

# Large surveys and determination of interstellar extinction

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Belgrade, Jul 1, 2010

# The task

- Fundamental scientific problem: investigation of galactic structure and interstellar medium distribution in the Galaxy
- Current goal: determination of stellar parameters and interstellar extinction value from photometric observations
- Method: use of multicolor photometry data, cross-matching objects in large surveys

# Outline

- Introduction: stellar parameters and extinction
- Galactic interstellar extinction models
- Large surveys: cross-matching
- Parametrisation of stars with Johnson photometry
- Parametrisation of stars with original photometry
- Photometrically unresolved binaries
- Summary

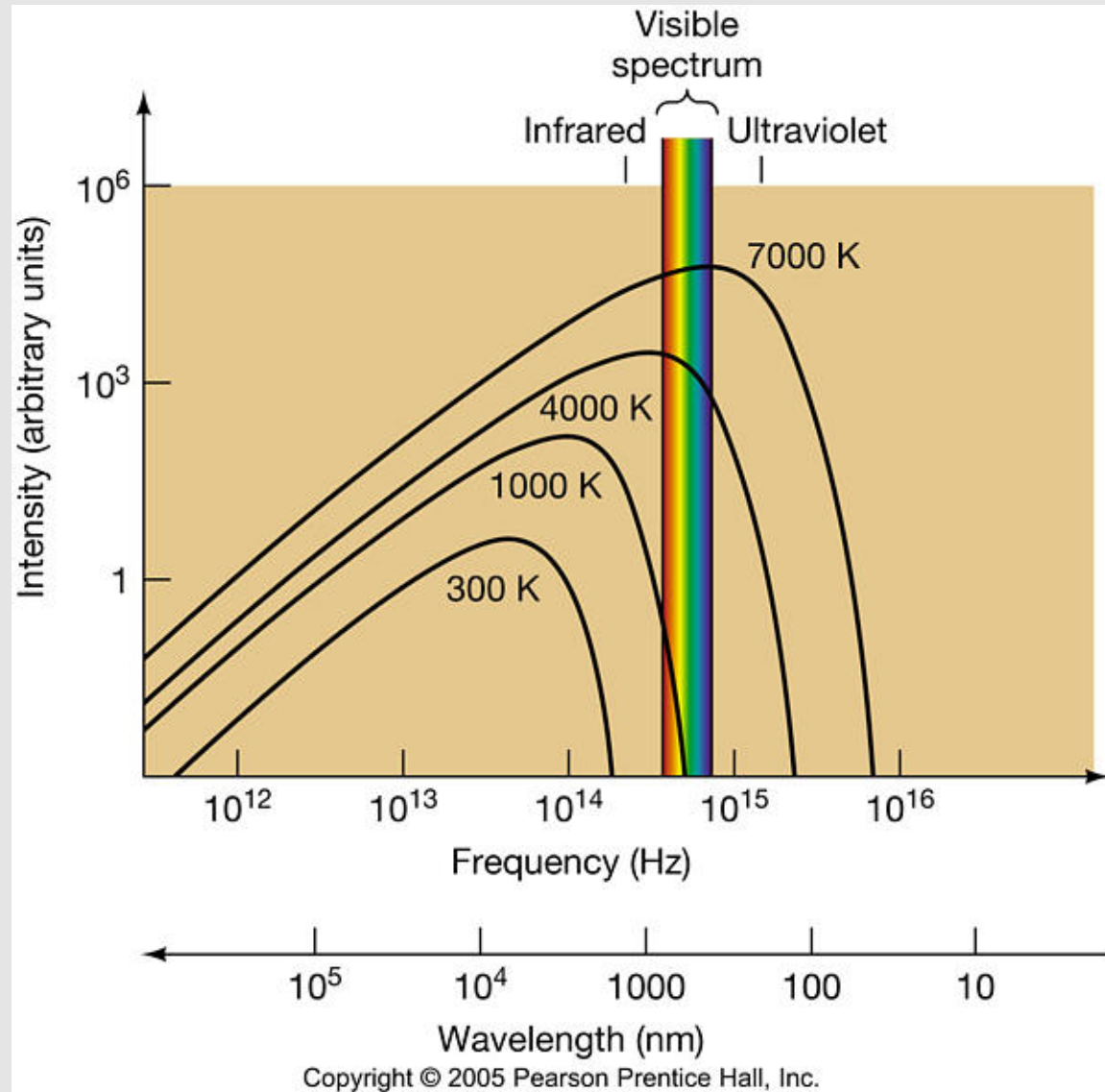
# Andromeda galaxy

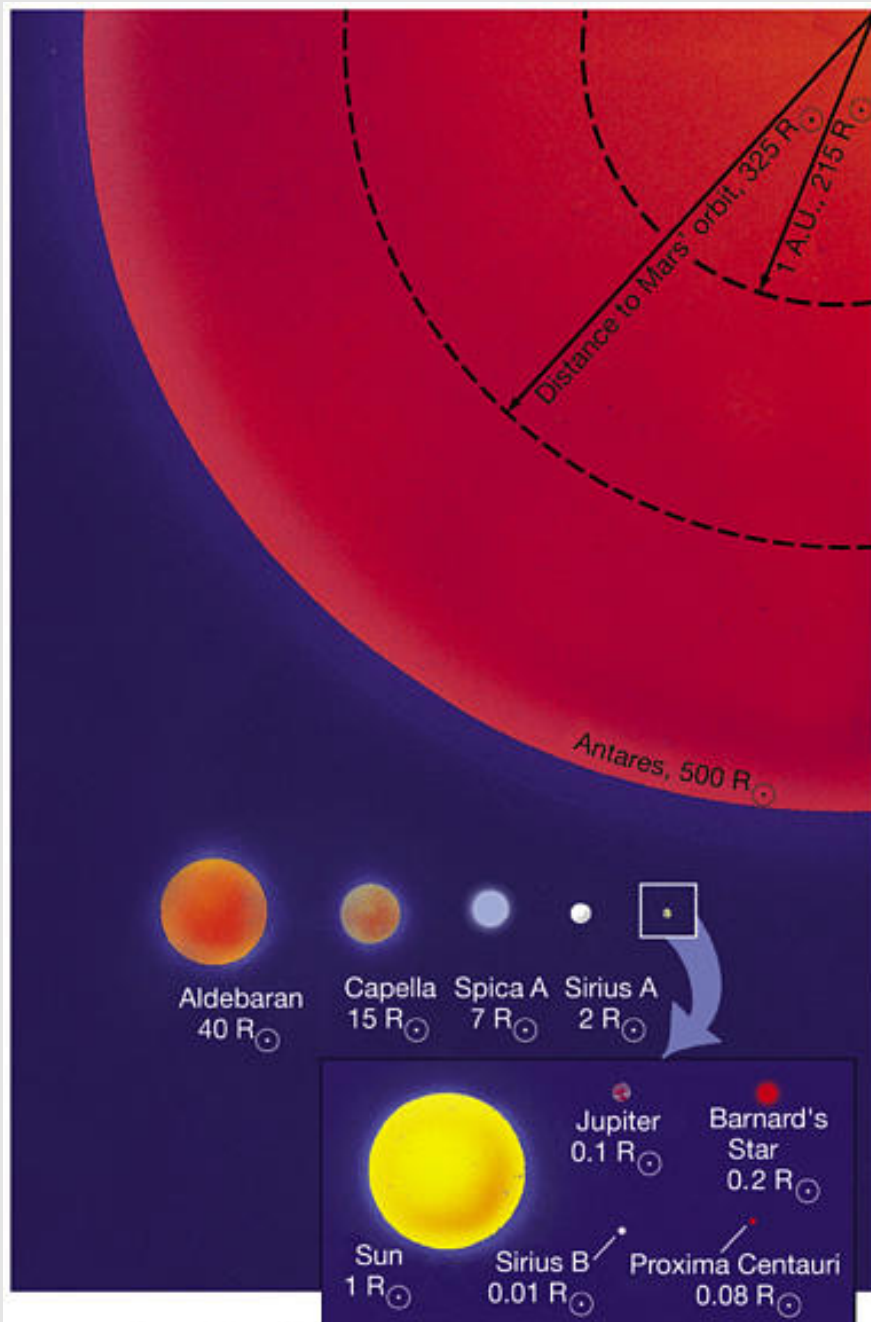


# NGC4565



# Spectral energy distribution of stars with different effective temperature

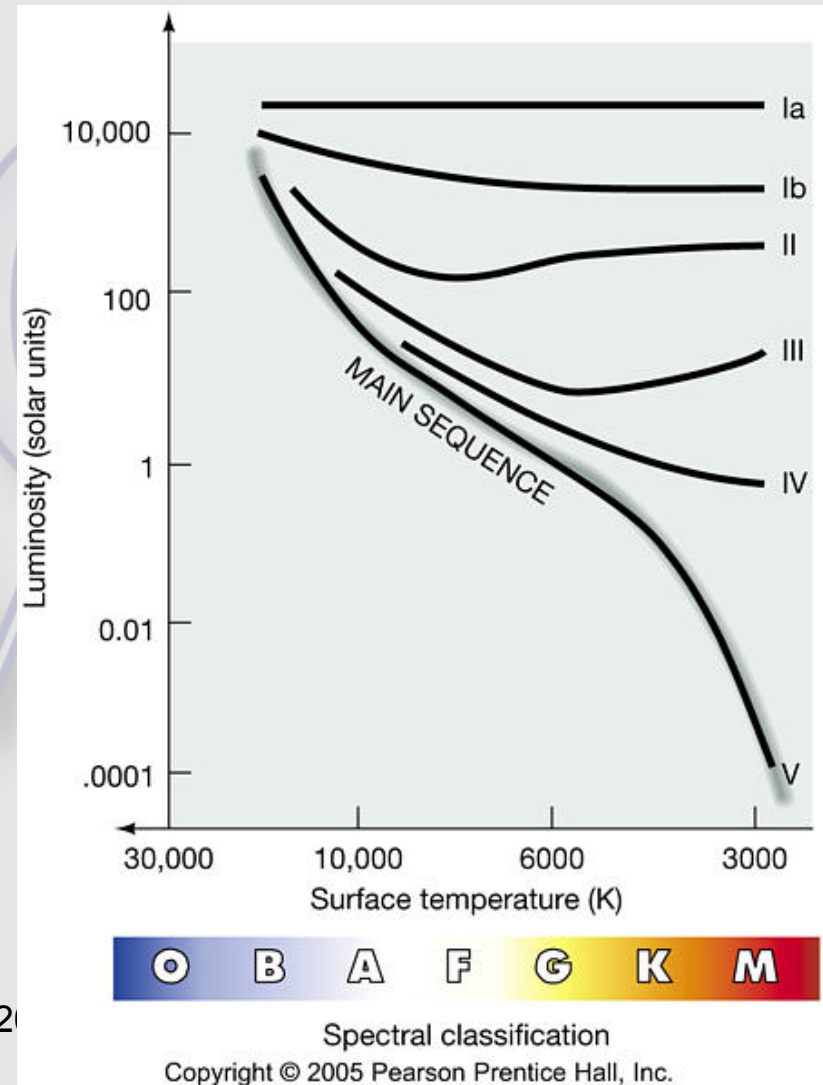
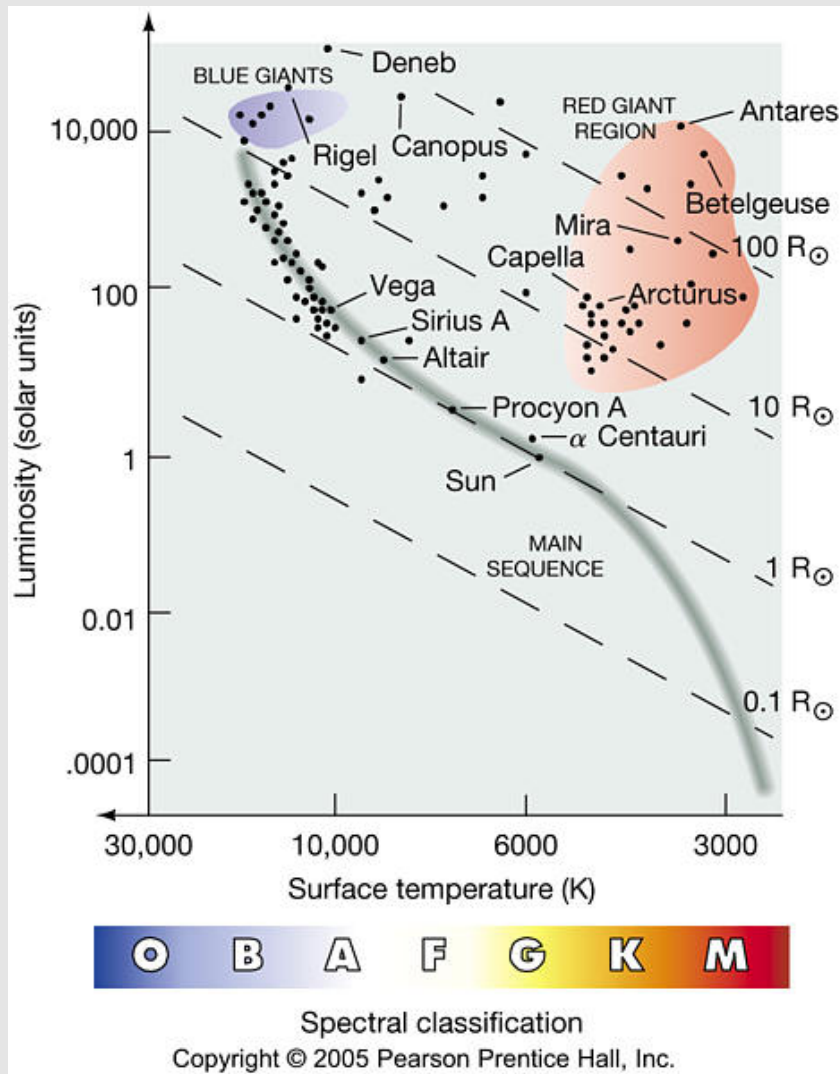


