National Astronomical Observatories
Center for Operation and Development of Guo Shoujing Telescope

Carbon stars from LAMOST DR4

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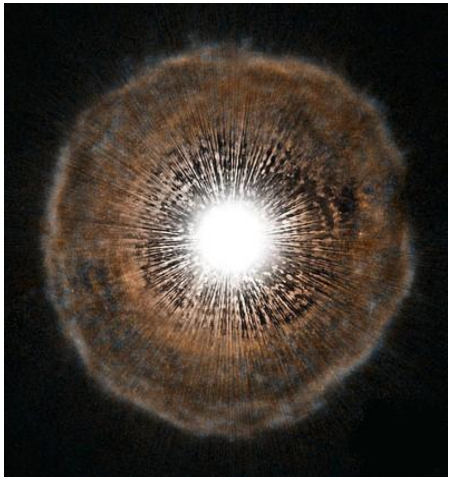
2017.02.19

Outline

- Background
- How to find carbon stars ?
- Spectra MK Classification
- Multiple-wavelength Data
- Compared with previous work

Background

- Definition of carbon star
  - C/O > 1
  - Optical spectra: CH, C2 or CN band
  - Infrared spectra: SiC band
- Origins of carbon
  - Giants: from the third dredge-up of TP- AGB phase
  - Dwarfs: from their companion
- Why is carbon star rare ?
  - The short time scale of TP-AGB phase (a few hundred years)
  - Only third dredge-up can convect carbon to surface
  - Only strong dredge-up can produce carbon stars
- Why do we study carbon stars?
  - Play an important role in the nuclear synthesis process
    - Synthesize about half of elements heavier than iron by the s-process
    - Synthesize carbon by the triple-alpha process
  - Help us to understand the evolution of galaxies
  - As probes to investigate the dark matter halo, Galactic potential, dwarf galaxies or stellar streams.



Background

- Detection History
  - Alksnis, A. et al. 2001, 10, 1 --- 6891 carbon stars
  - Christlieb, N. et al. 2001, 375, 366 --- 403 FHLCs --- HES spectra
  - SDSS
    - Margon, B., et al. 2002, 124, 1651 --- 39 FHLCs
    - Downes, R., A., et al. 2004, 127, 2838 --- 251 FHLCs
    - Green, P. 2013, 765, 12 --- 1220 FHLCs
    - Si, J.M., et al. 2014, 57, 176 --- 260 carbon stars
  - LAMOST
    - Si, J.M., et al. 2015, 15, 1671 --- 183 carbon stars
    - Ji, W., et al. 2016, 226, 1 --- 894 carbon stars
  - DFBS
    - Gigoyan, K.S., et al. 2012, 544, A95 --- 13 FHLCs
    - Gigoyan, K.S., et al. 2014 --- 54 FHLCs
    - Gigoyan, K.S., et al. 2015 --- 66 FHLCs

How to find carbon stars ?

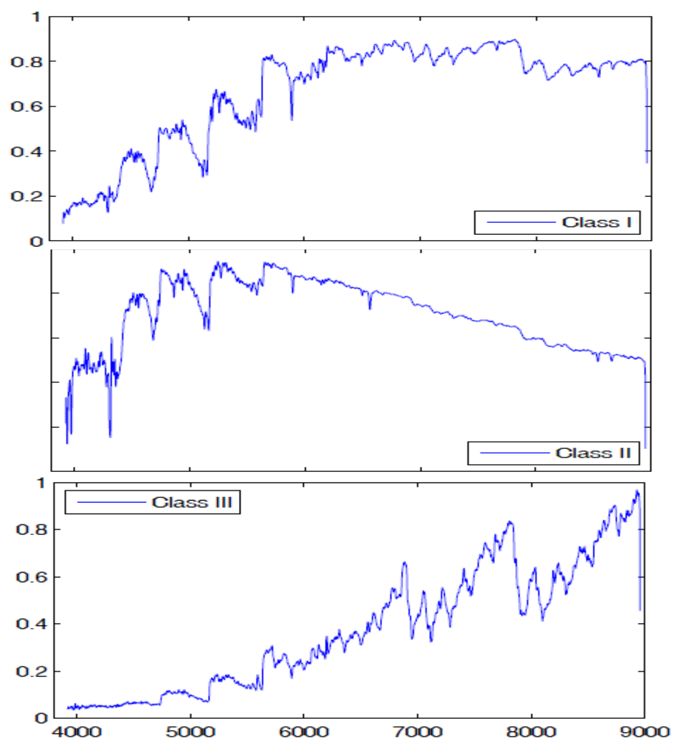
The process of finding carbon stars

Construction and Classification of positive sample set → **Spectra preprocessing** → **Research of Retrieval algorithms** → **Artificial identification**

How to find carbon stars ?

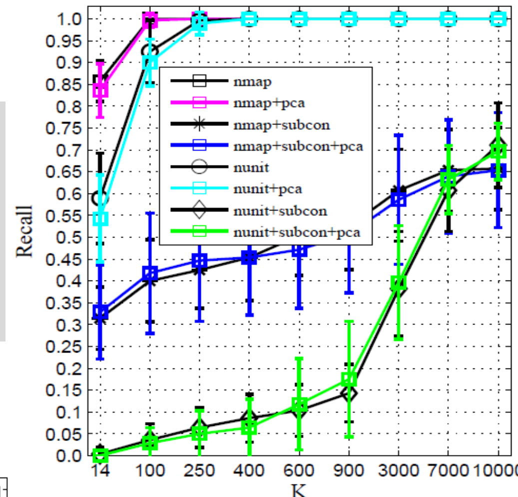
Construction and Classification of Positive Sample Set

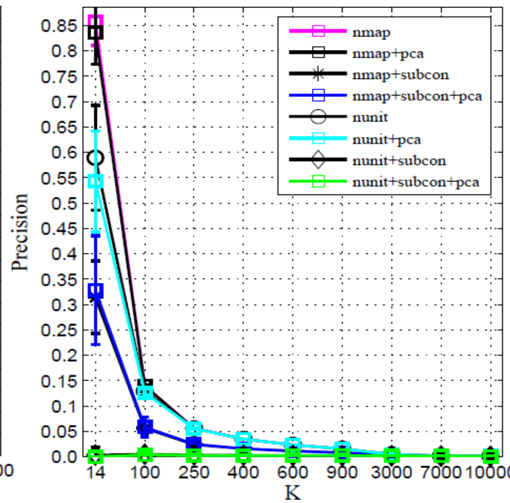
SDSS + LAMOST (1682) → Four steps → **Positive Sample Set （1050）** → **K-mean Clustering （50 groups）** → **Similarity Measurement**

