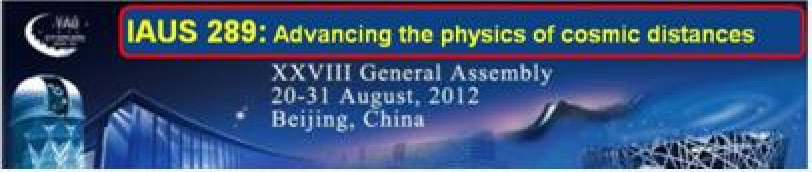








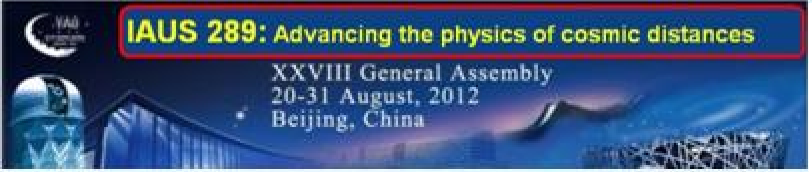
Some other examples of the light curve fitting



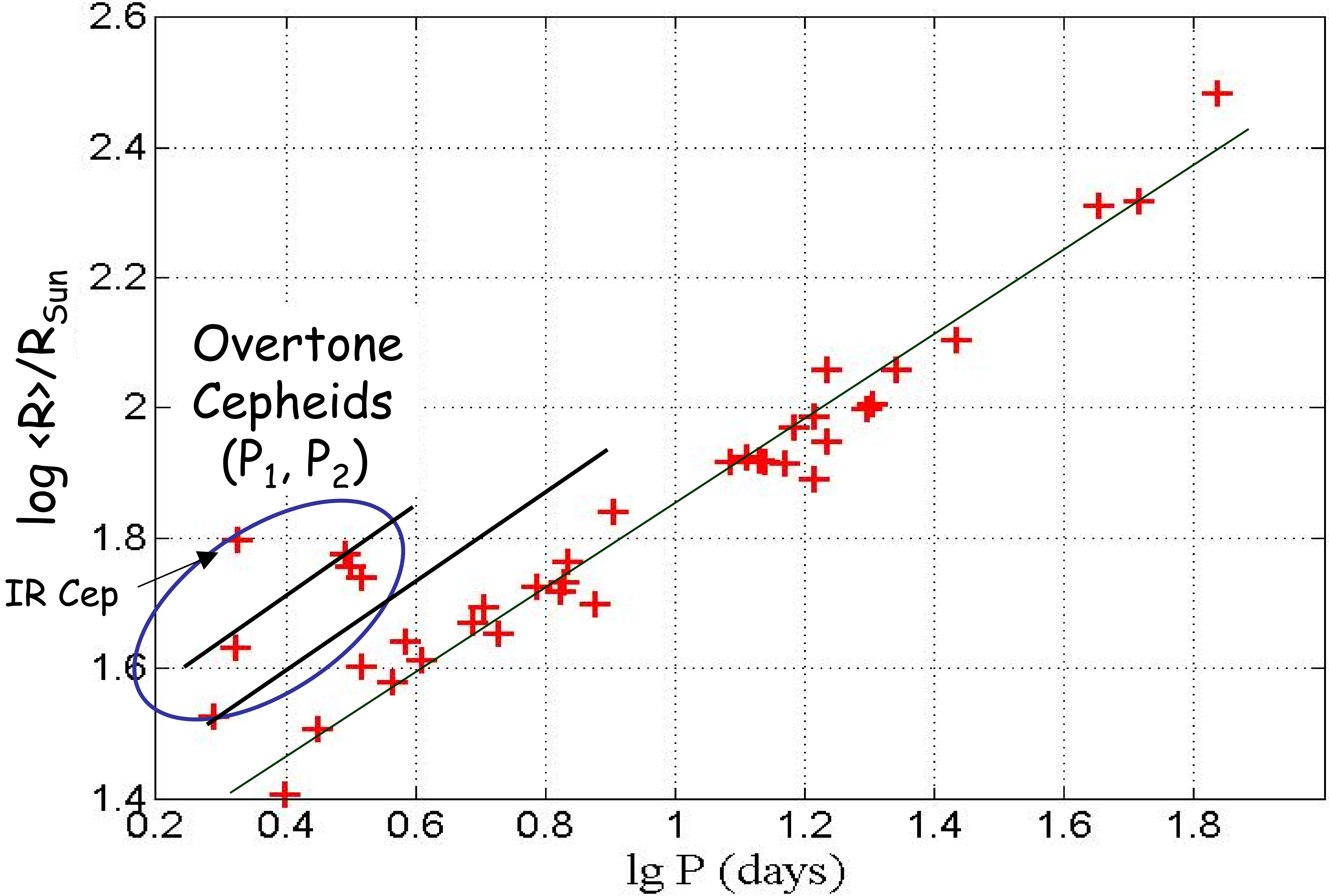
"Best Fit" T_{eff} calibrations:

- #1: Flower, 1996 - empirical
- #2: Bessel, Castelli, Plez, 1998 - theoretical
- #3: Worthey, Lee, 2011 - empirical

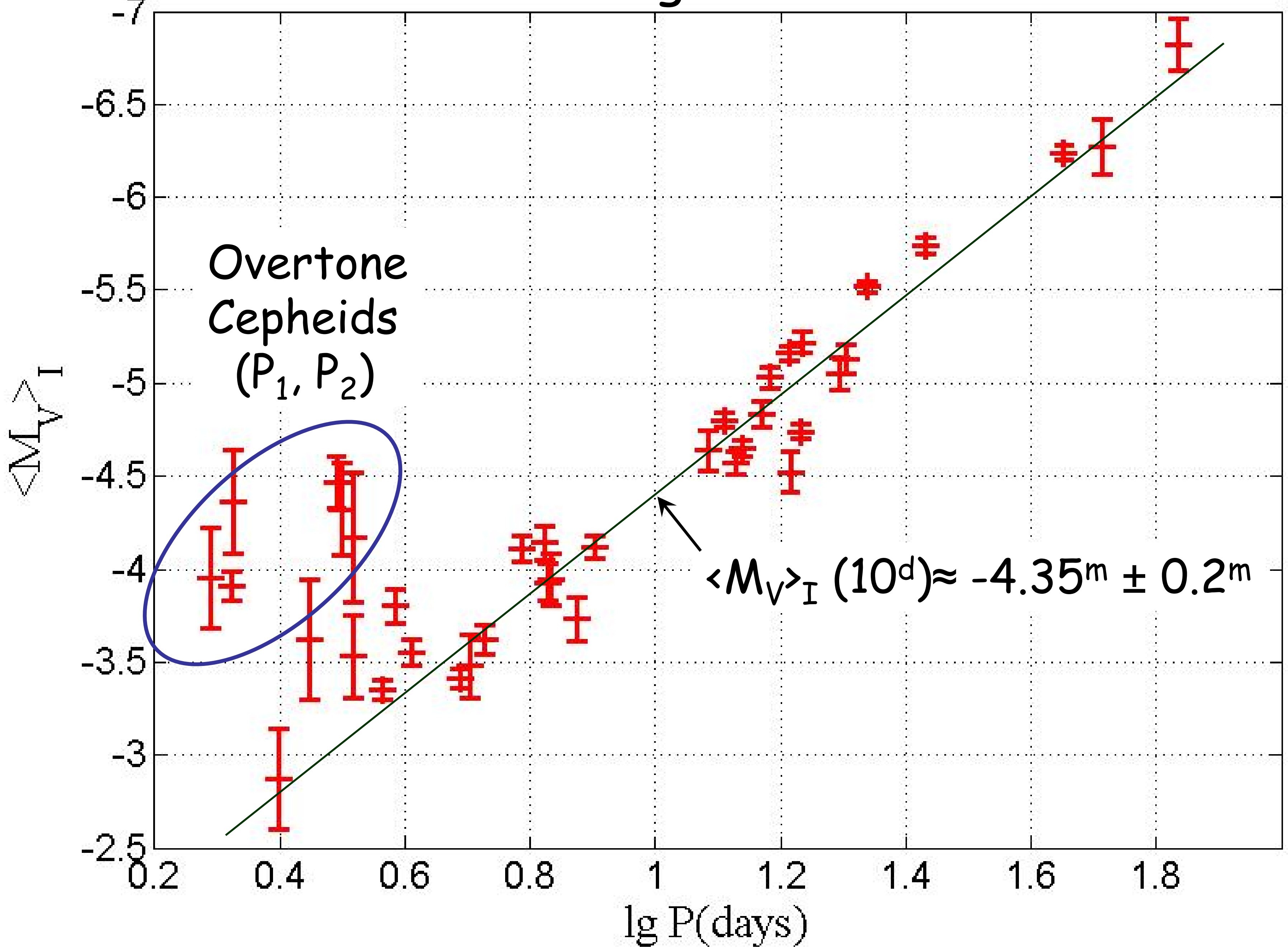
- "Worse" calibration: Gonzalez Hernandez, Bonifacio, 2009 (too high slope; derived mainly not from supergiants data)