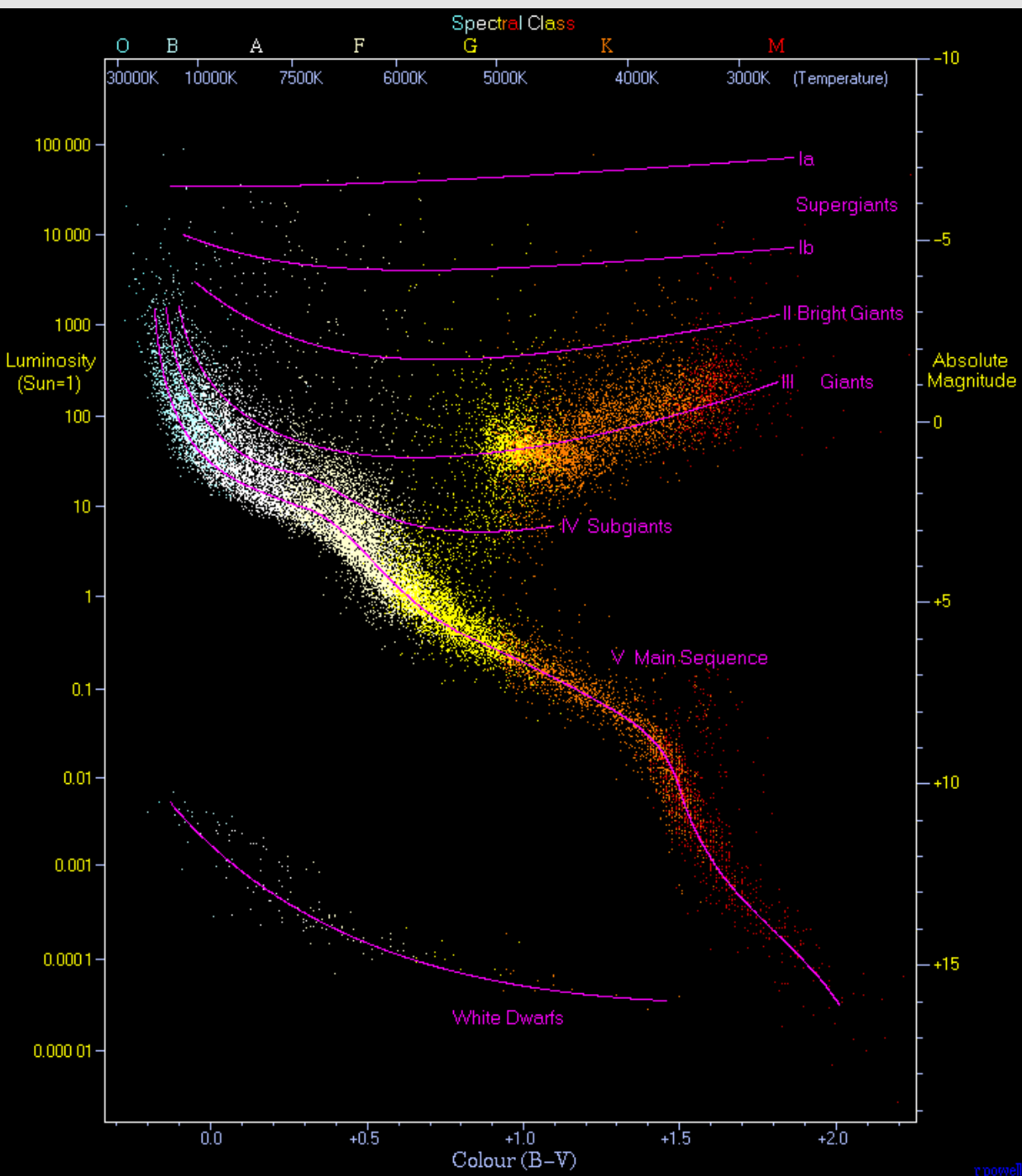


$$\text{Luminosity} \sim (\text{Radius})^2 \times T^4$$

le, Jul 1, 2010

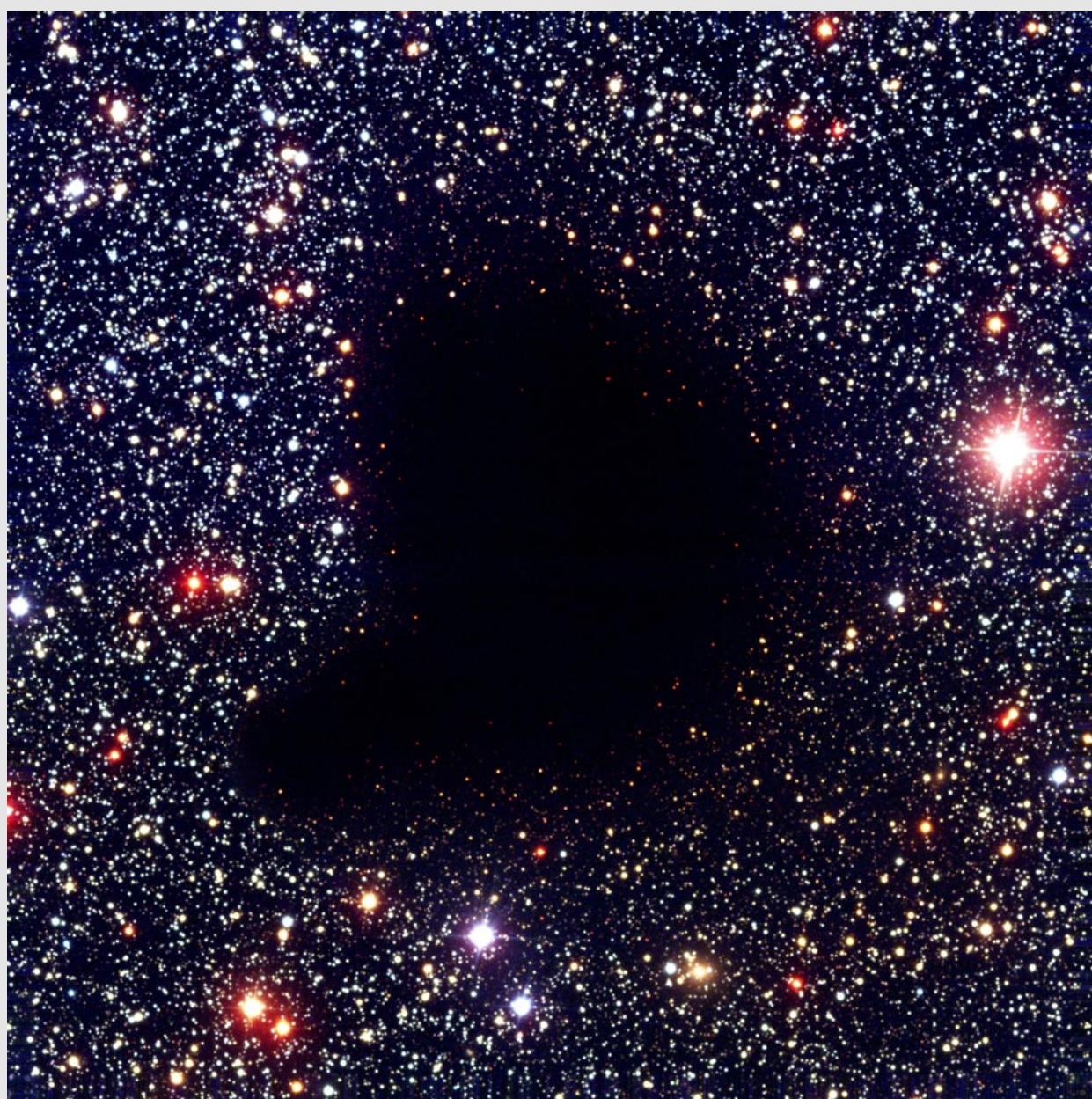
# The Hertzsprung–Russell diagram





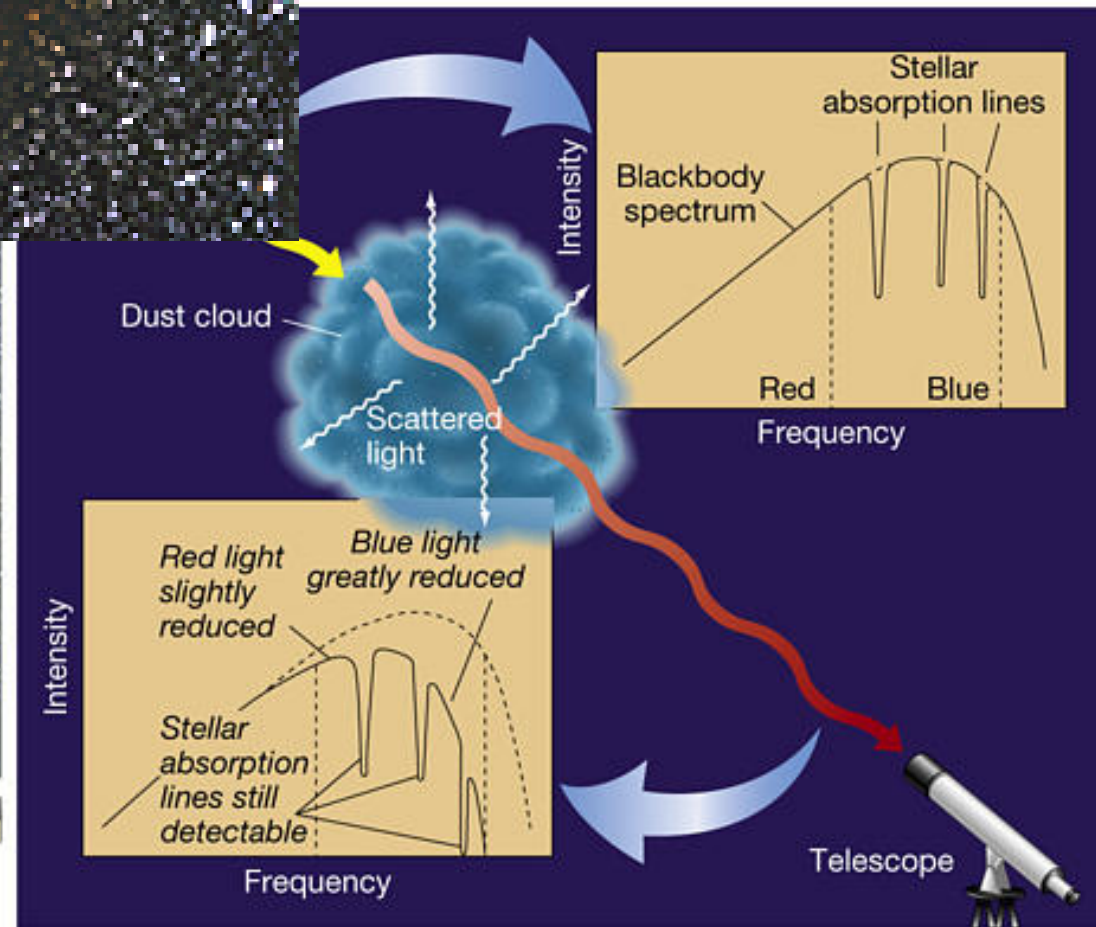
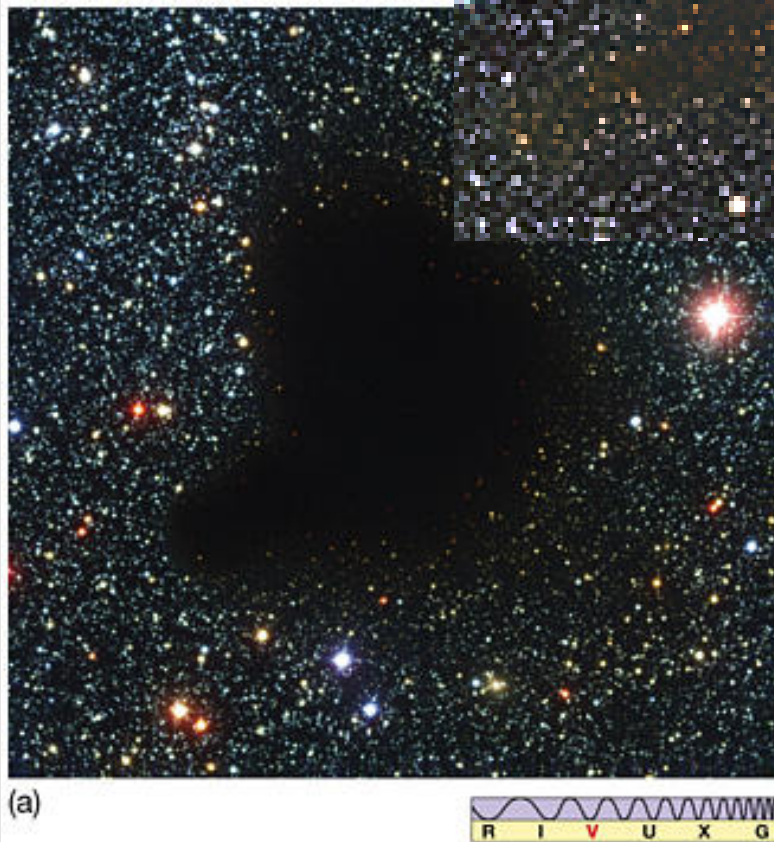
All the sequences  
are **bands** rather  
than lines

# Light absorption



Molecular  
cloud  
Barnard 68

# Absorption and reddening





- Dim, distant, dwarf planet Pluto can be hard to spot, especially in recent months as it wanders through the crowded starfields of Sagittarius and the central Milky Way. But fortunately for backyard Pluto hunters, it crossed in front of a dark nebula in early July. The diminutive world is marked with two short lines near the center of this skyscape recorded from New Mexico Skies on July 5. Pluto stands out only because obscuring dark nebula Barnard 92 (B92) blocks the background of the Milky Way's congeries of faint, innumerable stars.
- Another of astronomer E. E. Barnard's cataloged dark markings on the sky, B93, is easy to pick out just left of B92. Prominent at the lower left is open star cluster NGC 6603. In fact, Pluto, dark nebulae, and star cluster all lie within a portion of M24, also known as the Sagittarius Star Cloud, filling most of the frame.

Another  
example:  
Dim  
World,  
Dark  
Nebula  
(Credit &  
Copyright:  
Ray  
Gralak)



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- Large surveys: cross-matching
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Our goal is to design a procedure for construction of a 3D model of the galactic interstellar extinction.

# Galactic extinction models

- Three-dimensional models ( $A_v = f [l, b, d]$ ) are used to study Galaxy stellar populations. They are based
  - on spectral and photometric stellar data (Sharov 1963, Arenou et al. 1992)
  - on open cluster data (Pandey and Mahra 1987)
  - on star counts (Mendez and van Altena 1998)
  - on the Galactic dust distribution model (Chen et al. 1999, Drimmel et al. 2003)
- Total Galactic extinction maps ( $A_v = f [l, b]$ , see, e.g., Burstein and Heiles 1982, Schlegel et al. 1998) are most appropriate for extragalactic studies

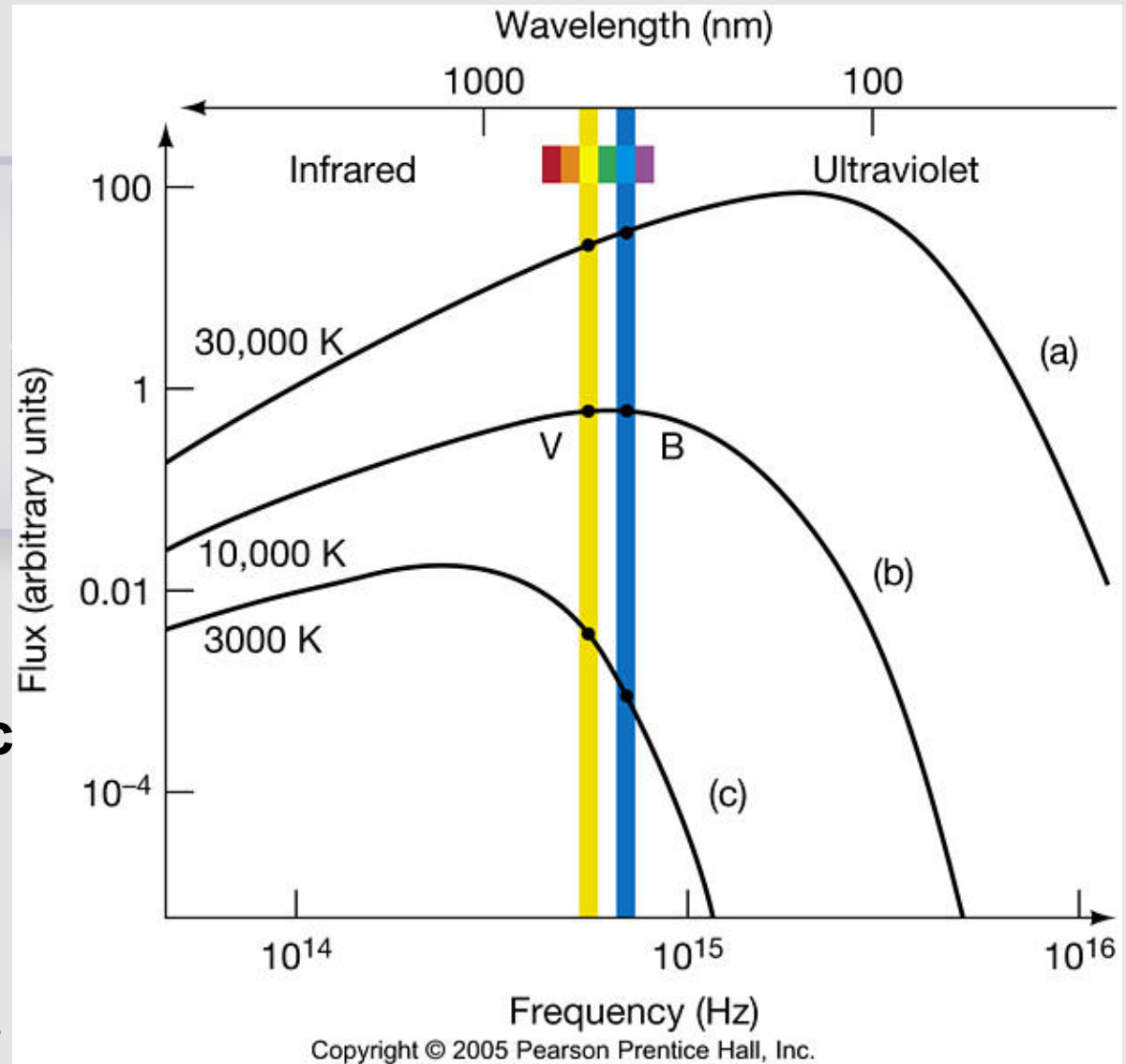
# Galactic extinction models

- **Three-dimensional models** ( $A_v = f [l, b, d]$ ) are used to study Galaxy stellar populations. They are **based**
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# Observational stellar color indices

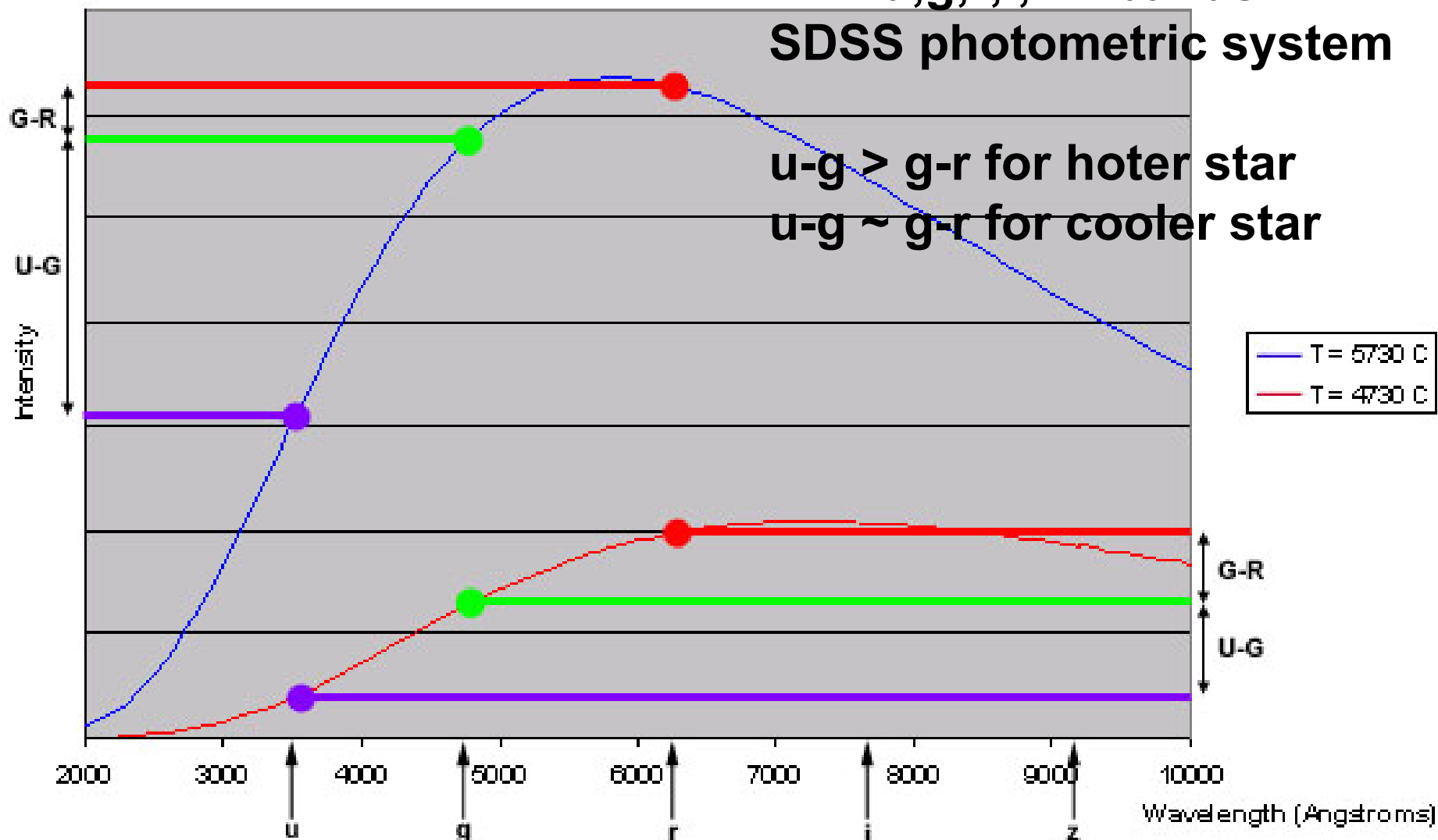
**B, V – bands in  
Johnson photometric  
system**