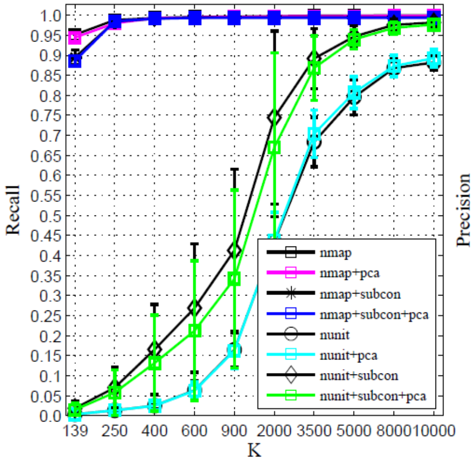


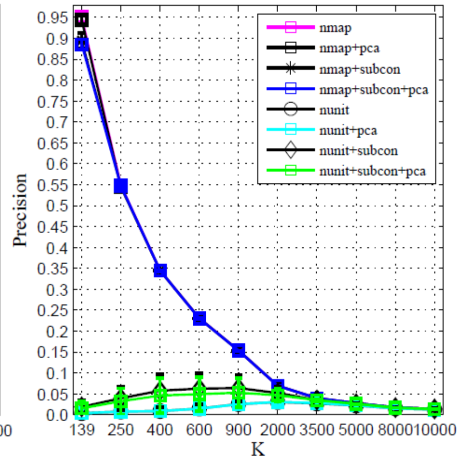
How to find carbon stars ?

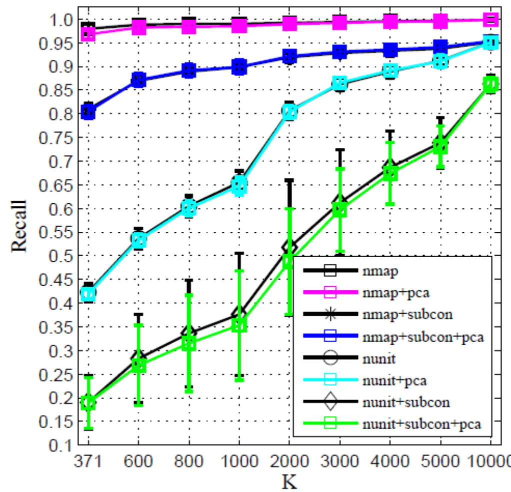
- Spectra Preprocessing Research
  - For each type of template spectra
  - Design eight preprocessing experiments
  - To investigate the effect of preprocessing methods on retrieval performance

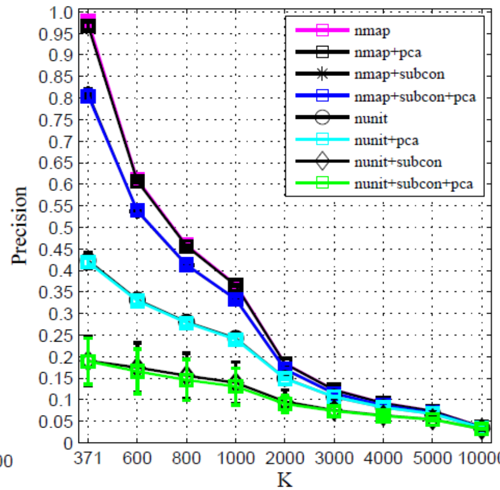






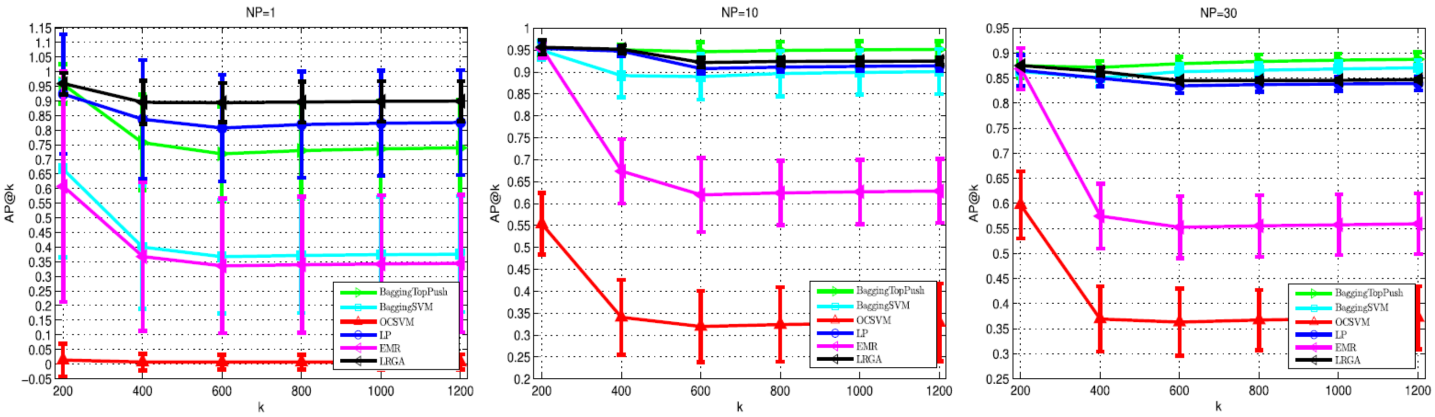




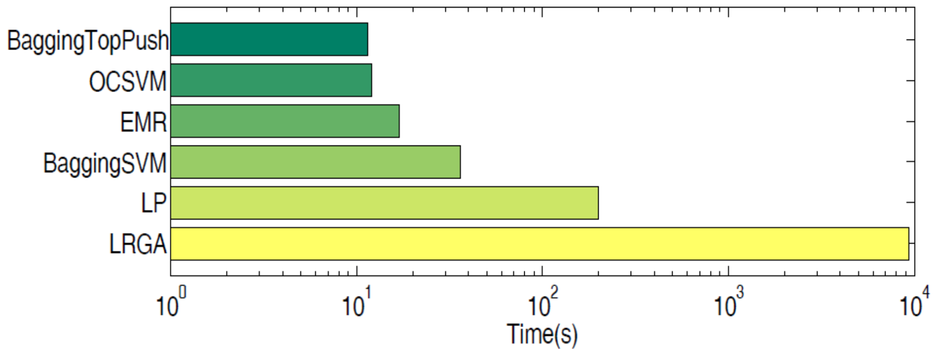


How to find carbon stars ?