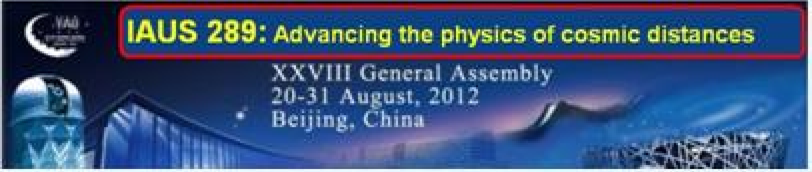


log P - <R> relation as most reliable diagnostic tool of the pulsation mode



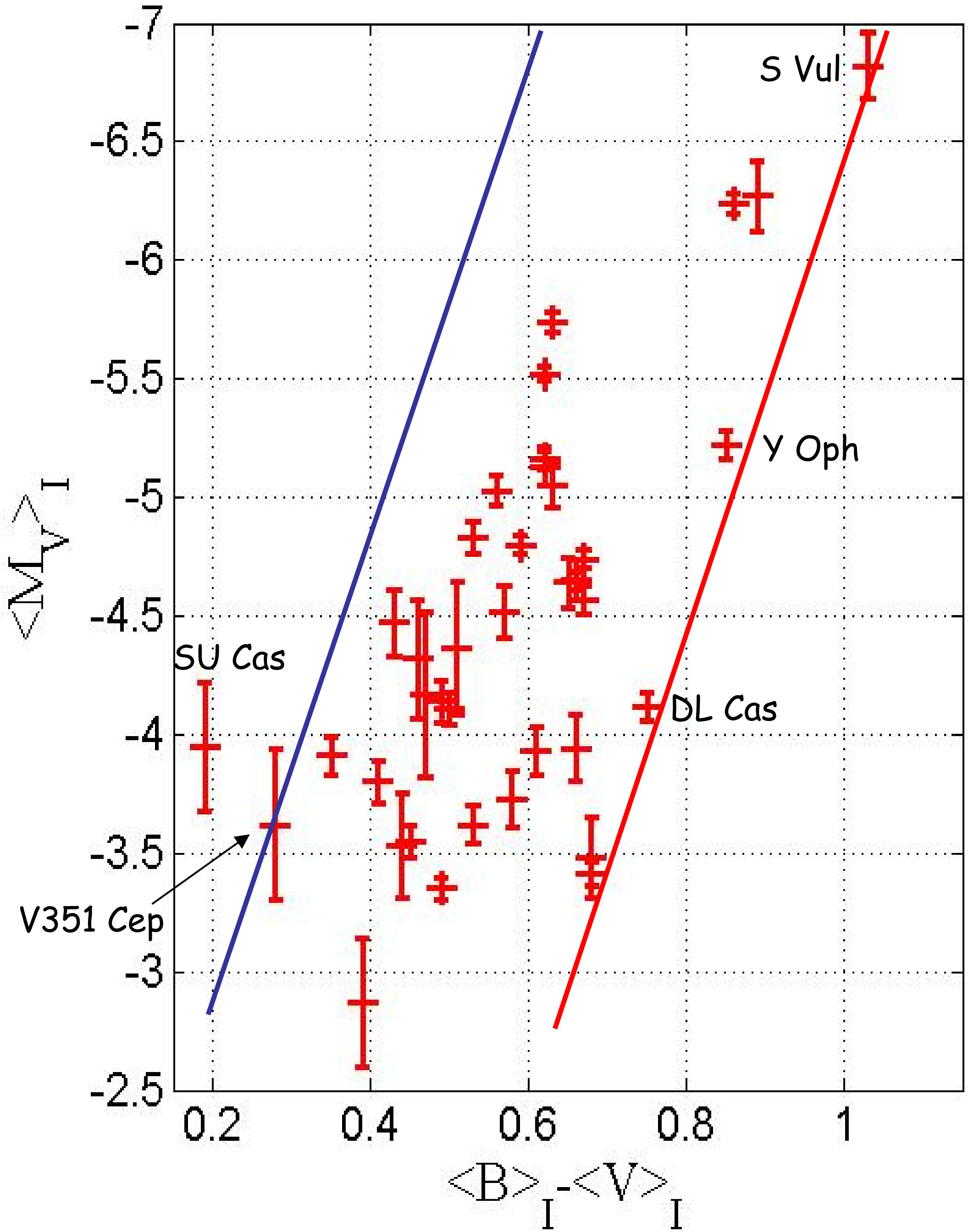
log P – L relation

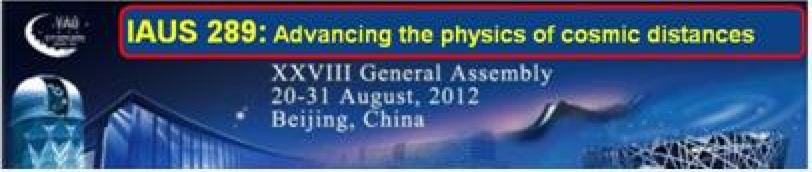




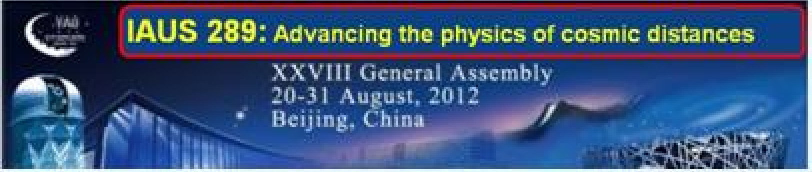
- Instability Strip for Cepheids with independent E(B-V) estimates made by new BBW variant

- Low amplitudes Cepheids:
- S Vul, Y Oph, DL Cas, SU Cas, V351 Cep
- IS edge ?