**$B-V < 0$  for hot stars  
 $B-V > 0$  for cool stars**



# Thermal Radiation Curves

**u,g,r,i,z – bands in  
SDSS photometric system**

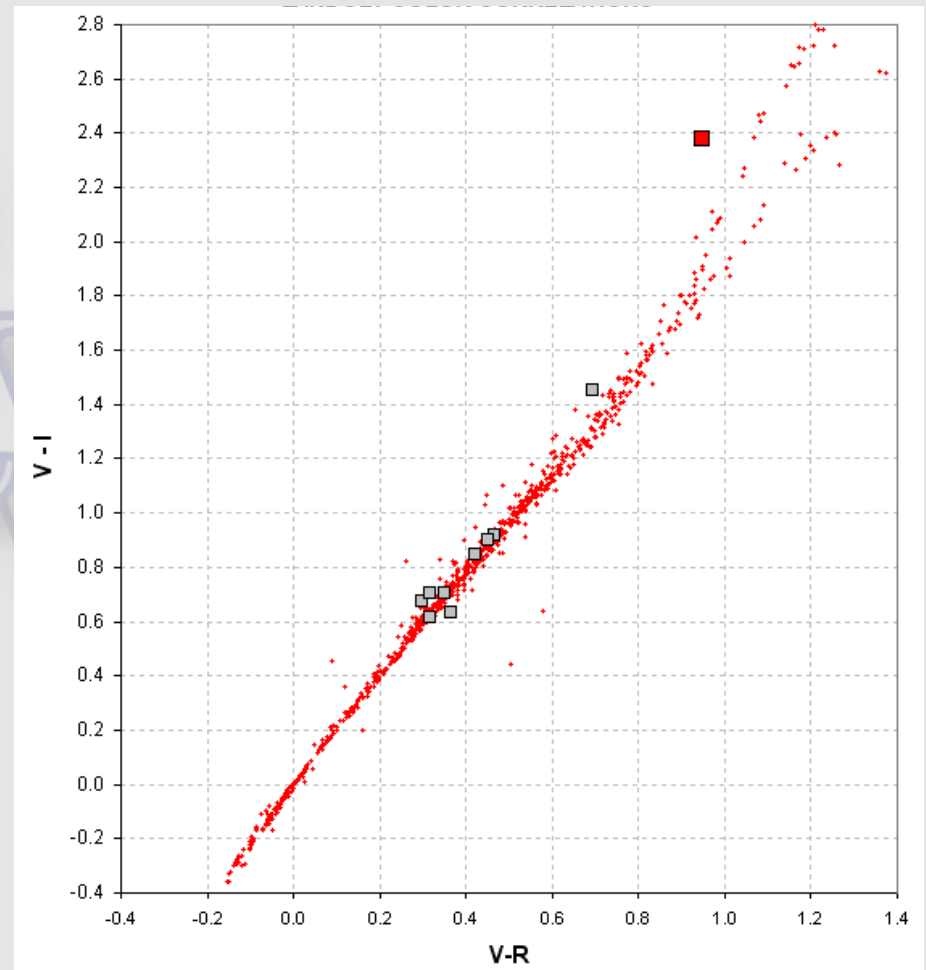
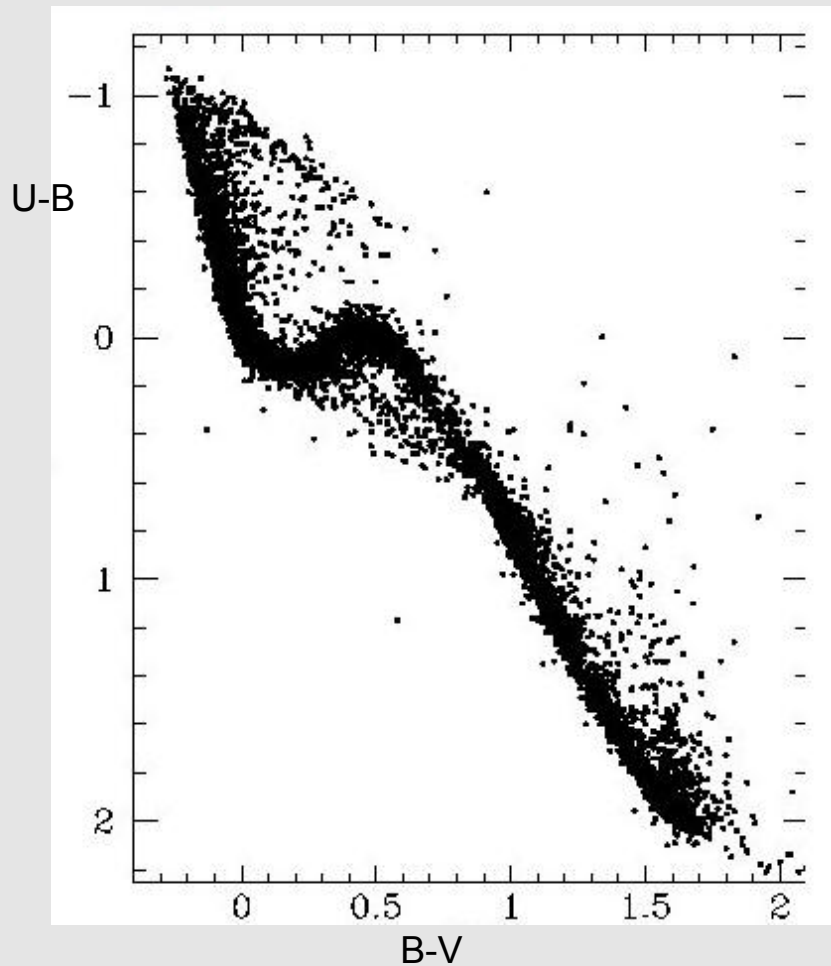


# Stellar colors and temperatures

**TABLE 17.1 Stellar Colors and Temperatures**

<b><math>\frac{B \text{ flux}}{V \text{ flux}}</math></b>	<b>Approximate Surface Temperature (K)</b>	<b>Color</b>	<b>Familiar Examples</b>
1.3	30,000	blue-violet	Mintaka ( $\delta$ Orionis)
1.2	20,000	blue	Rigel
1.00	10,000	white	Vega, Sirius
0.72	7000	yellow-white	Canopus
0.55	6000	yellow	Sun, Alpha Centauri
0.33	4000	orange	Arcturus, Aldebaran
0.21	3000	red	Betelgeuse, Barnard's Star

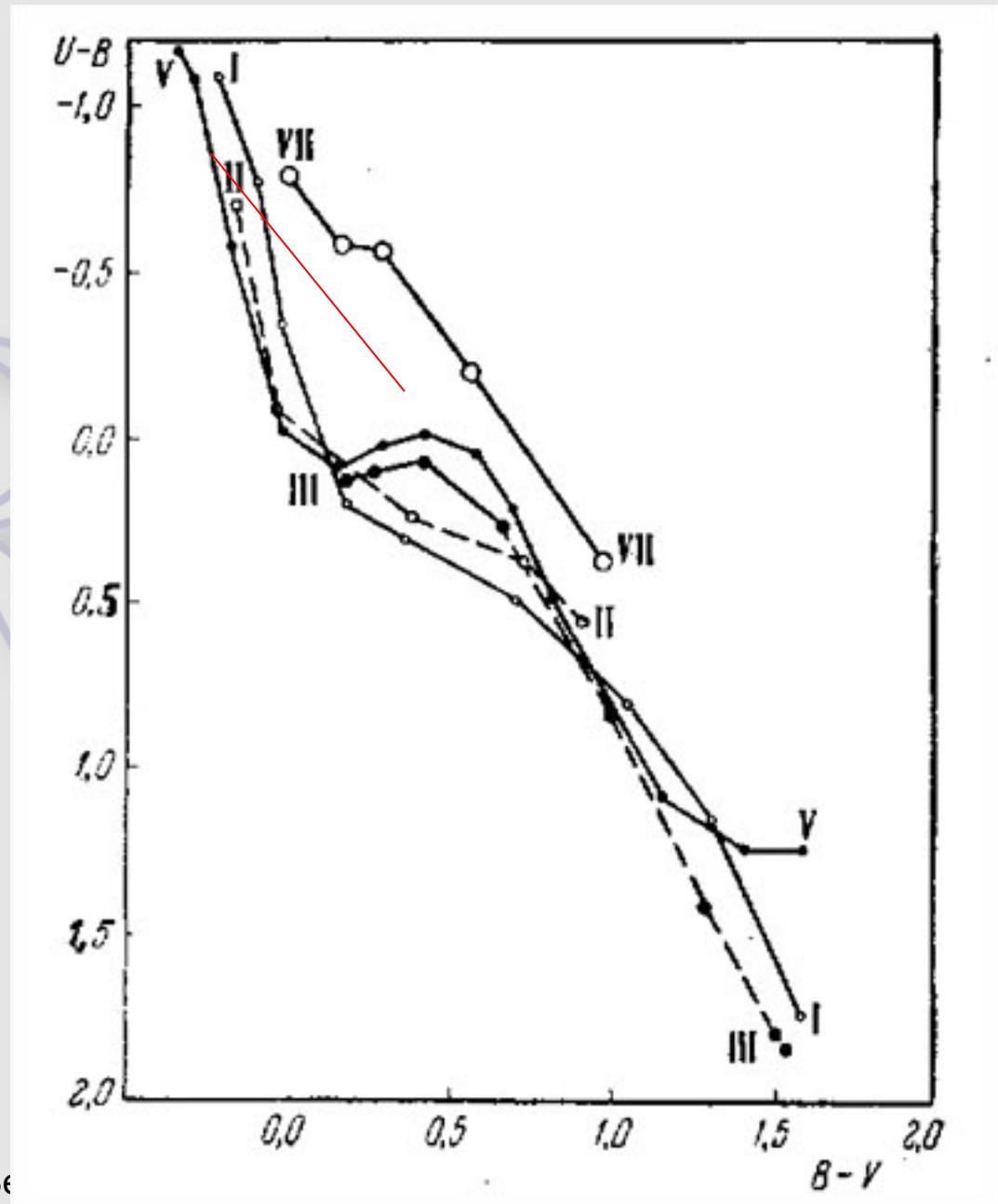
# Reddening on color index diagrams



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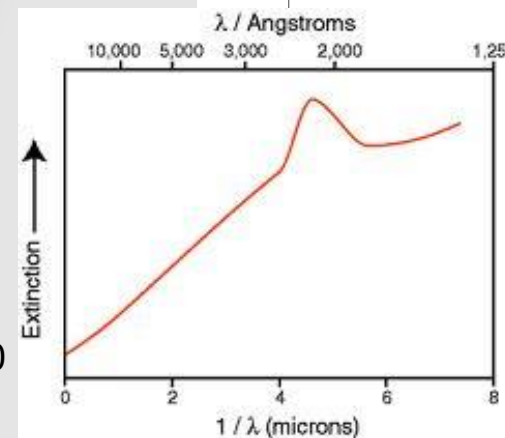
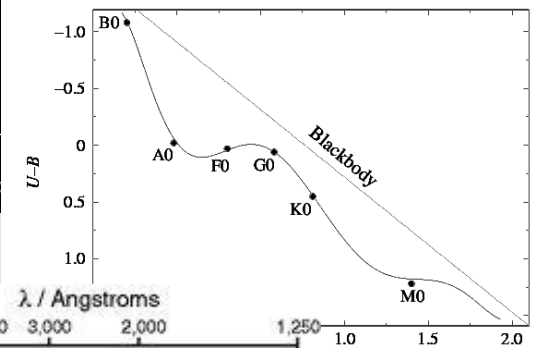
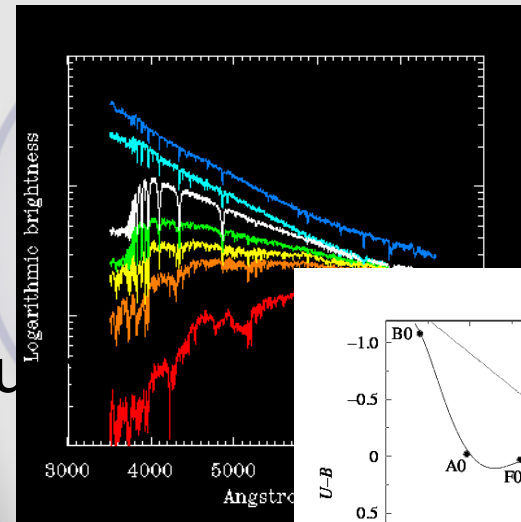
# Extinction on the color-color diagram

1. Select color indices (and spectral types) where extinction reddening and temperature reddening can be separated
2. Overcome luminosity class uncertainty
3. Determine the reddening lines slope
4. ...there are also observational errors...



# Extinction reddening and temperature reddening can be separated, when a significant deviation from monotonic function is observed

- in stellar spectrum, e.g.
  - Balmer jump area for B5-G0 stars
  - molecular bands in the spectrum of M stars
- in the Interstellar extinction law
  - extremely high extinction in a broad bump at about  $\lambda=2175 \text{ \AA}$



✓ Select

Redraw

Method

— Sharov

 $A_V = 1.4685$ 

— Neckel&amp;Clare

 $A_V = 0.5000$ 

— Pandey&amp;Mahra

 $A_V = 1.1077$ 

— FitzGerald

 $A_V =$  Not defined

— Sandage

 $A_V = 1.1125$ 

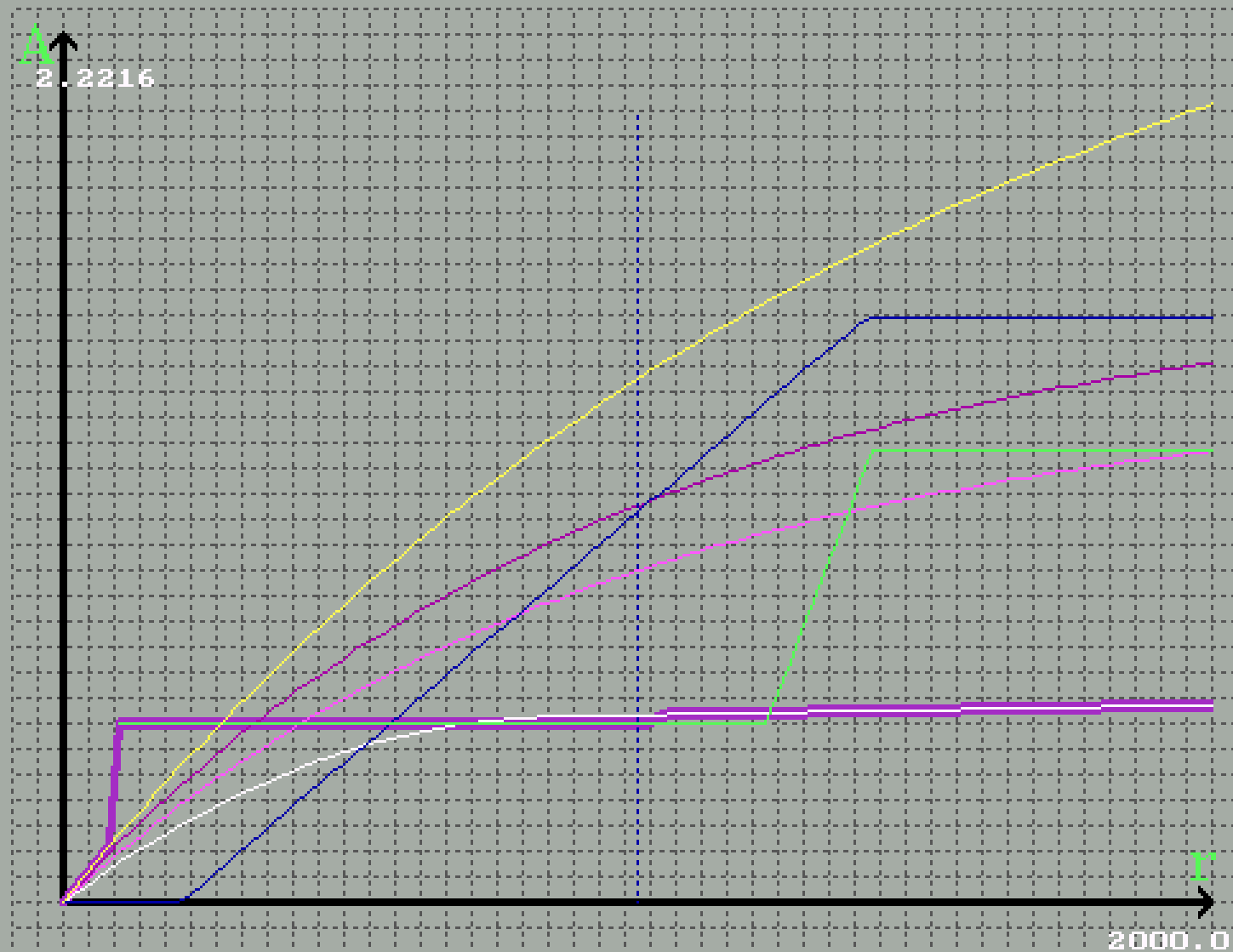
— de Vaucouleurs

 $A_V = 0.9305$ 

— Arenou

 $A_V = 0.5209$ 

— New Model 1

 $A_V = 0.5000$  $l$  $b$  $r$  (pc) $\lambda$  ( $\text{\AA}$ )

323

+6

1000

U

 $B_U$  $S_p$ 

Quit

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# Large surveys are on hand / coming

- While 3D models, using spectral and photometric data, were based on  $10^4 - 10^5$  stars.....
- ..... modern surveys (2MASS, DENIS, SDSS, GALEX, UKIDSS, ...) contain photometric (3 to 5 bands) data for  $10^7 - 10^9$  stars. But
  - one needs cross-identification between surveys
  - the surveys do not contain spectral data

# Catalog cross-correlation services

- The identification of objects requires the federation of multiple surveys obtained at different wavelengths and with different observational techniques. Such cross-matching of catalogs was laborious and time consuming
- Using VO data access and cross-correlation technologies a search for counterparts in a subset of different catalogues can be carried out in a few minutes

# Services to cross-match astronomical catalogs (matchers)

- OpenSkyQuery, NVO, (<http://openskyquery.net/Sky/skysite/>): friendly interface, absence of DENIS survey
- Crossmatch, RVO, ([vo.astronet.ru/cas/crossmatch.php](http://vo.astronet.ru/cas/crossmatch.php)): fast, output data list can be specified
- Multi-Catalogue Multi-Cone Search Download Manager, GAVO (<http://www.g-vo.org/mcmcs/>)
- Astrogrid project “Cross-matching Catalogues”: (<http://wiki.astrogrid.org/pub/Astrogrid/DataDocs/crossmatch.html>)
- SDSS SkyServer (<http://cas.sdss.org/>): cross-match SDSS with user lists
- Tools for cross-matching local data are included in TOPCAT, Aladin, ...