- Research of Retrieval algorithms
  - Six Machine Learning Algorithm Comparison
  - Time Consuming of Key steps of Bagging TopPush Algorithm

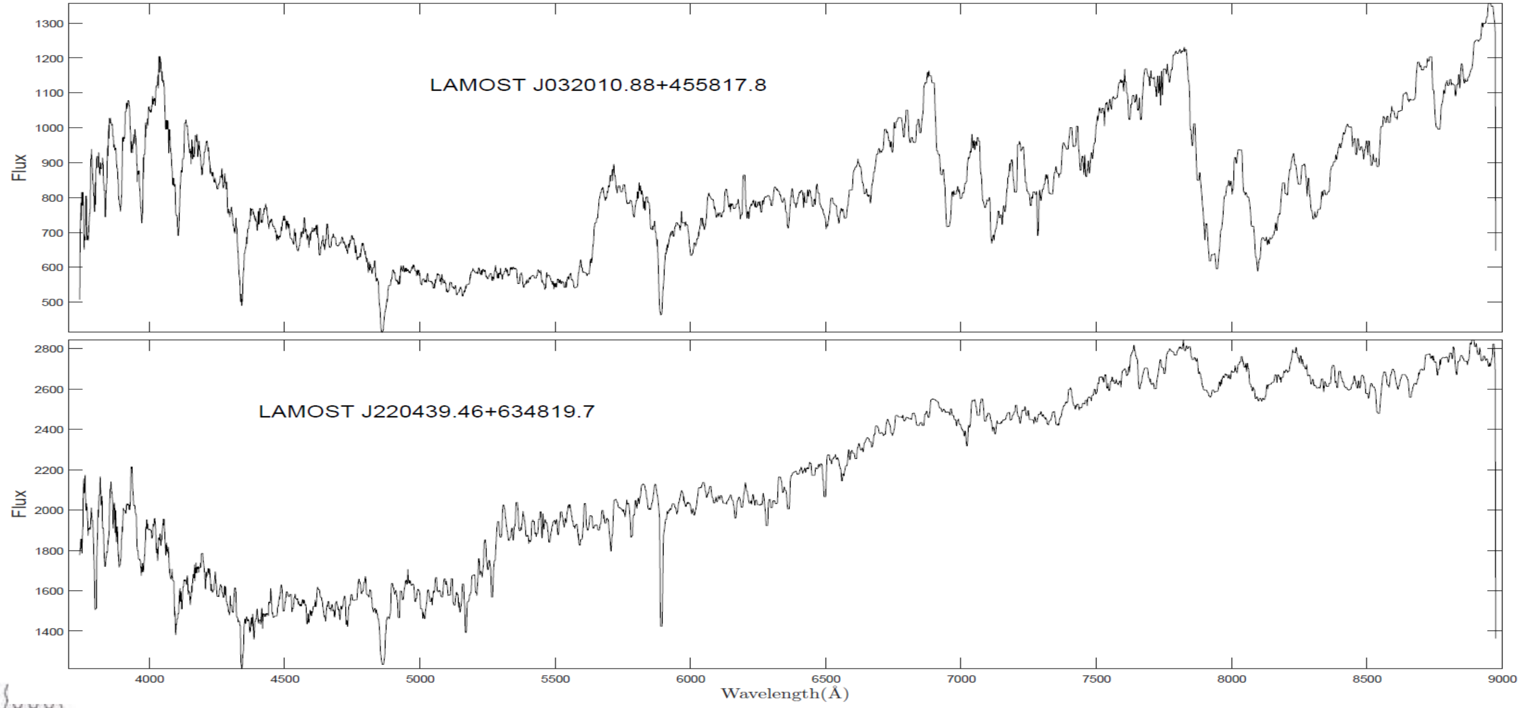


(a) NP=1 (b) NP=10 (c) NP=30



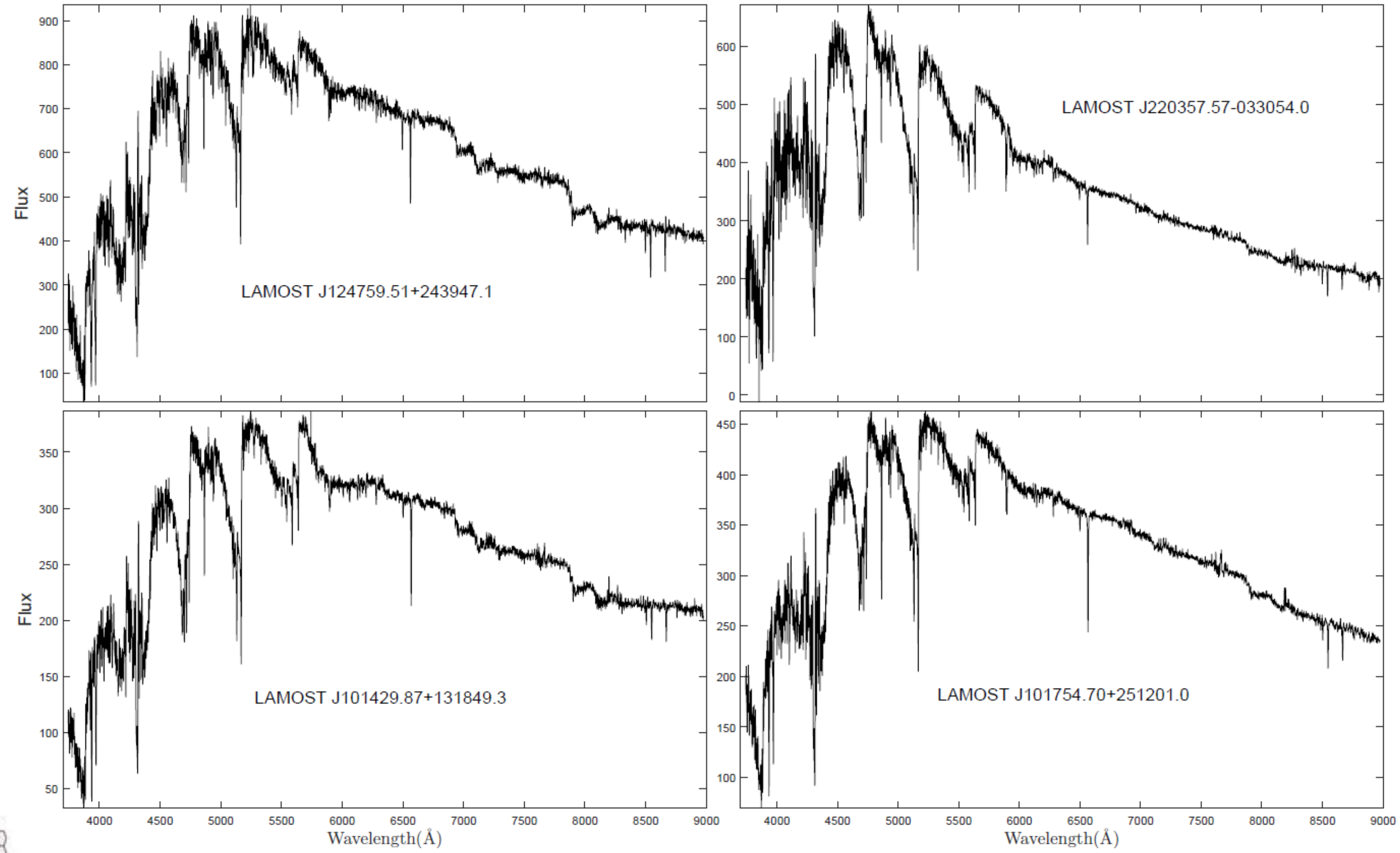
How to find carbon stars ?