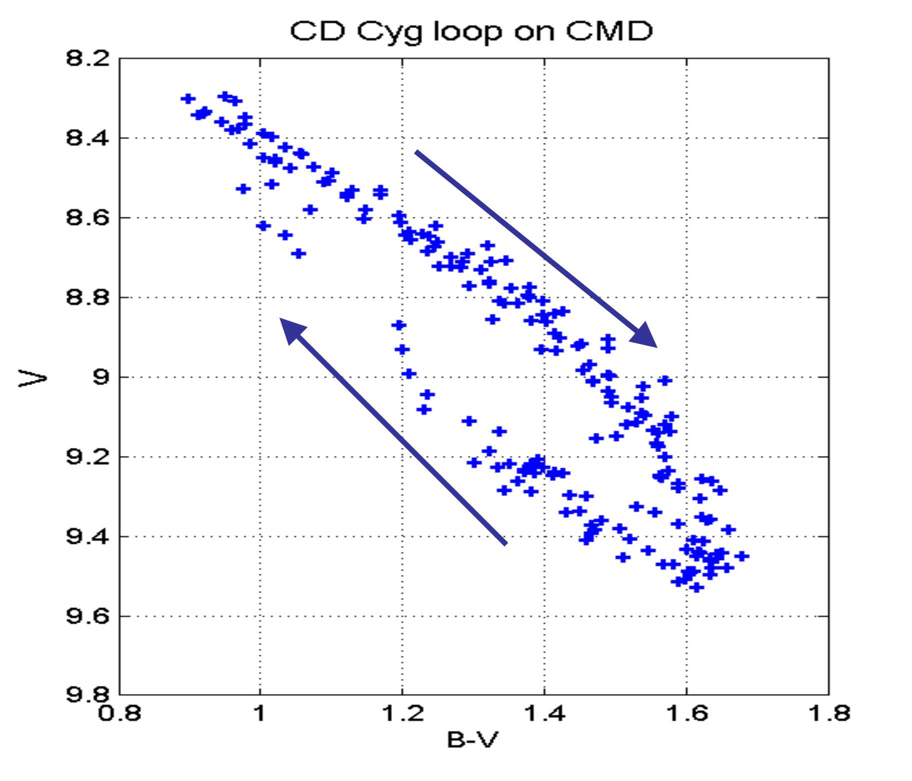


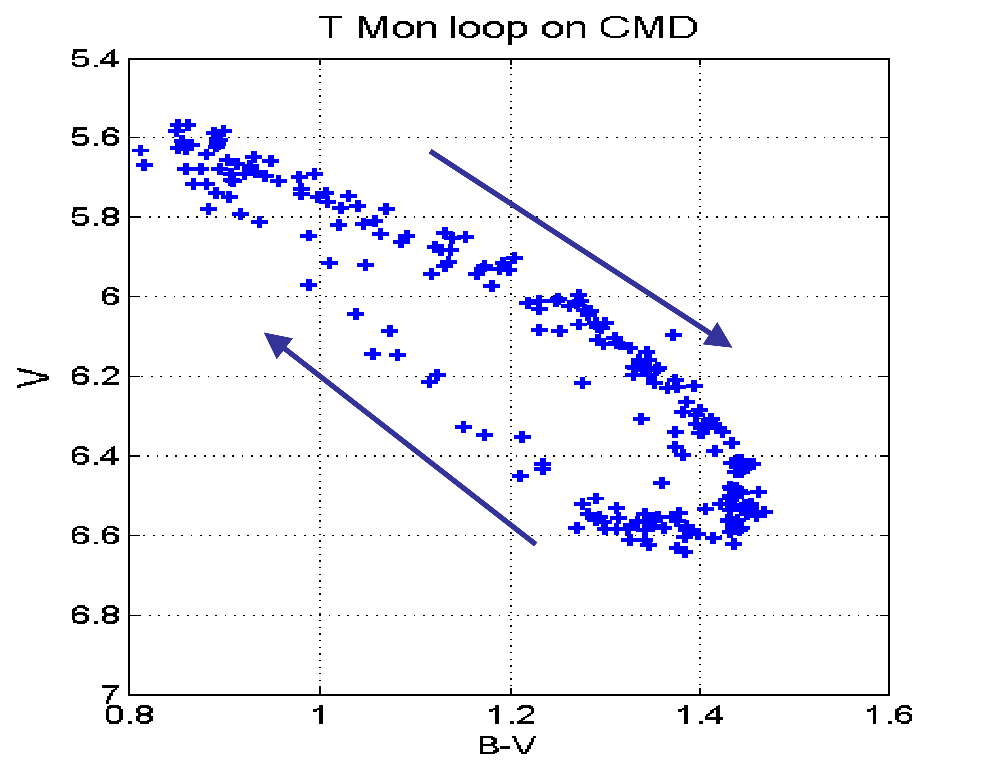
- New version of Balona's technique to a lesser extent, than Surface Brightness variant, uses calibrations of main astrophysical characteristics
- It seems to be perspective tool, and could be considered as the independent attempt to estimate the Cepheid's color excess
- The work is yet in progress, and short-range plans include CE estimates from all multicolor data available