# Scientific output

- A search for brown dwarf candidates in the Sloan and 2MASS catalogs (US NVO prototype) and a search for type 2 QSOs in the VLT, HST and Chandra data (AVO prototype) demonstrated the exciting result of a new object discovery
- Information on interstellar extinction may be obtained from modern large photometric surveys data

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# Interstellar extinction law

Rieke and Lebofsky 1985

$\lambda$	B	V	R	I	J	H	K
$E(\lambda-V)/E(B-V)$	1.	0.	-0.78	-1.60	-2.22	-2.55	-2.74
$E(B-\lambda)/E(B-V) \equiv k_\lambda$	0.	1.	1.78	2.60	3.22	3.55	3.74

# Procedure

- For every  $\lambda$  available in photometric survey:
  - calculate  $(B-\lambda)$
  - $E(B-\lambda) = (B-\lambda) - (B-\lambda)_0$
  - $E(B-V)_\lambda = E(B-\lambda) / k_\lambda$
- $(B-\lambda)_0$  – intrinsic color indices (they depend on spectral type, see, e.g., Straizys 1977 tables)
- Assuming that a star satisfies the interstellar extinction law, we can expect  $E(B-V)_\lambda$  be identical  $\forall \lambda$  ..... if we guessed spectral type
- So we should determine a spectral type that yields the most appropriate set of  $(B-\lambda)_0$  to produce as close values of  $E(B-V)_\lambda$  as possible

# The procedure repeated for all spectral types

- Mean  $E(B-V)_{\lambda}$  calculation,  $E = n^{-1} \sum_n E(B-V)_{\lambda_n}$
- Minimization of  $\Delta E^2 = \sum_n (E(B-V)_{\lambda_n} - E)^2$

# When spectral type is determined

- $M_B = M_B(\text{Sp})$
- $A_V = 3.1 \cdot E(B-V)$
- $A_B = 1.324 \cdot A_V$
- $\log r = 0.2 \cdot (B - M_B + 5 - A_B)$

...and construct a “ $r - A_V$ ” diagram

# 2' test area: $l=323$ , $b=+6$ (Lupus)

- Low latitude: to compare not only with “all-sky” maps (Sharov 1963, Arenou et al. 1992), but also with “galactic plane” maps (FitzGerald 1968, Neckel and Klare 1980)
- No dense molecular clouds
- Southern sky (DENIS covers)

Multicolor surveys: DENIS (I, J, K'),  
2MASS (J, H, K<sub>s</sub>), USNO-B (SERC-J)

	<b>B</b>	<b>J</b>	<b>H</b>	<b>K</b>
<b>Johnson</b>	4400	12500	15200	22000
<b>DENIS</b>		transformation equations J.M.Carpenter, 2000 J.D.Fernie, 1983		transformation equations J.M.Carpenter, 2000 J.D.Fernie, 1983
<b>2MASS</b>		transformation equations J.D.Fernie, 1983	transformation equations J.D.Fernie, 1983	transformation equations J.D.Fernie, 1983
<b>USNO-B</b>	4625			

# Transformation equations

- 2MASS  $\longrightarrow$  Johnson  
J.D.Fernie, 1983
- DENIS  $\longrightarrow$  2MASS  $\longrightarrow$  Johnson  
J.M.Carpenter, 2000  
J.D.Fernie, 1983

# Error budget

- Observational photometry errors: 0.1 for USNO and 0.01 for IR surveys
- Calibration tables errors (depending on spectral type): 0.05 – 0.1 for intrinsic color indices and 0.2 – 0.5 for absolute magnitudes
- Interstellar extinction law coefficients ( $k_\lambda$ ) error: 0.03
- Difference between calculated  $E(B-V)_\lambda$  does not exceed 0.05 ( $\lambda = J, H, K$ )

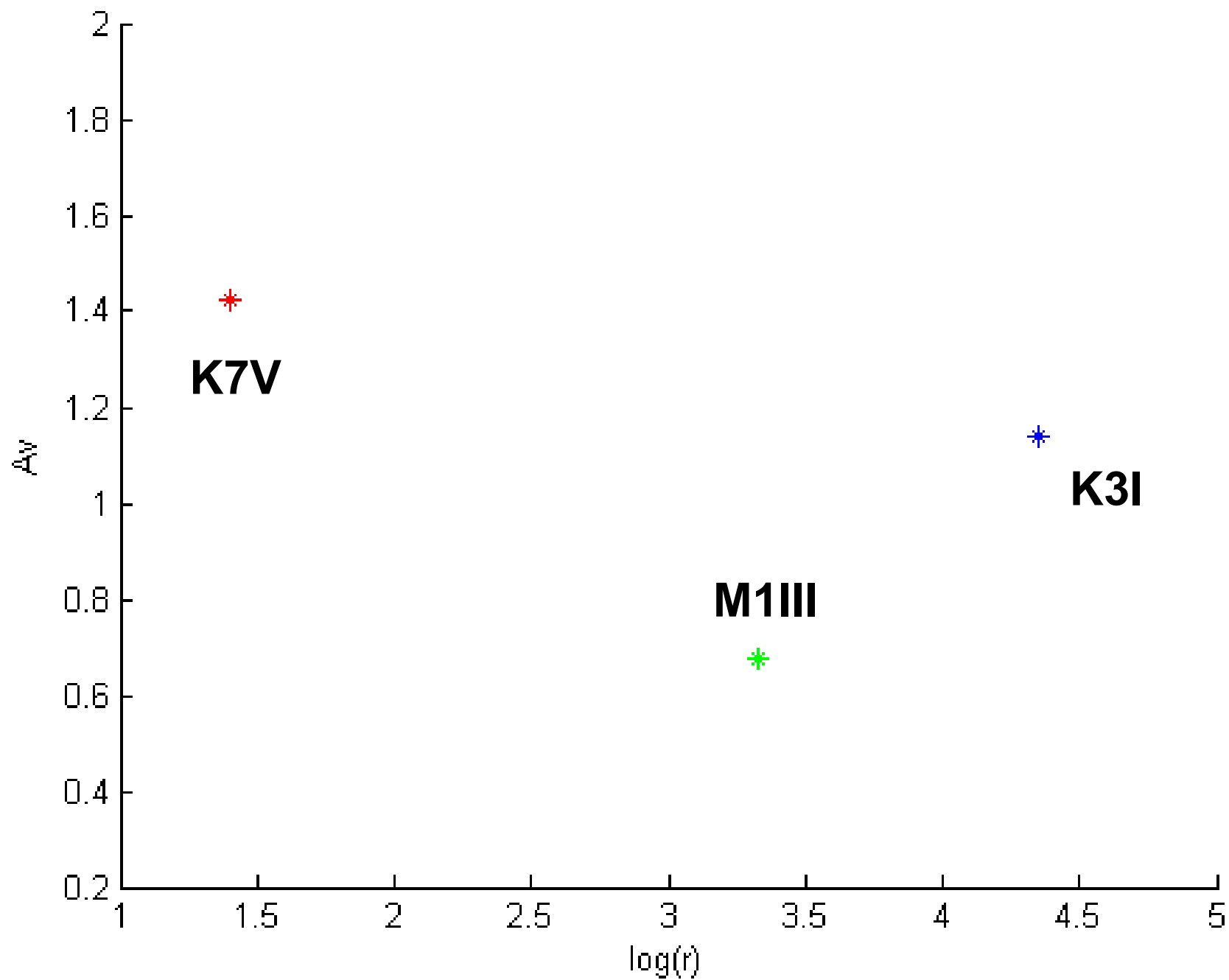
# Uncertainties of final parameters

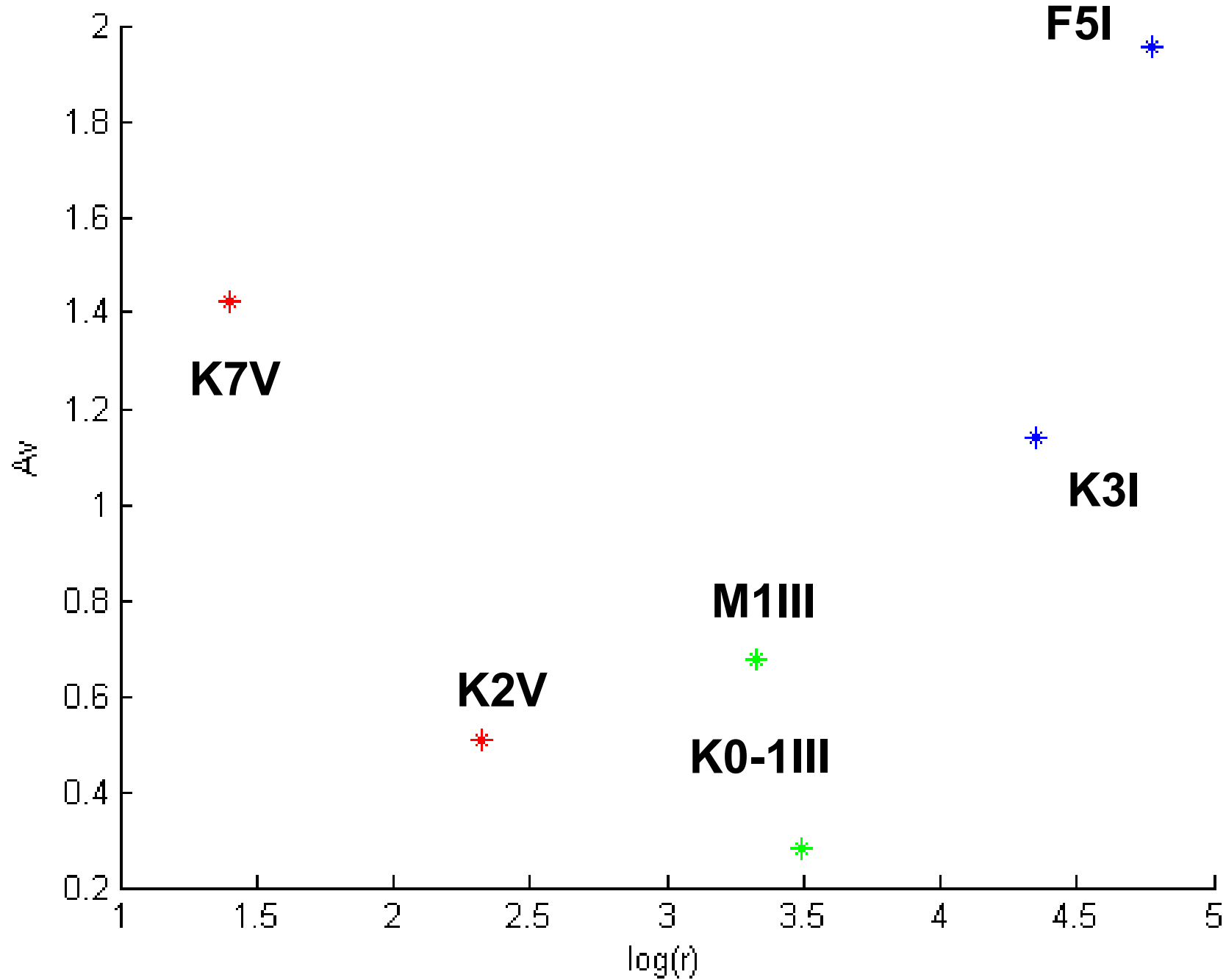
- The uncertainty of  $A_V$  is about 0.1 depending primarily on the errors of  $(B-\lambda)_0$
- The relative error of the distance is about 25%, depending primarily on the errors of absolute magnitudes

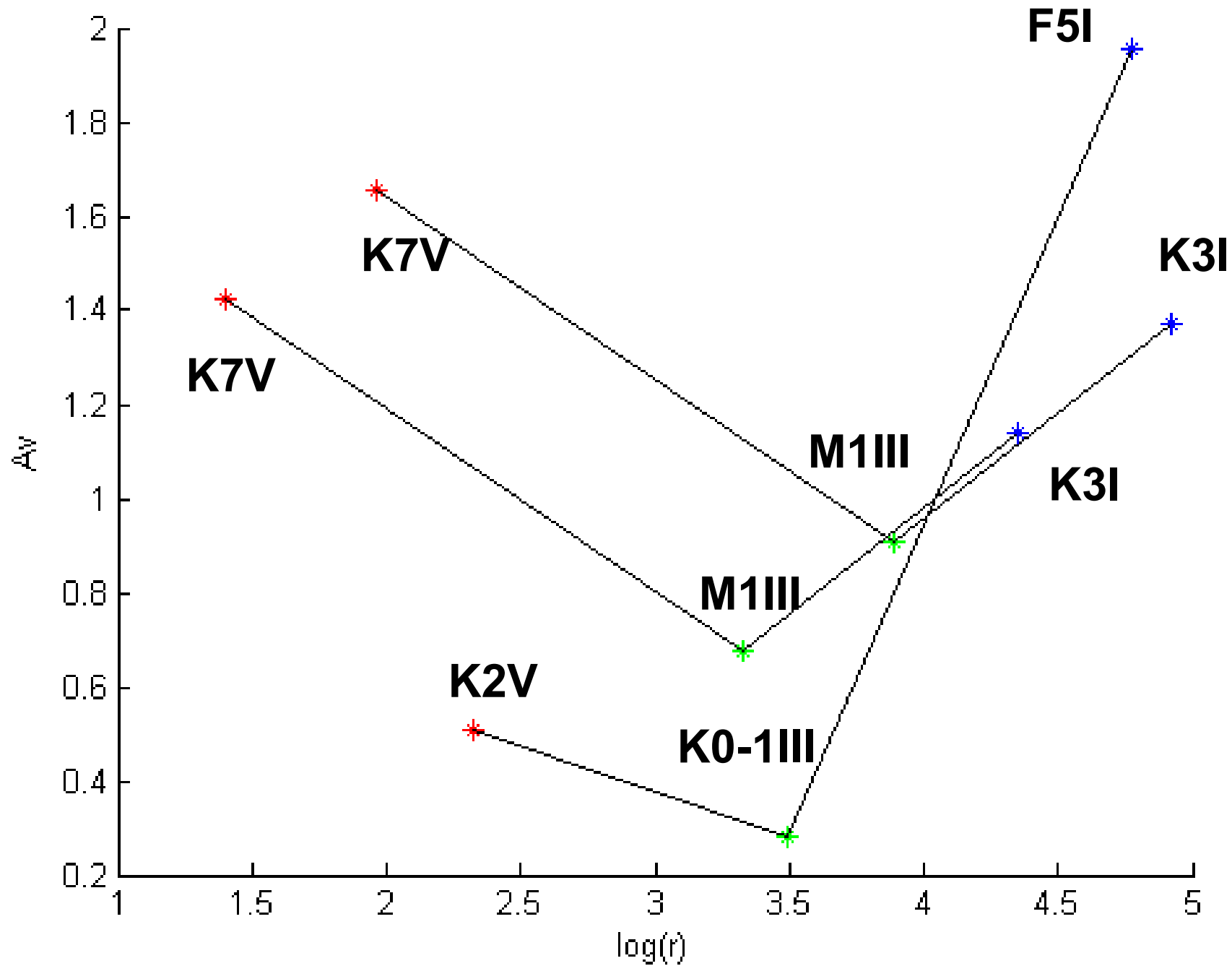
# Number of objects

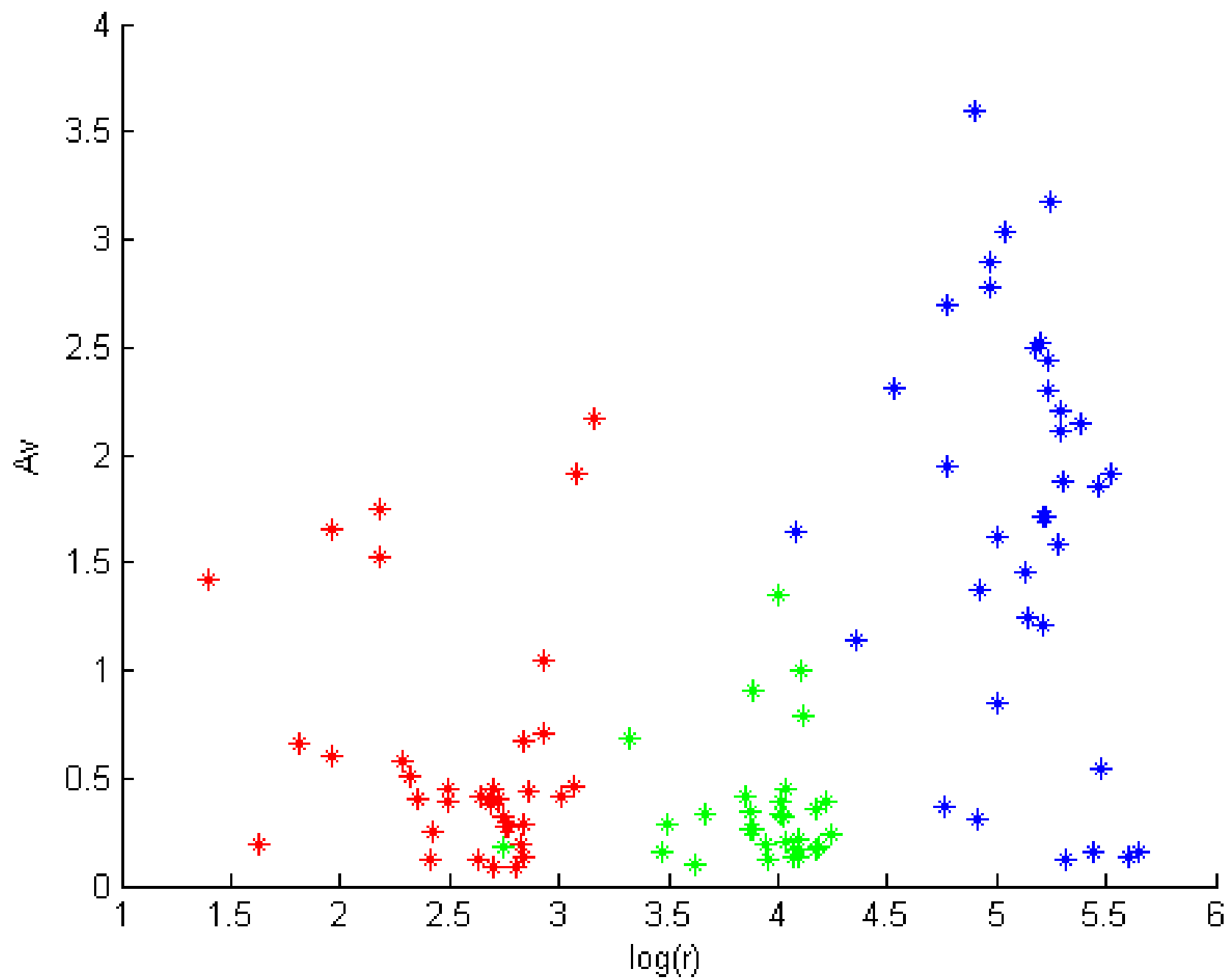
- Two-arc-minute test area contains 134 objects cross-identified in all three surveys (2MASS, DENIS, USNO-B)
- For 36 of them all required photometry is available: B(USNO-B), J(DENIS, 2MASS), H(2MASS), K(DENIS, 2MASS)