- Bagging TopPush Algorithm + over one billion spectra
  - 2651 carbon stars from LAMOST DR4
  - 1415 of them are new findings
  - 17 carbon-enhanced metal-poor main sequence turn off stars
  - Examples of Spectral Binaries



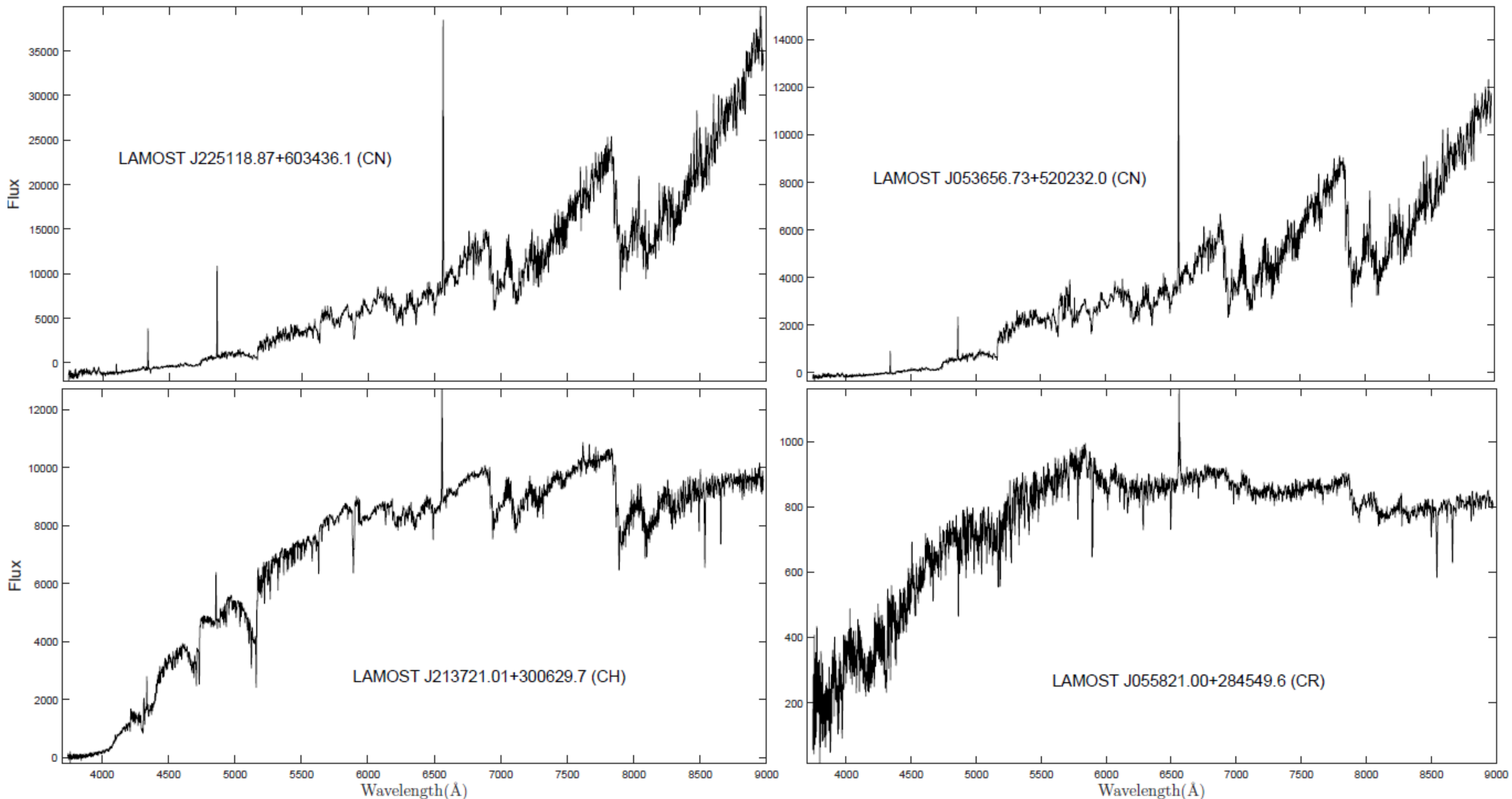
How to find carbon stars ?