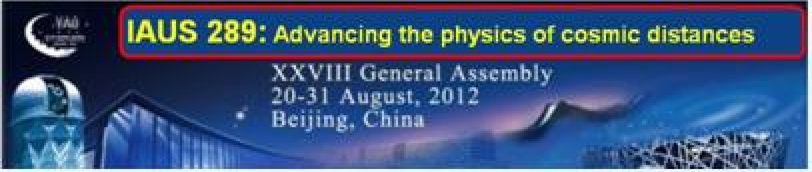


Natural extension: scientific justification

- The only Cepheid on CMD loop "replaces" stellar population with different colors, brightness, but with the same mass, distance, color excess, metallicity and nearly the same gravity (log g)







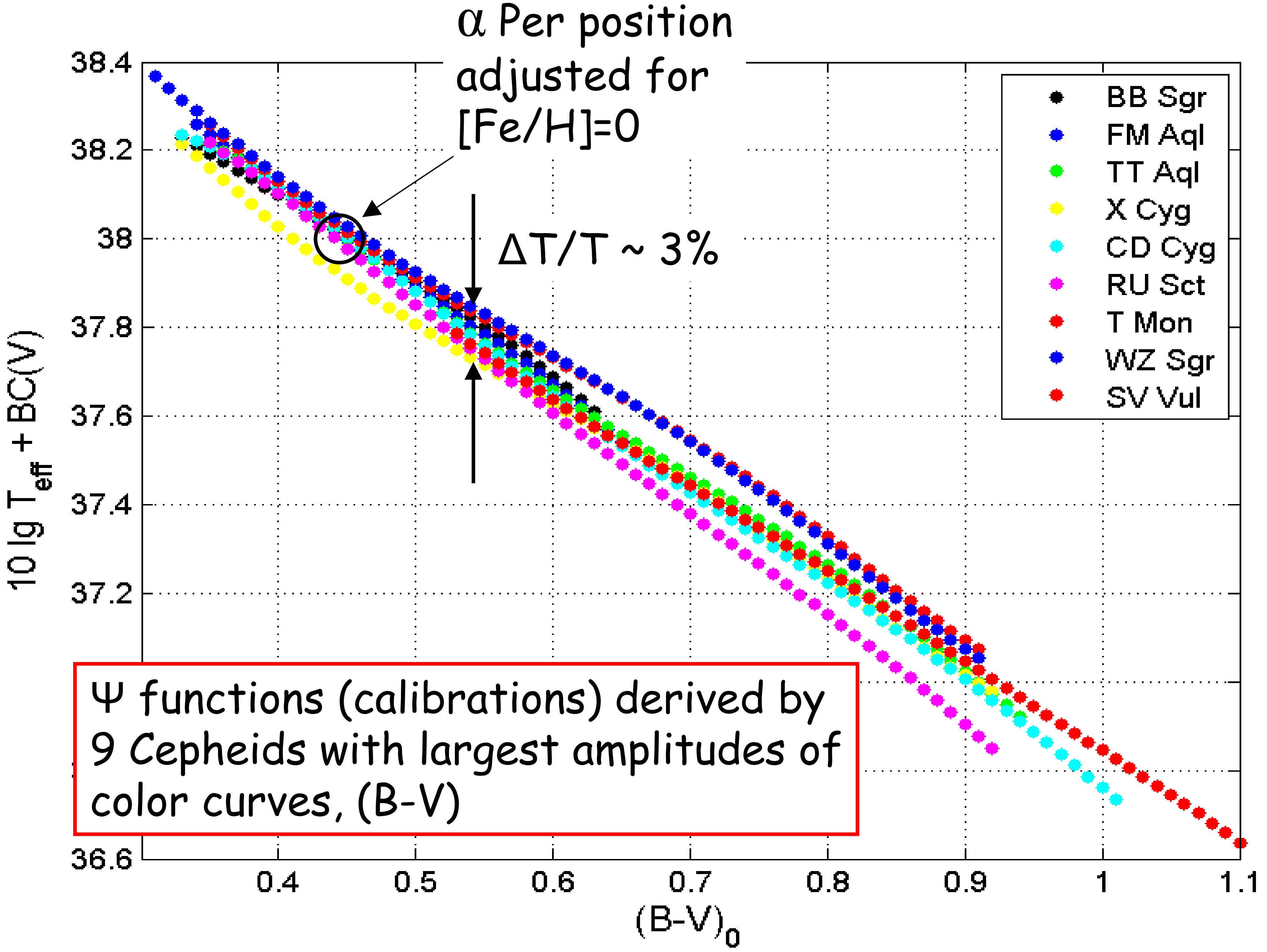
Natural extension of the technique: setting the calibration