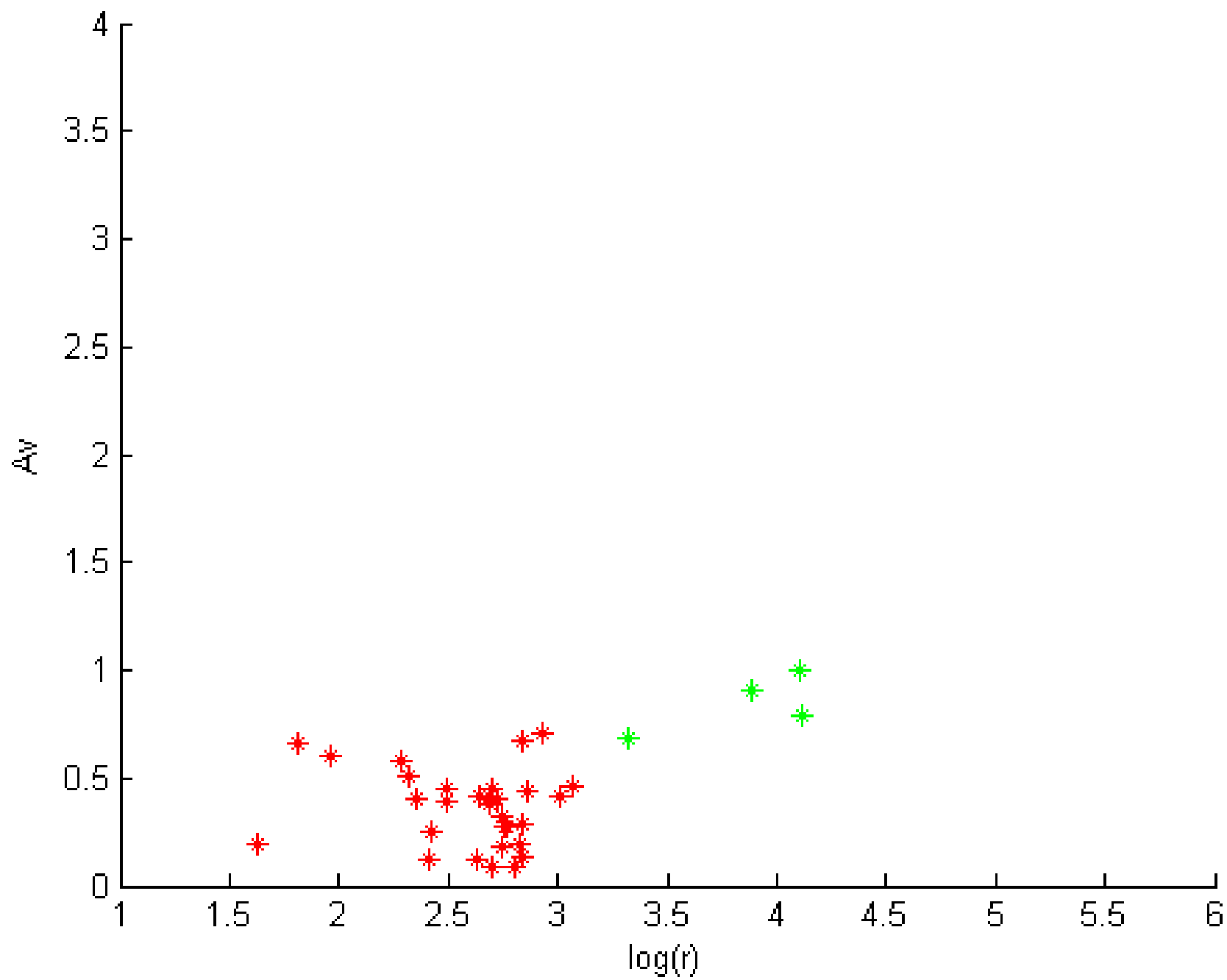
Compare with 0.0004 objects (on average) used in previous models

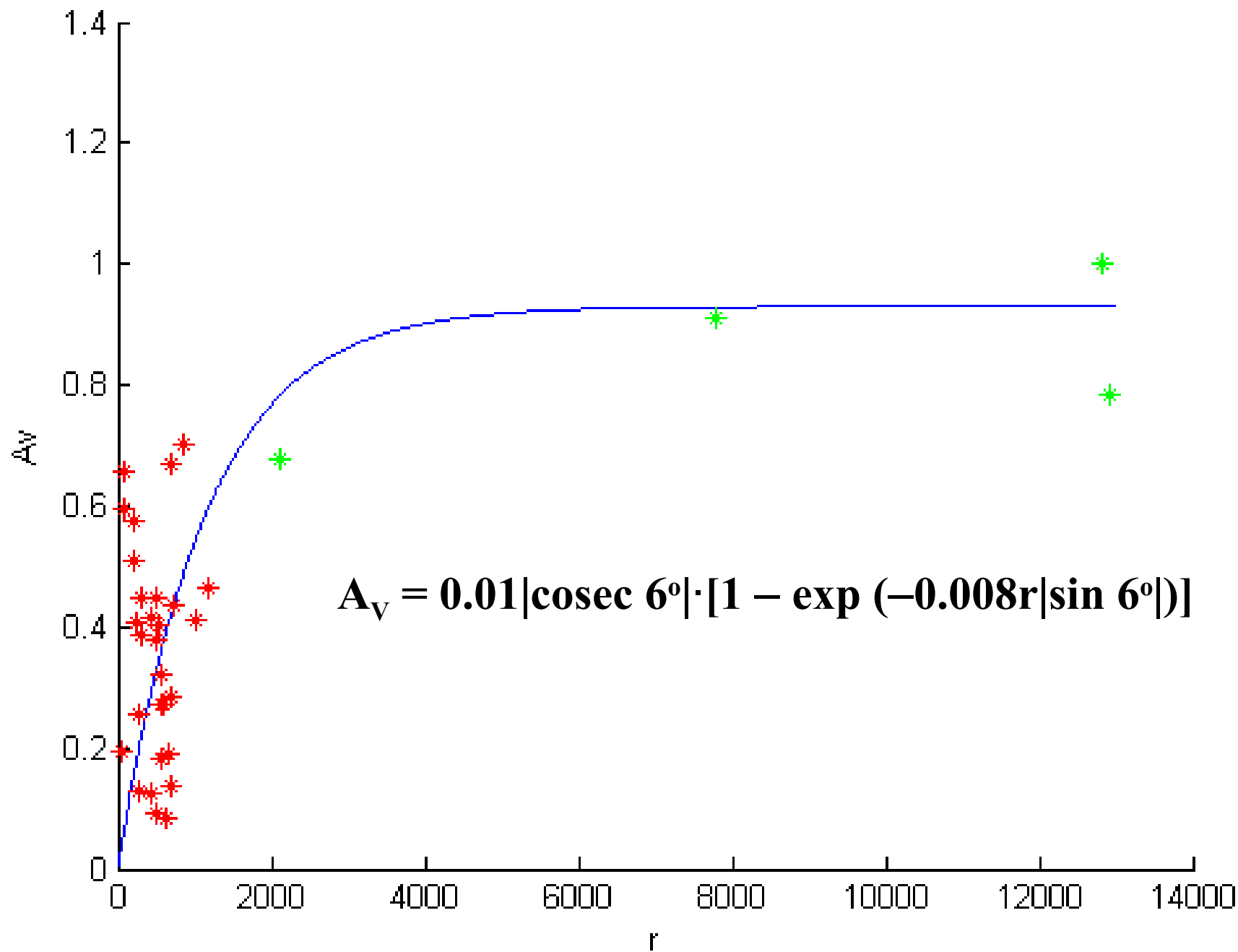




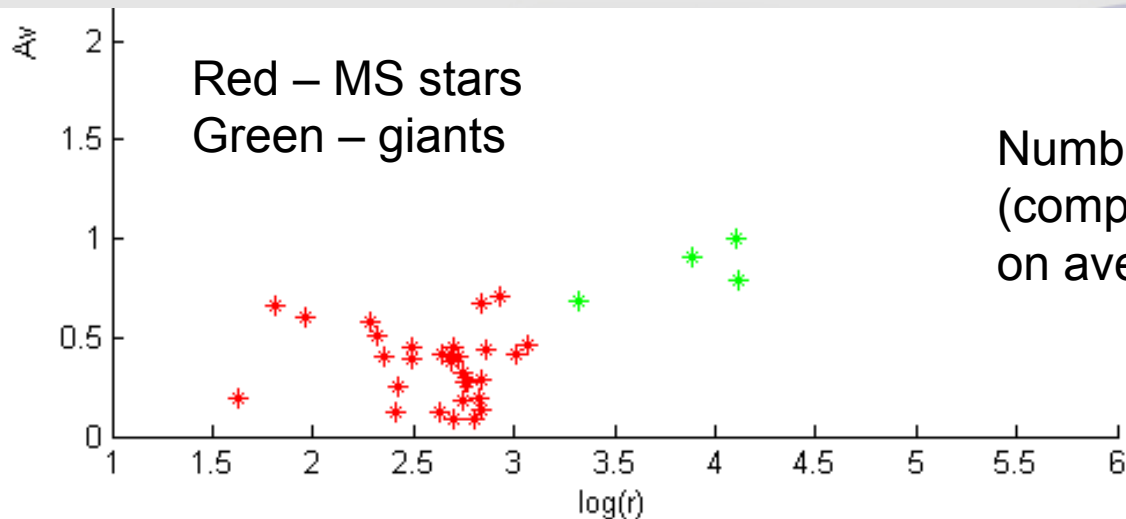








**Two-arcminute test area at  $l=323$ ,  $b=+6$ .**  
**Surveys used: 2MASS, DENIS, USNO-B.**  
**Original photometry is recalculated into Johnson (Malkov and Karimov 2006).**



Number of objects in the area – 36  
 (compare with 0.0004 objects, used, on average, in previous models).

**Result approximation by the Parenago cosecant law:**

$A_V = a_0 \beta |\operatorname{cosec} b| \cdot [1 - \exp(-r|\sin b|/\beta)] = 0.96 [1 - \exp(-0.00084 r)]$ , where  
 $a_0$  (magnitude of the extinction per parsec) is found to be 0.0008,  
 $\beta$  (semi-depth of the homogeneous absorbing matter) is found to be 125 pc,  
 $b$  (galactic latitude) is  $+6^\circ$

✓ Select

Redraw

Method

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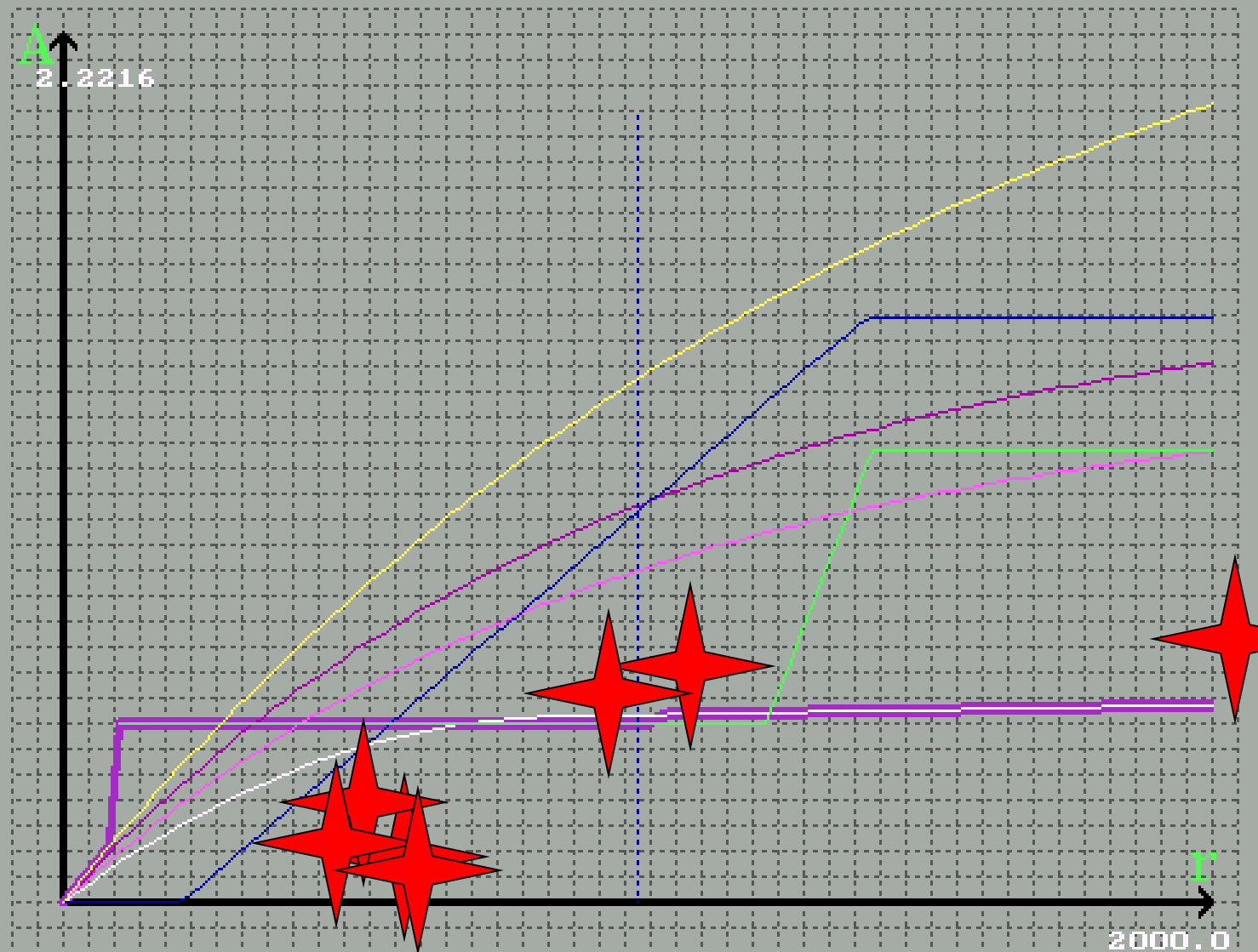
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l

b

r (pc)

 $\lambda$  (Å)

323

+6

1000

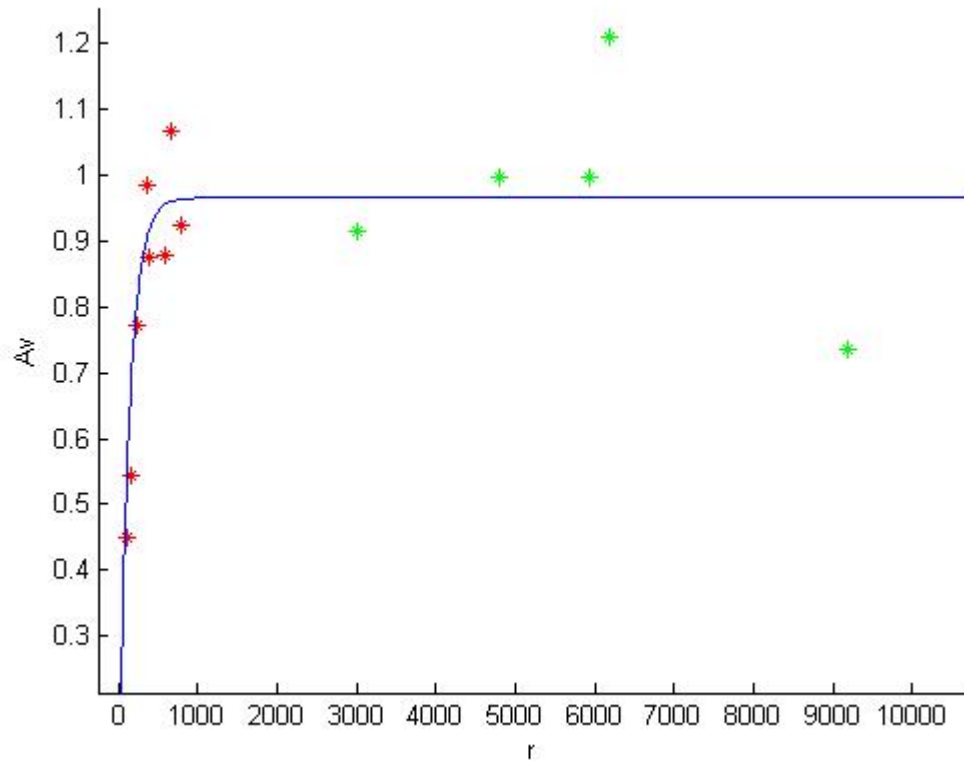
U

B\_U

Sp

Quit

Another  
area:  $l=314$ ,  
 $b=-62$

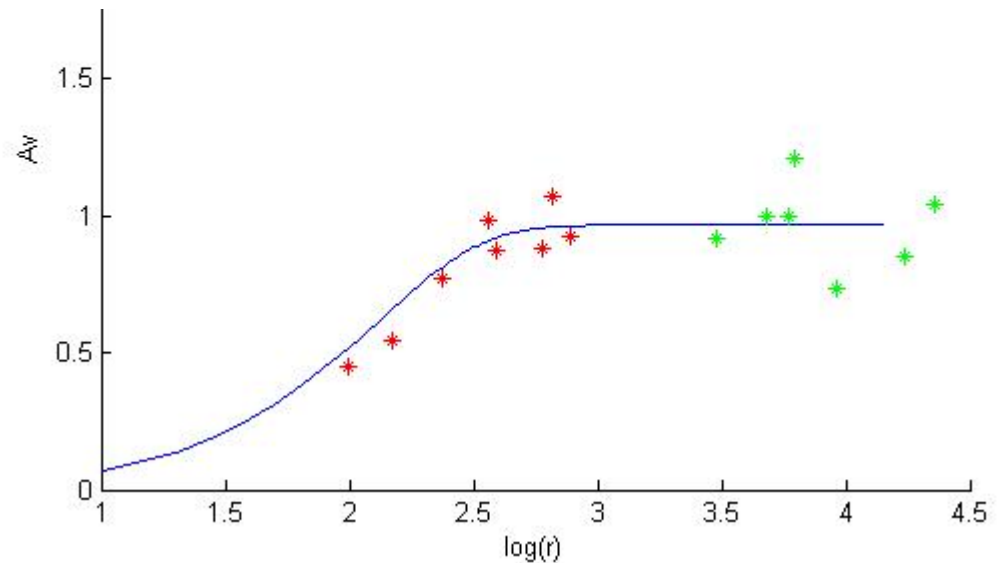


$$A = a_0 \beta |\sin^{-1} b| \times \left[ 1 - e^{-\frac{|\sin b|}{\beta} r} \right],$$