Example of G-type carbon stars



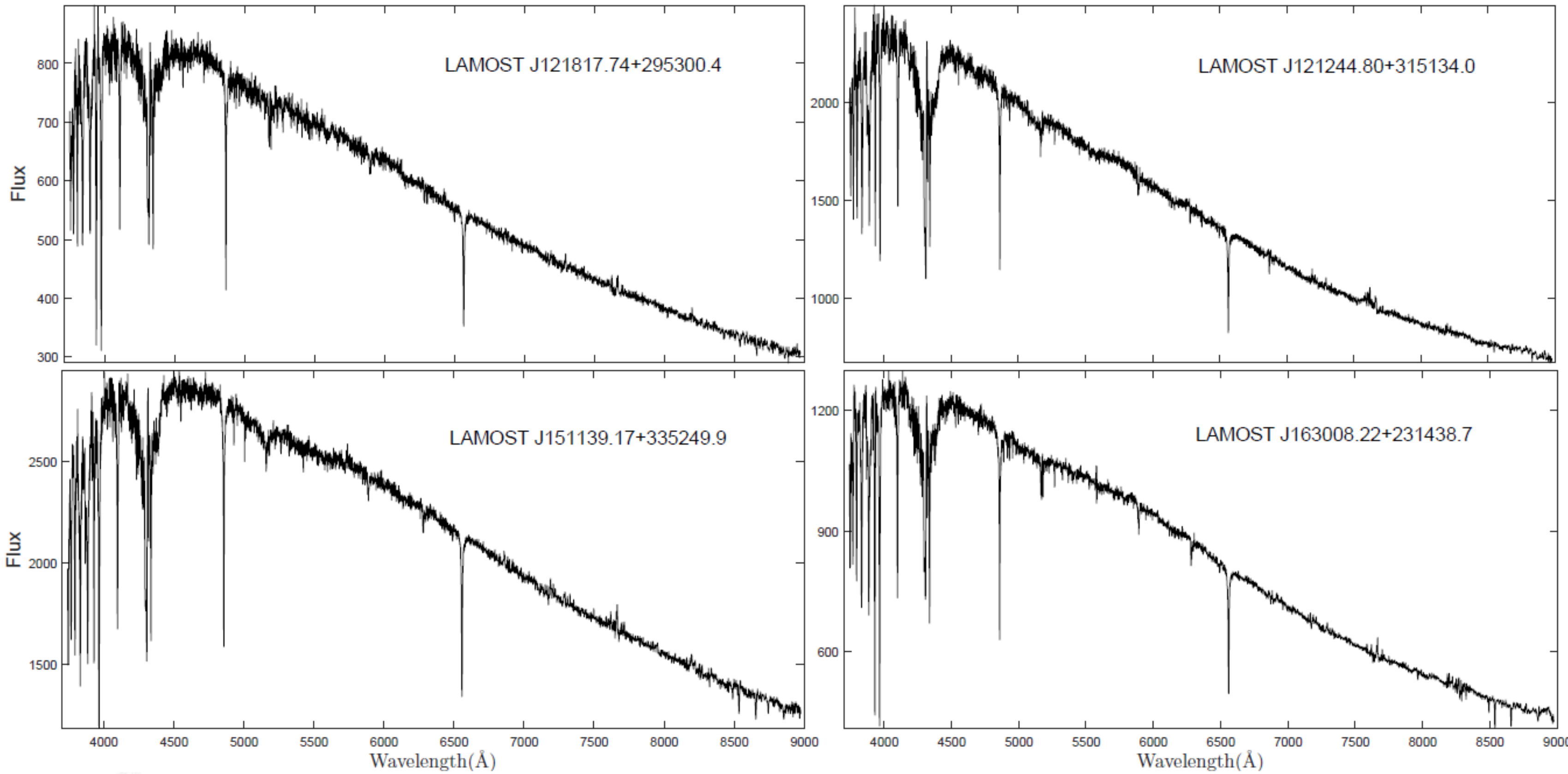
How to find carbon stars ?

Examples of emission line carbon stars



How to find carbon stars ?

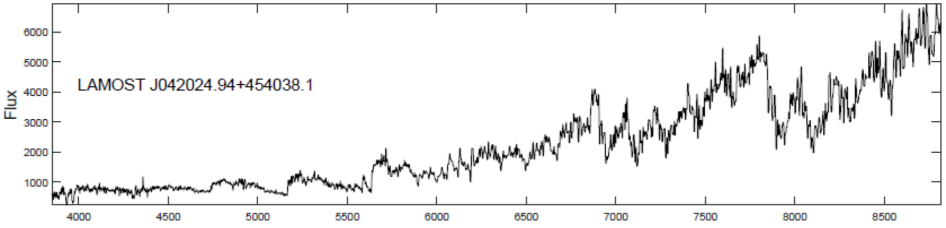
Examples of carbon-enhanced metal-poor main sequence turn off stars

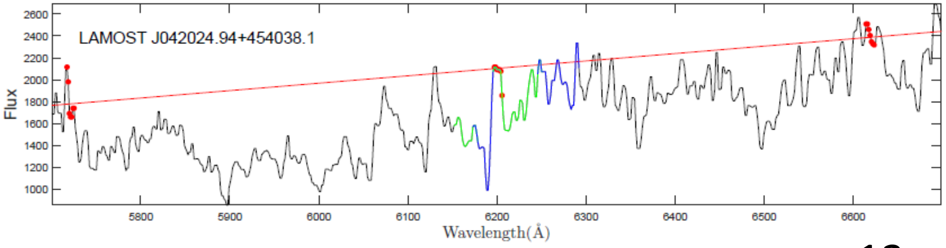


Spectral MK Classification

Sub-type	Criteria
C-H	1) Prominence of the secondary P-branch head near 4342 Å; 2) Strong G-band (CH band); 3) Hβ and Ba II at 4554 Å are clearly noticeable; 4) Hα and Ba II at 6496 Å are noticeable; 5) Blend feature of Na I D1 and Na I D2 is not distinguishable; 6) Ca I at 4226 Å is marginally noticed.
C-R	1) Strong Ca I at 4226 Å; 2) Na I D1 and Na I D2 blended line have two distinct dips; 3) Weak Hβ and Ba II at 4554 Å blended with atomic and molecular lines; 4) Weak Hα and Ba II at 6496 Å blended with the CN bands around 6500 Å.
C-N	1) No flux at $\lambda < 4400$ Å; some very late type C-N can be flat even at $\lambda < 5000$ Å; 2) Strong Ba II at 6496 Å; 3) Weak Hα.
C-J	1) A high isotope ratio of ^{13}C to ^{12}C with j-index ≥ 4.
Ba	1) Strong lines of s-process elements, particularly Ba II at 4554 Å and Sr II at 4077 Å.