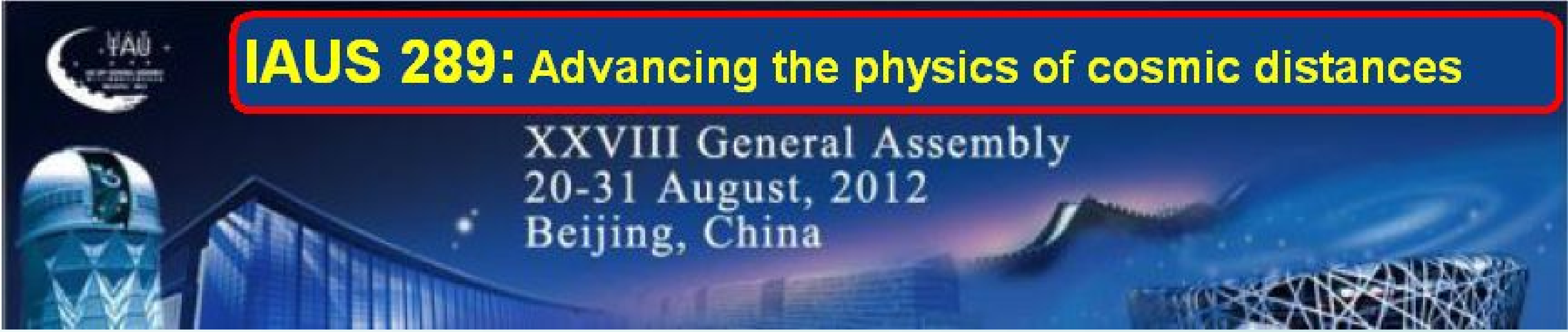
- Now present the function $\Psi(CI_0) = (10 \cdot \log T_{eff} + BC)$ as a power series
- $\Psi = \sum_{k=1,\dots,N} a_k \cdot (CI - CE - CI^{ST})^k + (10 \cdot \log T^{ST} + BC^{ST})$

Calibration zero-point

with unknown parameters $\{a_k\}$ and CE (here CI^{ST} – normal color of the standard star chosen, with the effective temperature T^{ST})

Standard must have *[Fe/H]* and *log g* close to the Cepheid studied


α Per position
adjusted for
[Fe/H]=0
ΔT/T ~ 3%
BB Sgr
FM Aql
TT Aql
X Cyg
CD Cyg
RU Sct
T Mon
WZ Sgr
SV Vul
38.4
38.2
38
37.8
37.6
37.4
37.2
36.6
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
10 lg T_eff + BC(V)
(B-V)_0
Ψ functions (calibrations) derived by
9 Cepheids with largest amplitudes of
color curves, (B-V)


IAUS 289: Advancing the physics of cosmic distances
XXVIII General Assembly
20-31 August, 2012
Beijing, China

Thank you !