$$a_0 \approx 0.00748,$$

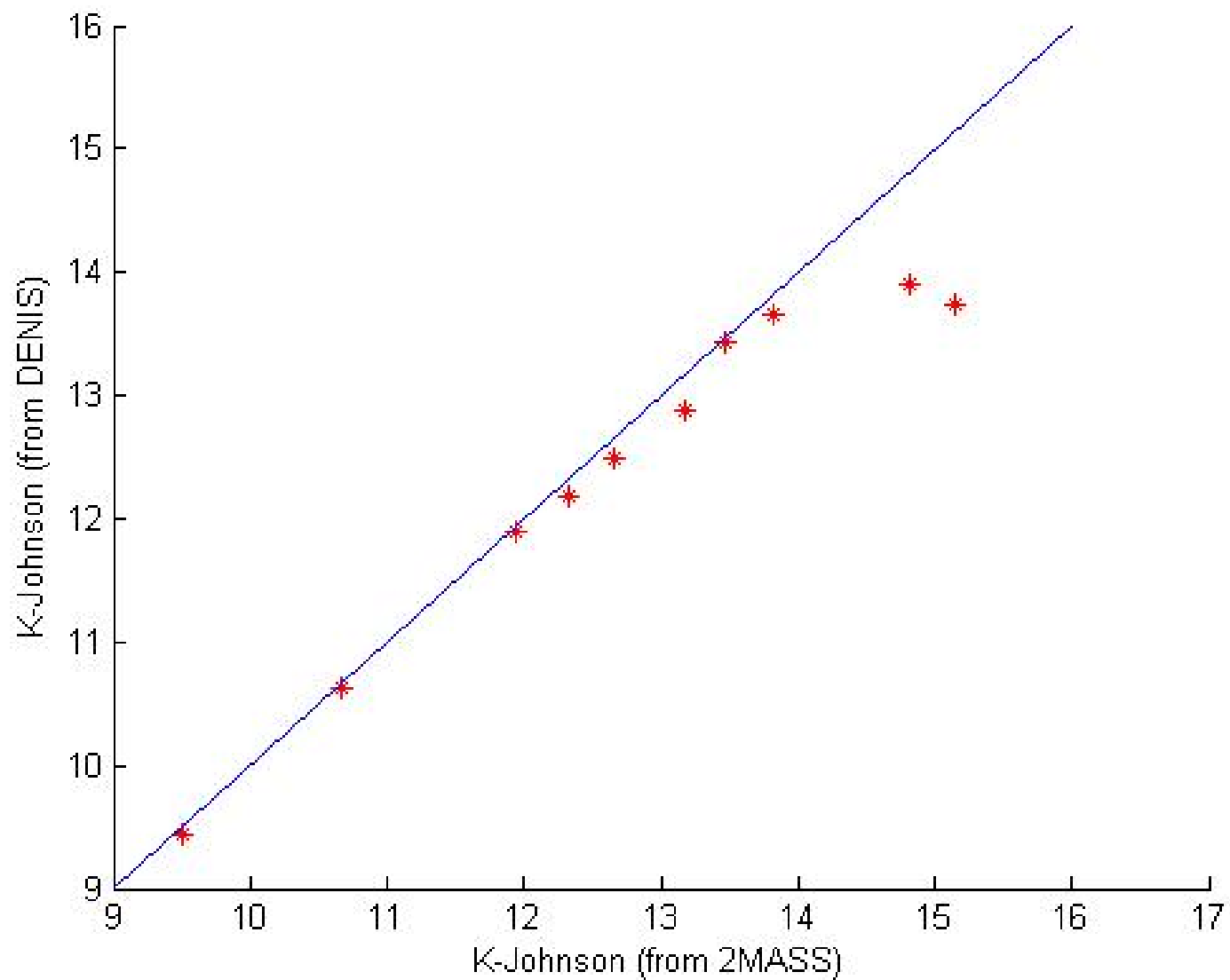
$$\beta \approx 114,$$

$$b = -62.$$



# Problem of false solutions

- Variable stars, some types of double stars, solar system and extra-galactic objects should be somehow removed from the sample
- Limiting distances should be estimated for each area
- Cross-check data: calculate Johnson bands (e.g., K) from different surveys (2MASS and DENIS) and compare them



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# Advantages of the method

- No need for observational spectral type and trigonometric parallax.
- $10^4 - 10^6$  times more stars are used, than in “classical” models.
- Limiting distances are significantly more than  $10^2 - 10^3$  pc, used in “classical ” models.

# Requirements to the method

- Regions with anomalous interstellar extinction law (dense dark nebulae and star formation regions containing young stars, dust and gas) should be excepted (or regional variations in the uniform interstellar extinction law should be taken into account).
- Transformation equations between original and Johnson photometric systems (or intrinsic color indices and absolute magnitude tables as well as interstellar extinction law for original photometric system) should be available (or constructed in the frame of the current project) for all surveys.
- Variable stars, some types of double stars, solar system and extra-galactic objects should be somehow removed from the sample.
- Photometric systems and stellar spectral classes should be selected, where temperature reddening can be clearly distinguished from interstellar reddening.

# Additional technical requirements

- SDSS, DENIS, 2MASS, DPOSS, UKIDSS, USNO-B photometry should be recalculated into the 13-color system, using appropriate modern calibration relations
- Modern  $(B-\lambda)_0$  and  $M_\lambda(\text{Sp})$  calibration tables should be used (FitzGerald 1970, Ducati 2001, ...) or constructed

# The main defect of the procedure

- Transformation relationships (between Johnson and original photometry) are derived statistically, i.e., for a mixture of stars of different luminosity classes.
- Consequently, they can not be used for determination of some luminosity classes

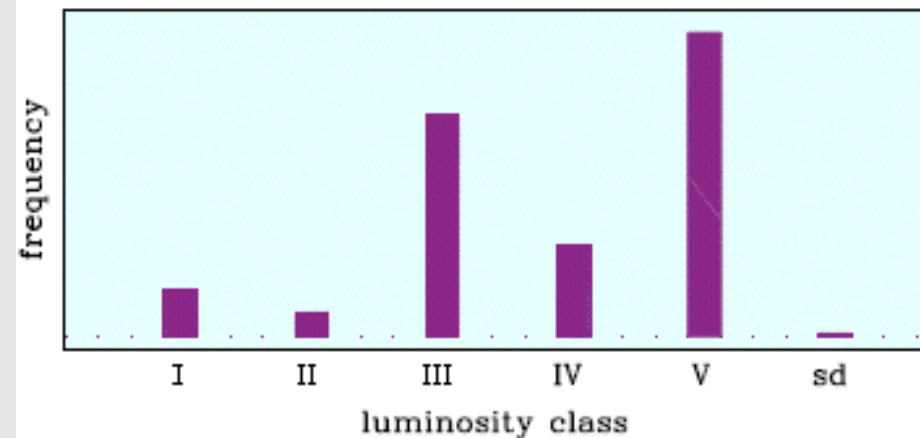
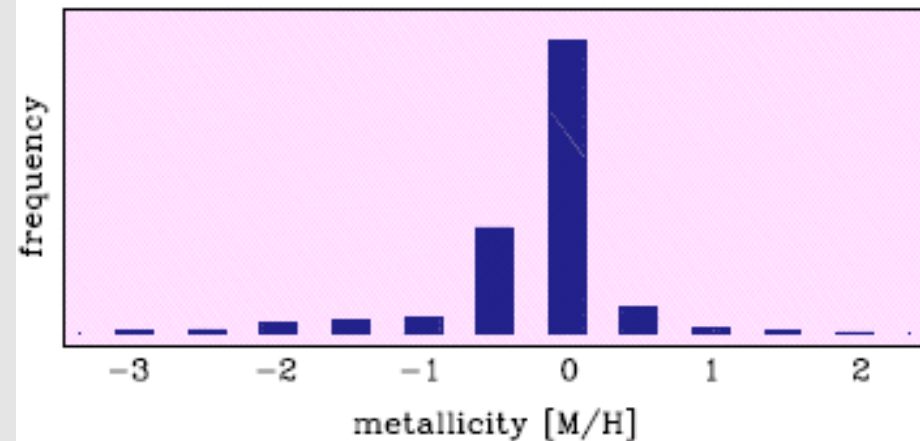
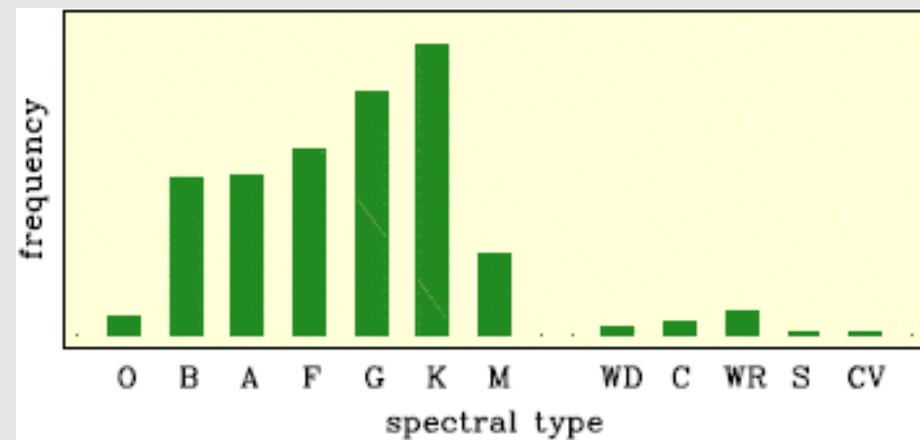
# Solution

- One can model intrinsic color indices in original photometric systems. To do this, one needs
  - theoretical or empirical SED for stars of various spectral types
  - response curves of original photometric systems
  - interstellar extinction law

# Outline

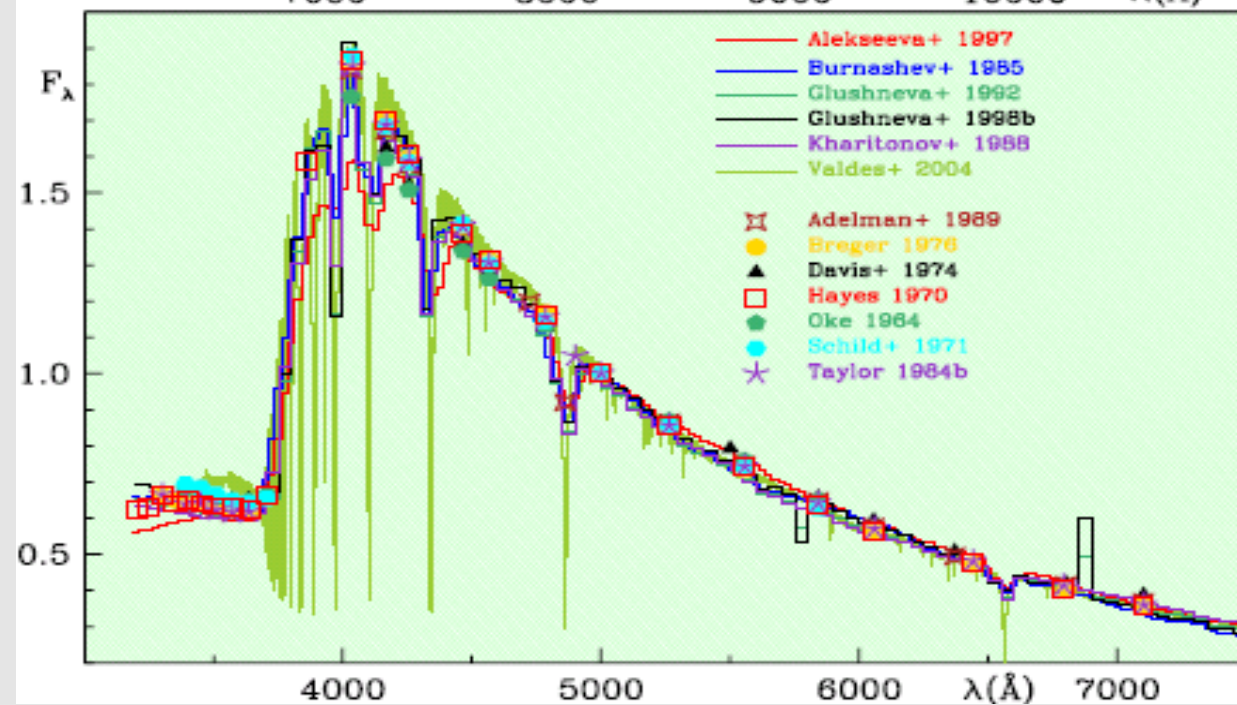
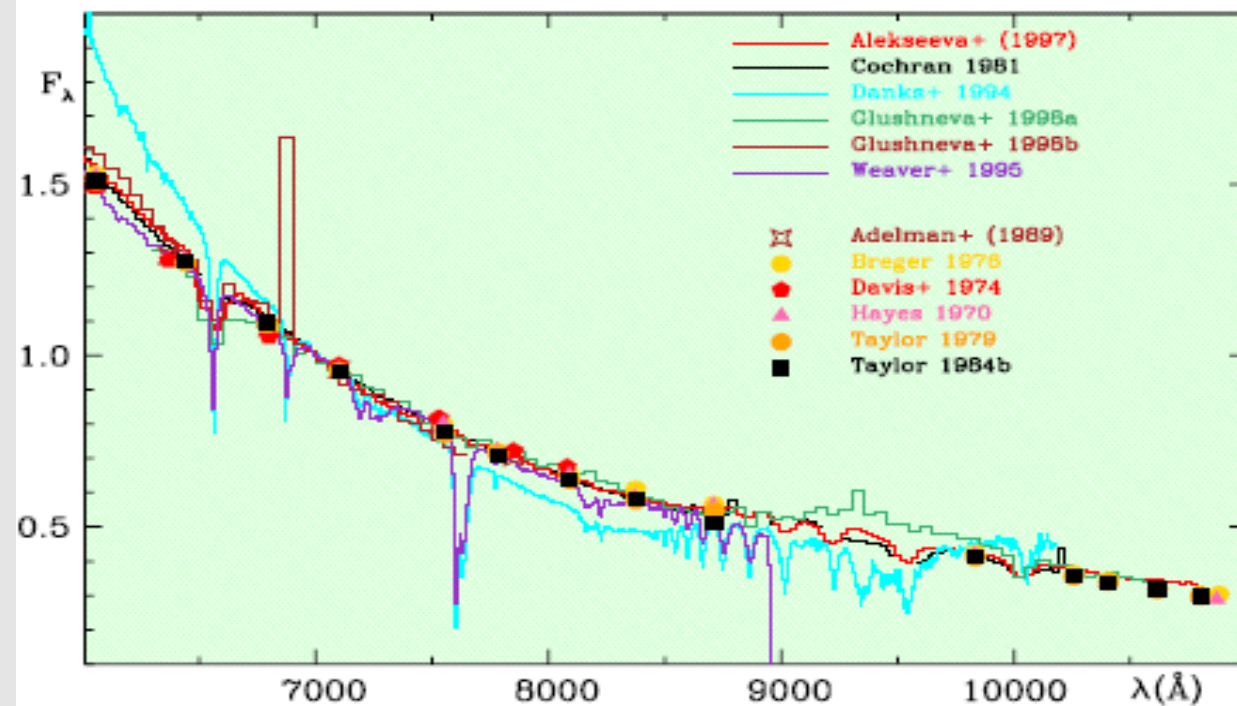
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# Observed spectra



- Distribution of ~9500 stars whose spectrum is present in the libraries of optical spectra
- Asiago Database of Spectroscopic Databases (<http://web.pd.astro.it/adsd/>, Sordo R. and Munari U. 2006 A&A 452, 735)

# SEDs of $\gamma$ Gem (A0IV)



# Modelling: choice of spectral library

- An analysis shows that Pickles A.J. (1998, Publ. Astron. Soc. Pac. 110, 863) is one of the best empirical libraries
- Drawbacks:
  - LC are from I to V (no WDs),
  - Spectral type serves as an input parameter (usage of continuous parameters –  $T_{\text{eff}}$ ,  $\lg g$ , ... – is more comfortable)
  - Early type stars (O-B3) remain reddened

# Modelling: response curves and interstellar extinction law

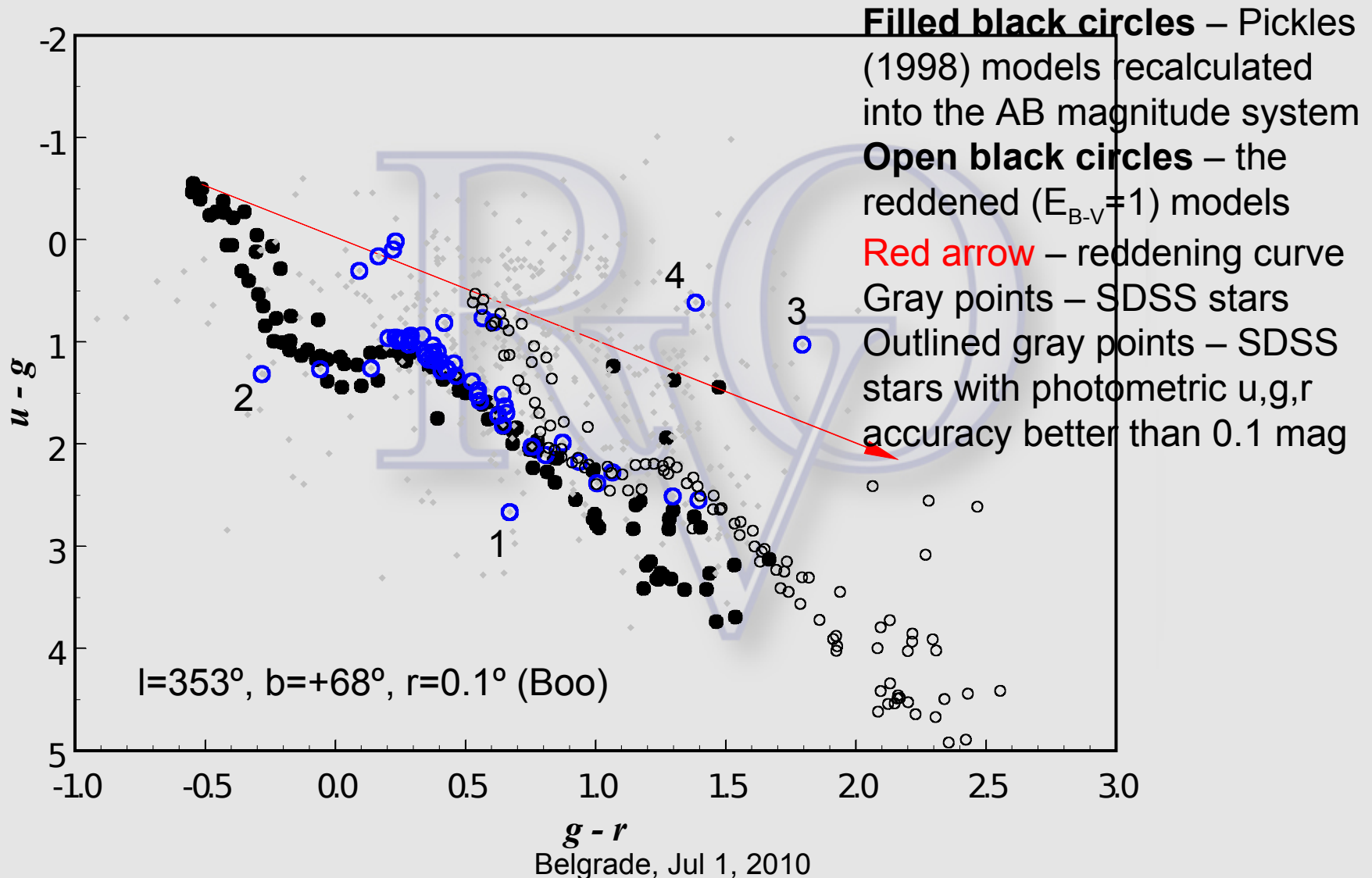
- Response curves of UV photometry surveys
  - SDSS
  - GALEX
  - Gaia
- Fluks et al. (1994) interstellar extinction law

Synthetic stellar magnitude for k-th band of photometric system is calculated as

$$m_k = 2.5 \log \sum E(\lambda) T_k(\lambda) + C_k, \text{ where}$$

- $E$  – spectral energy distributions taken from Stellar spectral flux library (Pickles 1998),
- $T_k$  – response functions of the original photometric system (for Gaia: Jordi and Carrasco 2007),
- $C_k$  – correction coefficients chosen so that  $m_k(A0V)=0$  for all  $k$ .