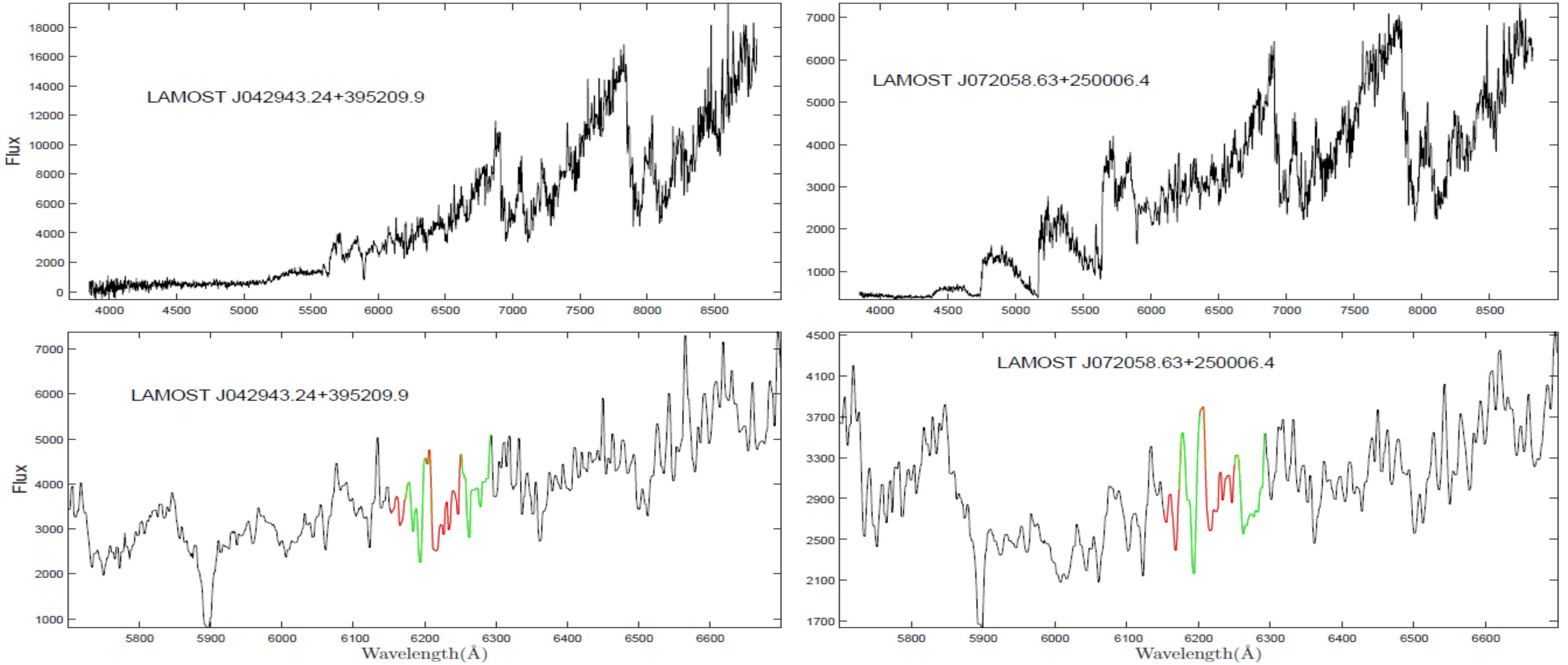
- Spectral MK Classification
  - Classification Criteria
  - CJ stars --- J index >= 4 (ApJ, 2009, 705, 1298)
  - CH, CR, CN, and Ba stars --- artificial identification
  - Classification Results
    - CH: 864
    - CR: 226
    - CJ: 400
      - CJ(N) : 353
      - CJ(H): 41
      - CJ(R): 6
    - CN: 266
    - Ba: 719
    - Unknown: 164
    - Binary: 12 (No spectra type)