# SDSS: theory and observations

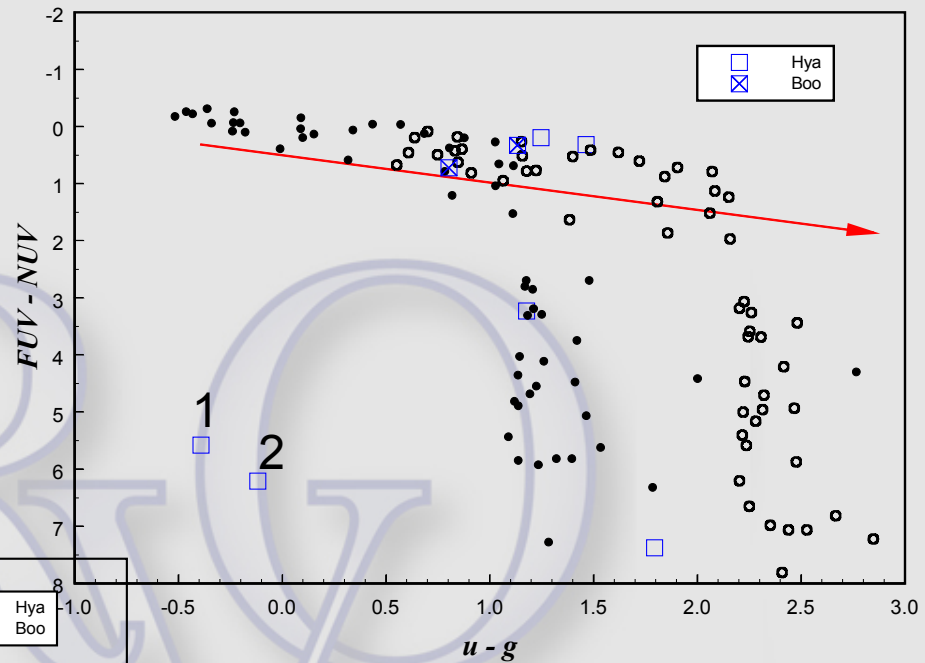
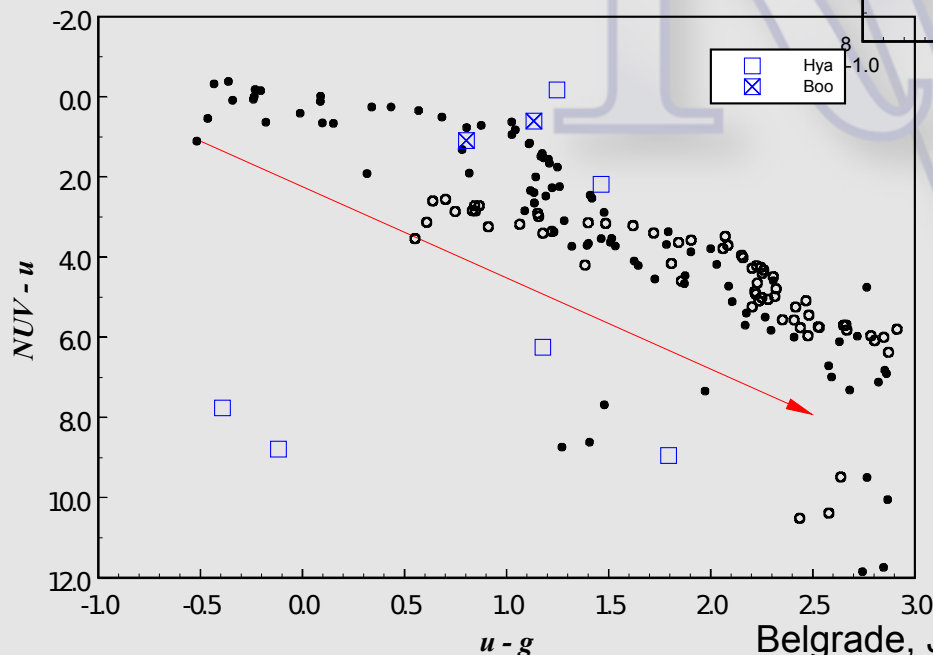


# GALEX/SDSS:

## theory and observations

$l=353^\circ$ ,  $b=+68^\circ$ ,  $r=0.1^\circ$  (Boo)

$l=228^\circ$ ,  $b=+27^\circ$ ,  $r=0.1^\circ$  (Hya)



**Filled black circles** – Pickles (1998) models recalculated into the AB magnitude system

**Open black circles** – the reddened ( $E_{B-V}=1$ ) models

**Red arrow** – reddening curve

**Blue squares** – GALEX/SDSS stars

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# Possible reasons for disagreement of observational and simulated points:

- Observational error, misprint in catalogue or cross-matching error
- The star is a variable
- The star belongs to other LC
- Non-stellar nature of the object (galaxy, ...)
- Non-standard interstellar extinction law in the area
- ...?
- The star is a photometrically unresolved binary

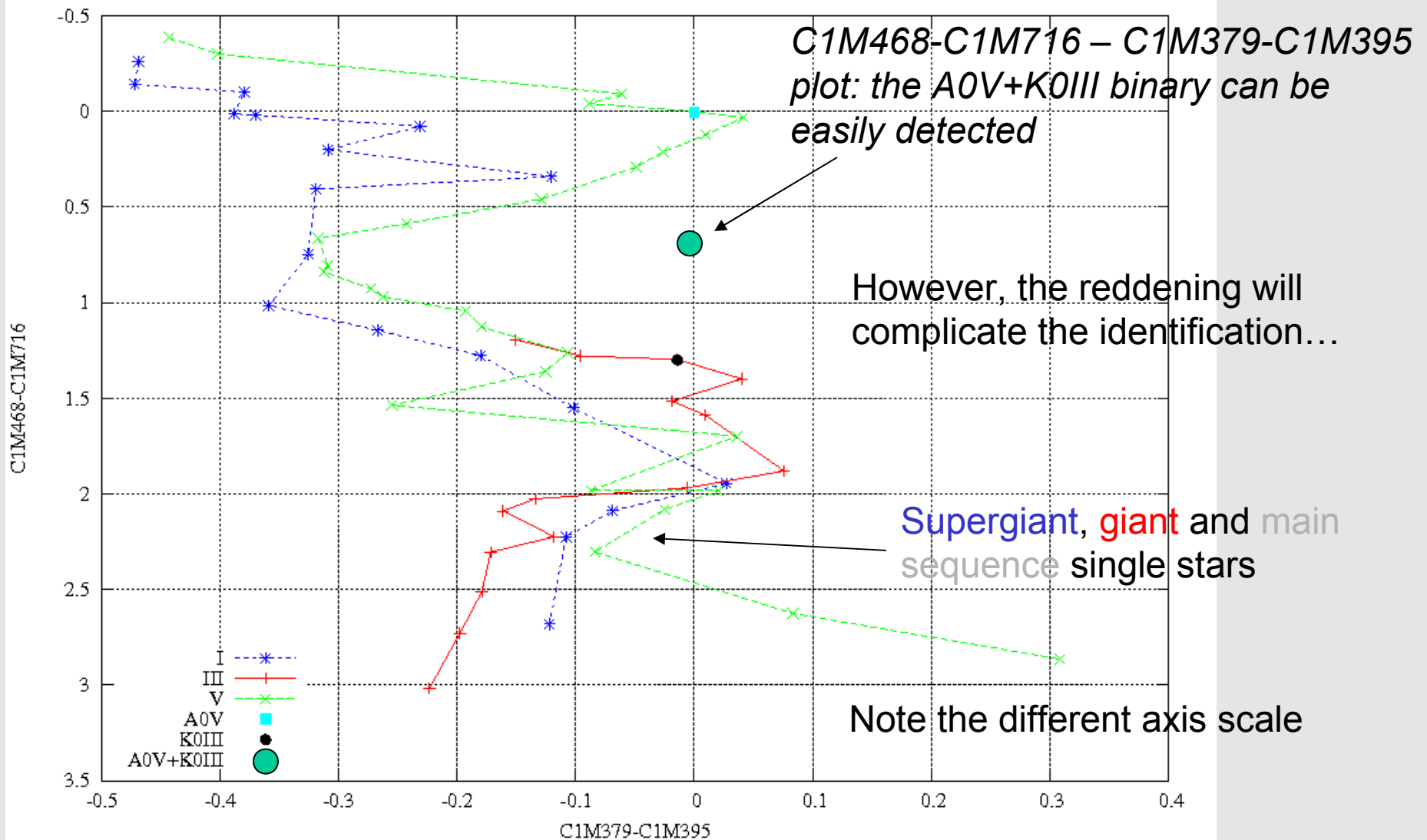
# Outline

- Introduction: stellar parameters and extinction
- Galactic interstellar extinction models
- Large surveys: cross-matching
- Parametrisation of stars with Johnson photometry
- Parametrisation of stars with original photometry
- Photometrically unresolved binaries
- Summary

# Unresolved binaries simulation

- Some photometrically unresolved binaries exhibit colors different enough from ones of single stars.
- Such binaries can be separated from single stars in some color index diagrams.
- The goal is to specify those binaries and those color index diagrams.

# An example: Gaia colors for A0V+K0III



# The following pairs can be unfiled:

- Evolutionary meaningless pairs.
- Pairs with components of very different luminosity ( $\Delta m > 3^m$ ).
- Pairs with components of similar temperature ( $\Delta \text{Sp} < 1/2$  spectral type, this approximately gives  $\Delta \log T_{\text{eff}} < 0.1$  for hot stars, and  $< 0.02$  for cool stars). *However, such pairs are recognizable on color-magnitude plots, as they have an increased luminosity for a given color.*

For remaining ~420 types of pairs, “best” Gaia color index diagrams are found

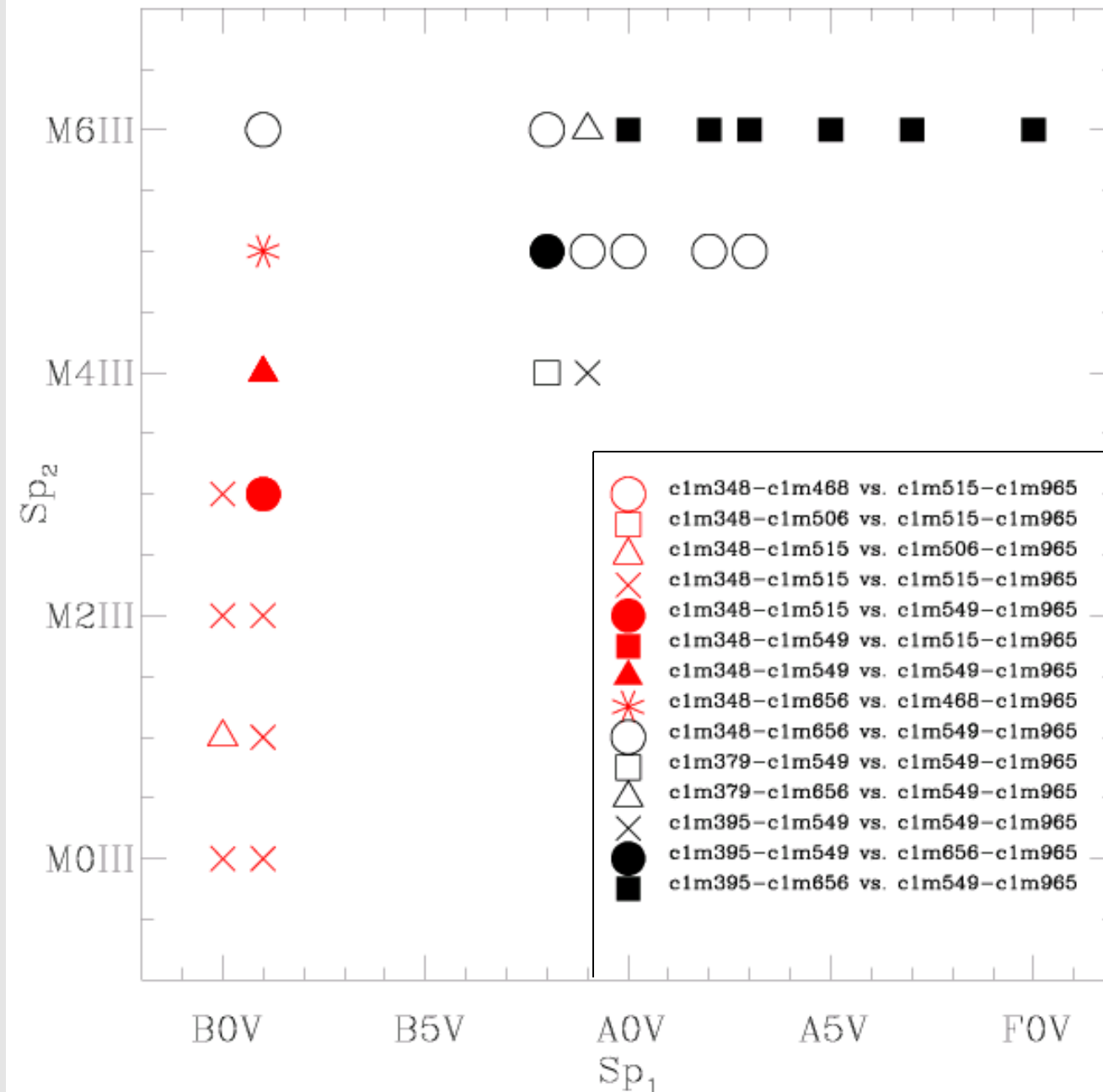
For every possible couple of spectra a two-color Gaia diagram can be found, where a separation of such a binary from the nearest single star is a maximum:

Binary star	Best two-color diagram for separation	Separation from the nearest single star, mag
1. B0V+F5I	c1m348-c1m515 – c1m861-c1m965	0.1
2. B8V+M3III	c1m395-c1m549 – c1m549-c1m965	0.9
3. A0V+M6III	c1m395-c1m656 – c1m549-c1m965	1.4
...	...	...
419. K3V+M1V	c1m410-c1m549 c1m716-c1m747	0.1

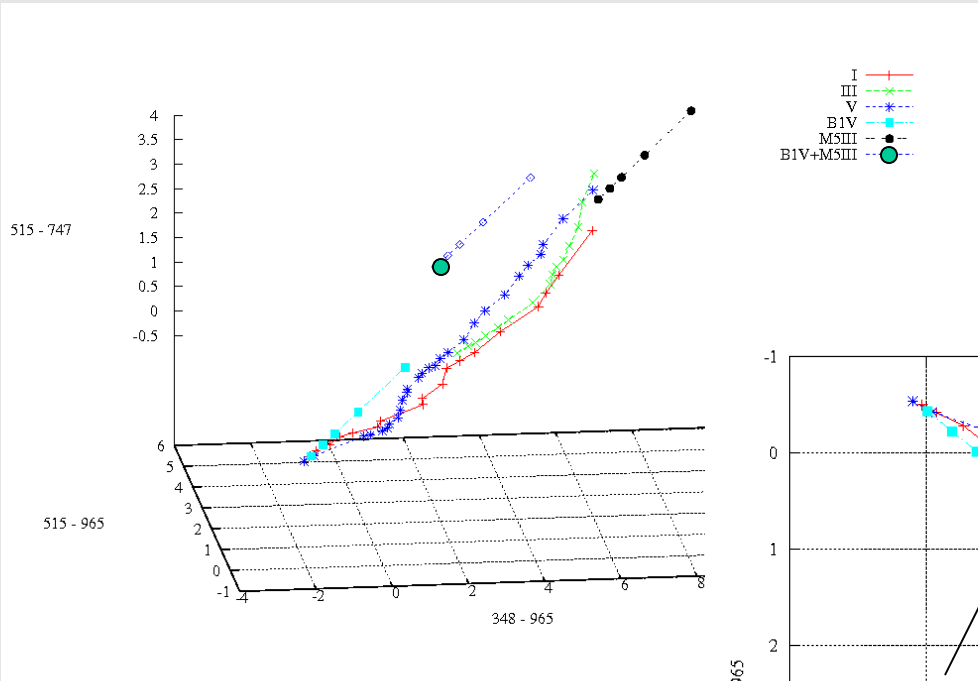
Primary vs.  
secondary  
spectrum plot  
(fragment):  
best two-color  
diagram for  
every binary is  
indicated

Only pairs are indicated,  
where separation from  
single stars  $> 1^m$  can be  
reached

Note the importance of  
extreme (m348 and  
m985) bands!