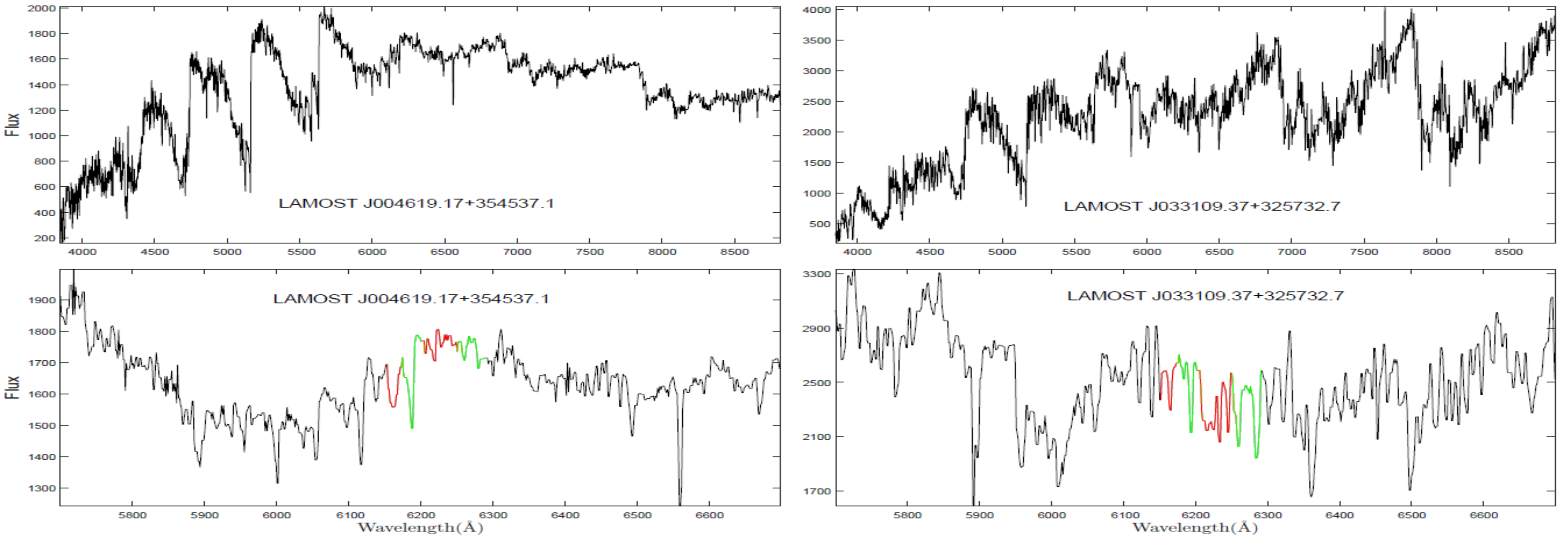
Spectral MK Classification

Two CJ(N) stars



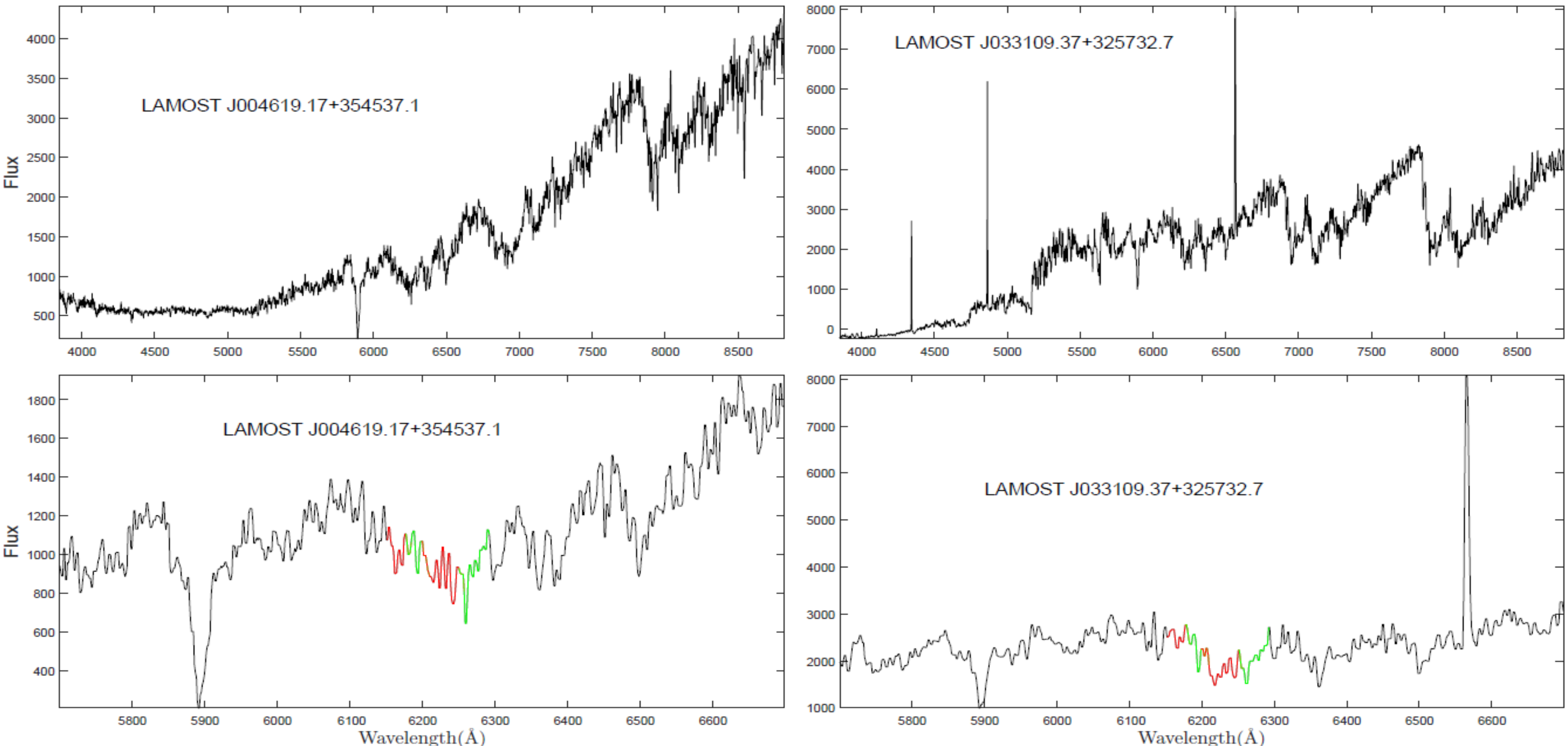
Spectral MK Classification

CJ(H) and CJ(R) stars

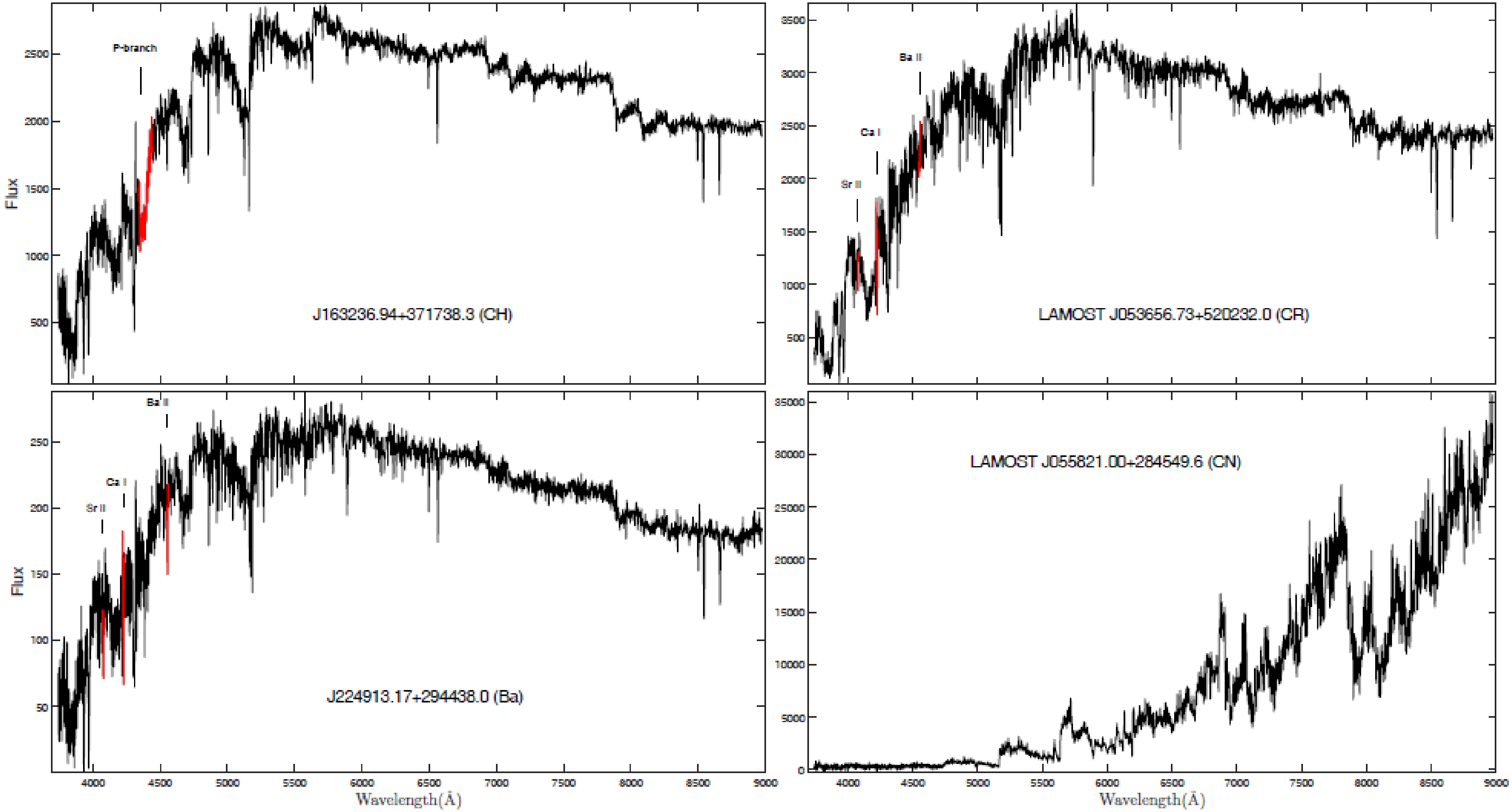


Spectral MK Classification

CJ(binary) and CJ(EM) stars



Spectral MK Classification



Finding carbon stars

- Parameter Catalog for carbon stars of LAMOST DR4
  - Designation
  - Equatorial Coordinates
  - Signal to Noise ratio
  - PPMXL proper motion
  - UCAC4 proper motion
  - GALEX photometry
  - Pan-STARRS photometry
  - 2MASS photometry
  - Wise photometry
  - Flag_new: new finding or not
  - Flag_type: a spectral binary, a G-type star, a emission line star, or not
  - Spectra_type: CH, CR, CJ, CN, and Ba