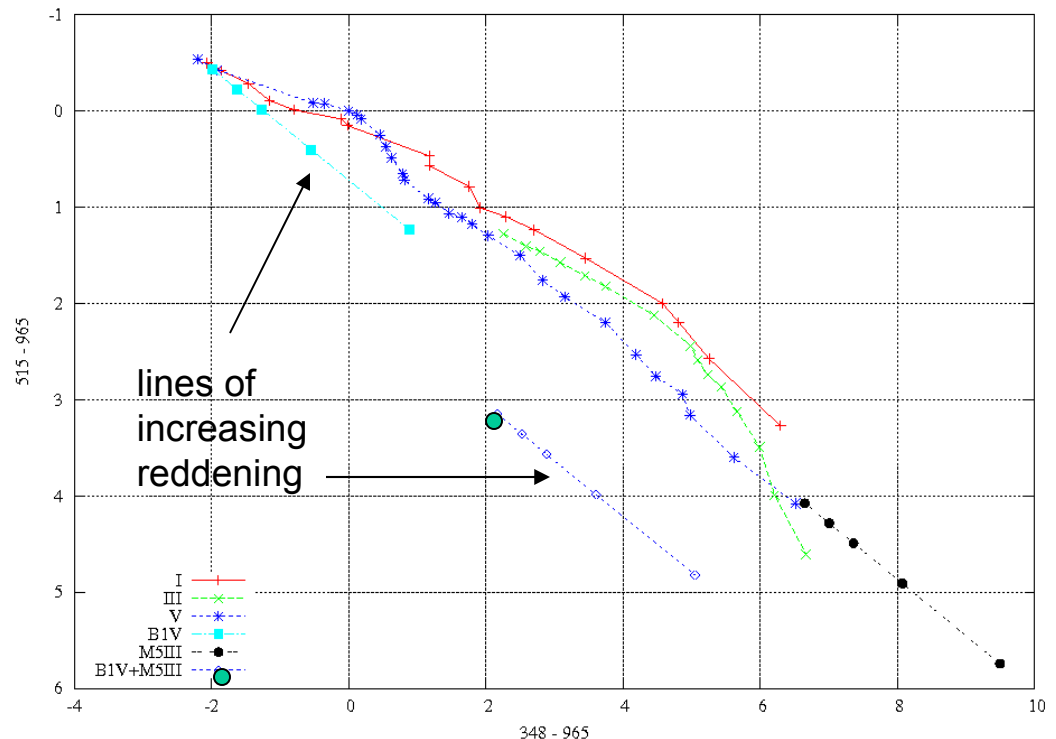


# Another example: B1V+M5III, Gaia photometry

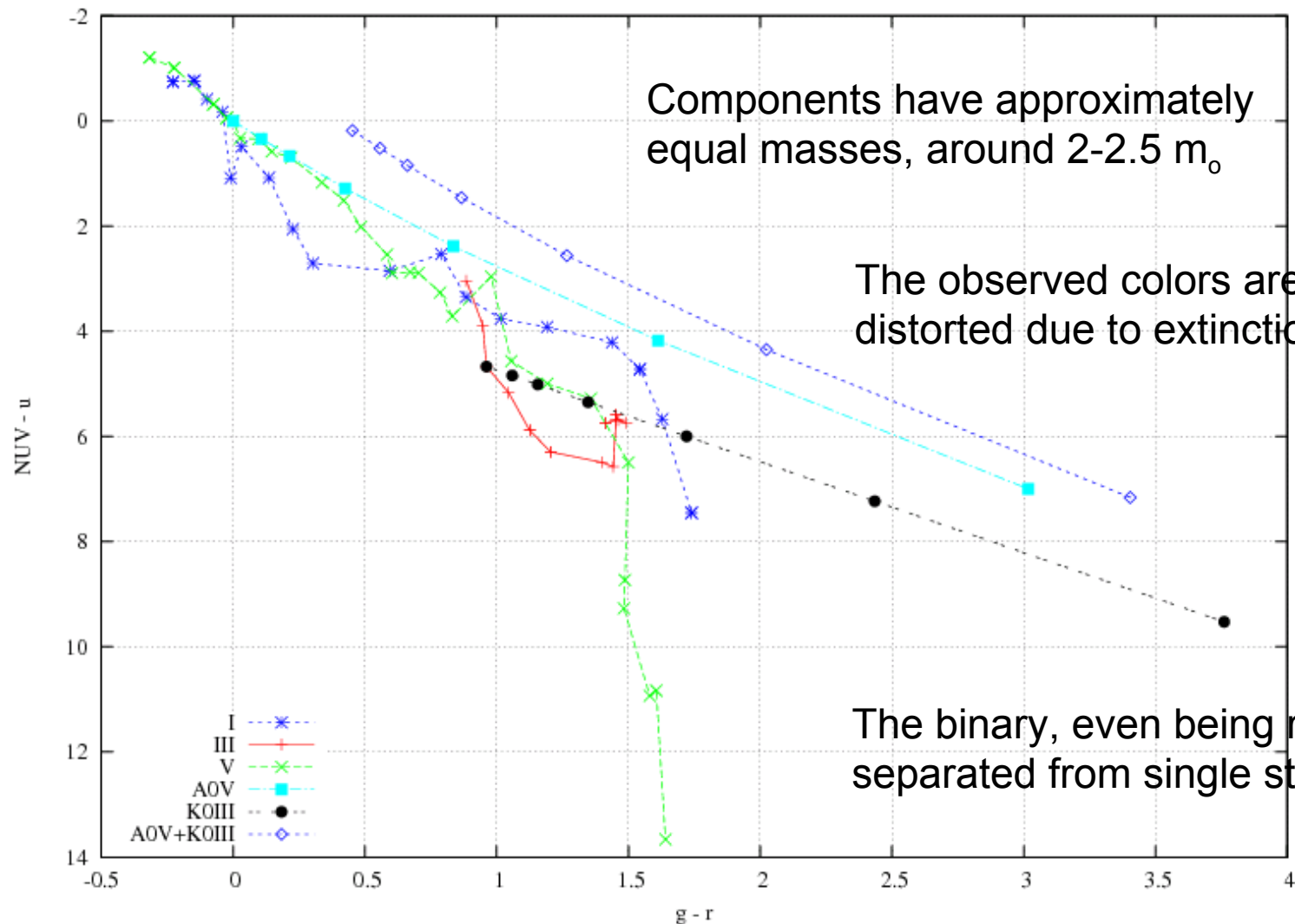


Here interstellar extinction  
does not prevent to discover  
the pair

Note: this pair was/is not a detached  
binary, as the more evolved  
component is the less massive one:  
 $\text{mass}(\text{B1V})=15m_{\odot}$ ,  $\text{mass}(\text{M5III})=1m_{\odot}$



# A0V+K0III GALEX/SDSS photometry

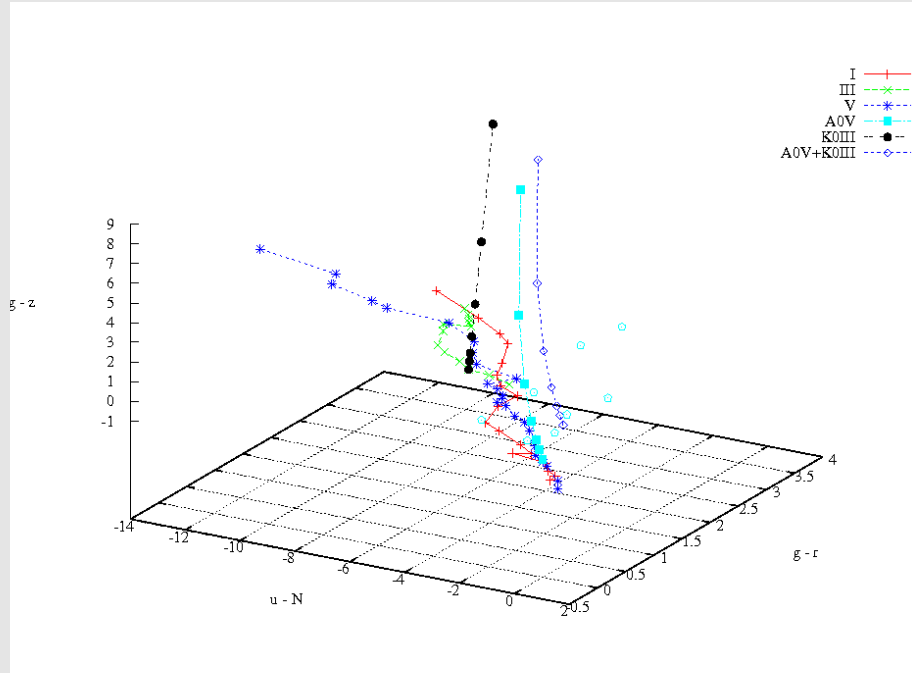


Components have approximately equal masses, around  $2-2.5 m_{\odot}$

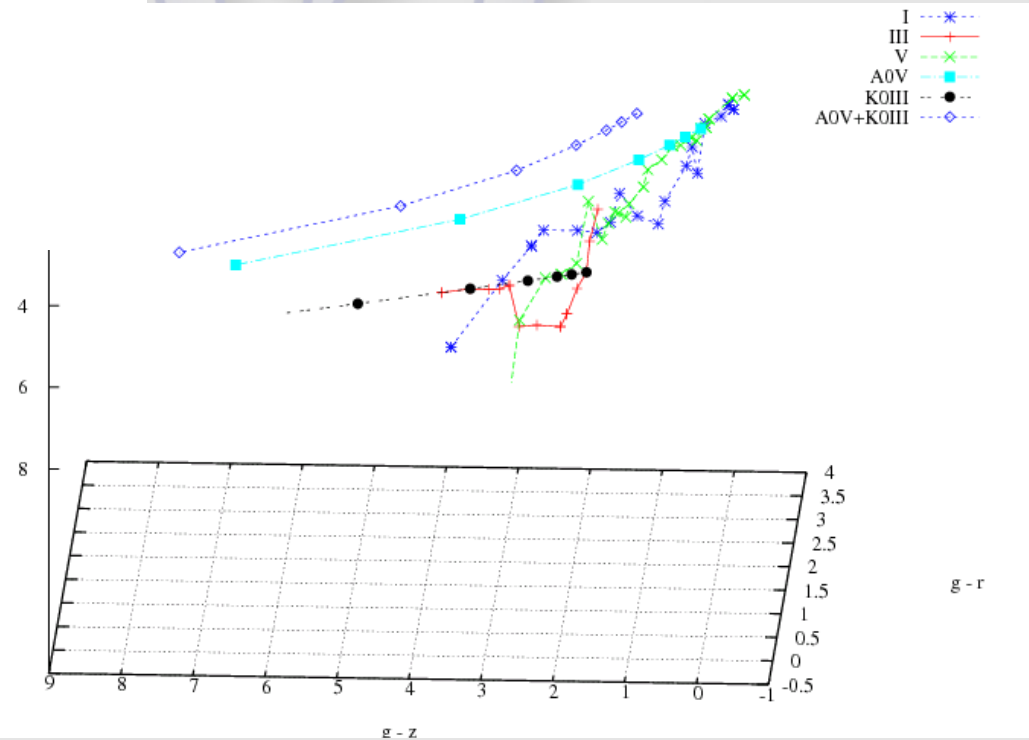
The observed colors are **significantly** distorted due to extinction.

The binary, even being reddened, is separated from single stars.

# A0V+K0III GALEX/SDSS photometry



NUV - u



# SDSS: theory and observations

1: probably G5I, D=0.9 mag

2: probably B8V+M1III, D=1.1 mag

3: probably A2I+K3I, D=1.8 mag

4: probably B3I+G8I, D=1.2 mag

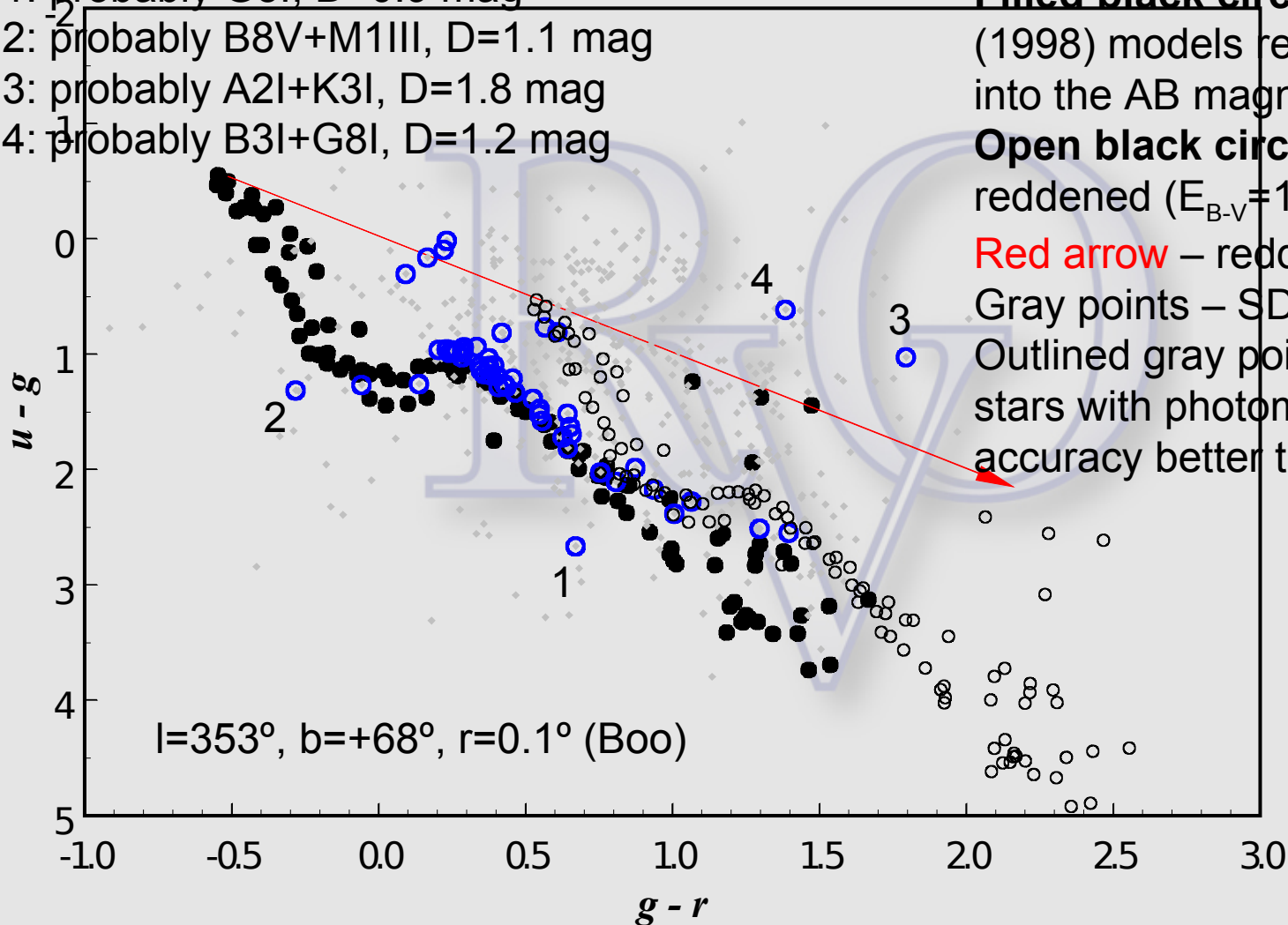
**Filled black circles** – Pickles (1998) models recalculated into the AB magnitude system

**Open black circles** – the reddened ( $E_{B-V}=1$ ) models

**Red arrow** – reddening curve

Gray points – SDSS stars

Outlined gray points – SDSS stars with photometric u,g,r accuracy better than 0.1 mag



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# GALEX/SDSS:

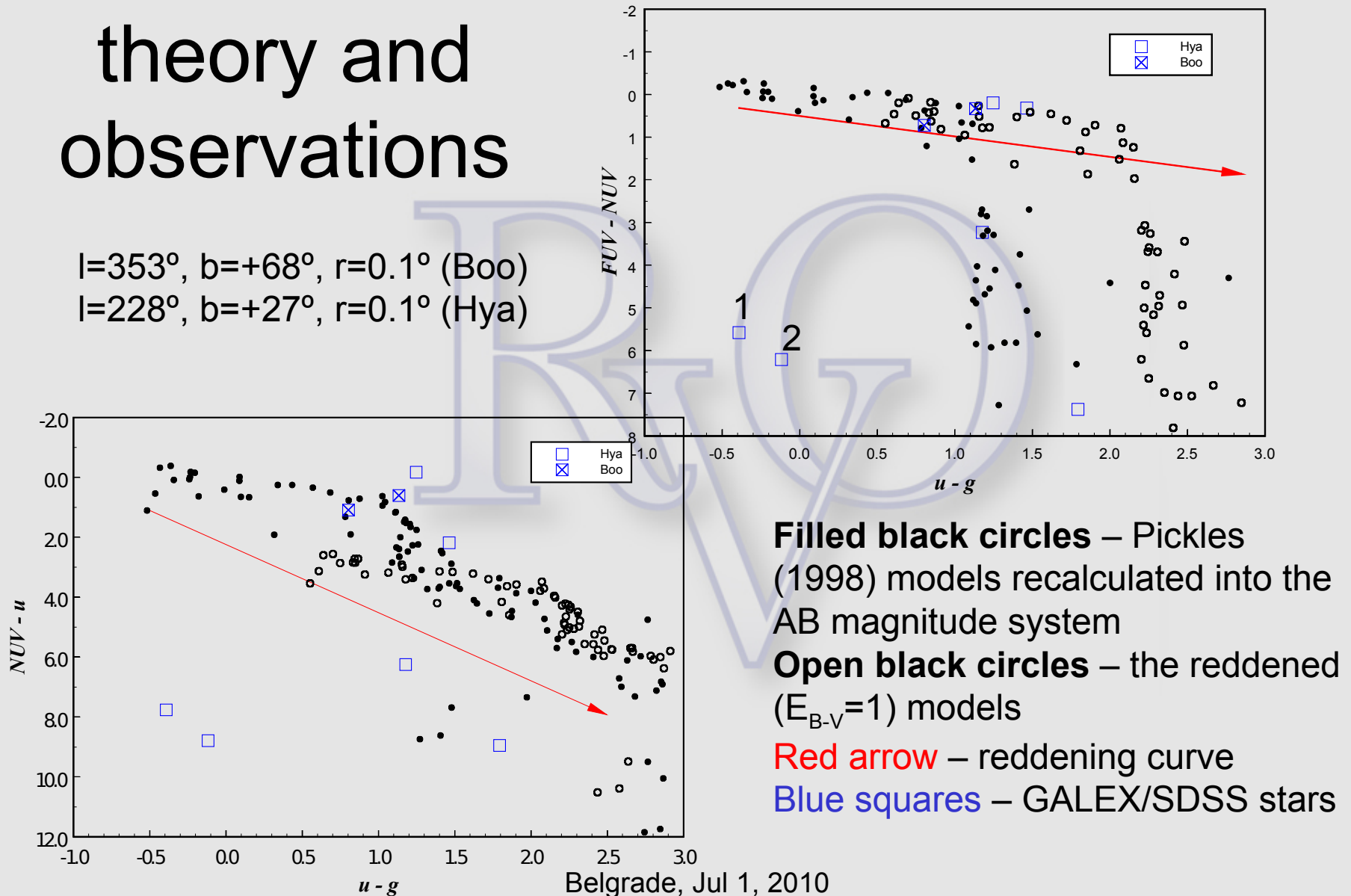
## theory and observations

$l=353^\circ$ ,  $b=+68^\circ$ ,  $r=0.1^\circ$  (Boo)

$l=228^\circ$ ,  $b=+27^\circ$ ,  $r=0.1^\circ$  (Hya)

1: probably B0I+K3I,  $D=3.0$  mag

2: probably B1I+K3I,  $D=2.0$  mag



Belgrade, Jul 1, 2010

# Summary

- Cross-match of large photometric surveys is made, and modern VO facilities (OpenSkyQuery, RVO tool, GAVO matcher, etc.) for cross-matching are compared
- A tool for simulation of color index diagrams and parameterization of stars is constructed.
- Modern (GALEX, SDSS, soon GAIA) photometry can be used for [*even reddened*] single-binary star separation and for parameterization of stars.
- Gaia color indices, suitable for single-binary star separation, are found

# Future work

- Cross-matching of current surveys (GALEX, SDSS; together with UKIDSS, DENIS, 2MASS photometry) and incorporation of coming data (Gaia, WSO-UV, Lira-B, Sveccha), using VO techniques.
- Parameterization of single and, when possible, binary stars.
- Parenago cosecant law will be substituted by a more complicated formula as one approaches the galactic equator, where it is essential to take into account absorption in clouds.
- On-line model will be constructed.
- Determination of extinction value in a given area, and construction of a 3D galactic interstellar extinction map.

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