Finding carbon stars

- Parameter Catalog for 17 CEMP MSTO stars of LAMOST DR4
  - Designation
  - Equatorial Coordinates
  - Signal to Noise ratio
  - Atmospheric Parameters
  - Radial Velocities
  - PPMXL proper motion
  - UCAC4 proper motion
  - GALEX photometry
  - Pan-STARRS photometry
  - 2MASS photometry
  - Wise photometry

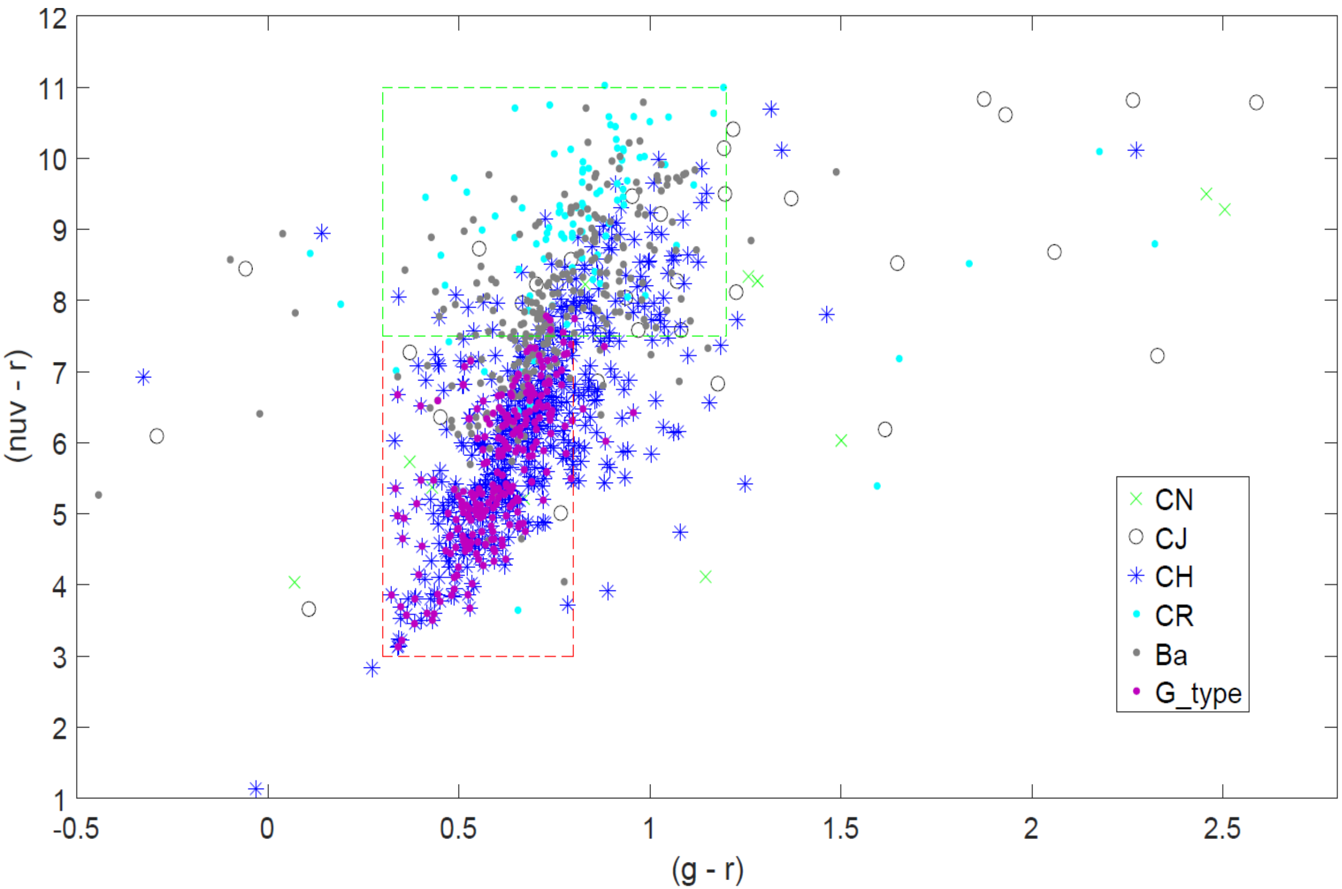
Multiple-wavelength Data

- GALEX Ultraviolet Detections
  - 1099 detections
  - 26 FUV-detections --- likely have white dwarf star companions
  - 1098 NUV-detections

Designation	fuv (mag)	fuv_err (mag)	nuv (mag)	nuv_err (mag)
LAMOST J005749.75+013835.2	22.14	0.10	21.99	0.16
LAMOST J020726.72+453216.9	20.92	0.34	20.51	0.28
LAMOST J050736.14+305149.6	21.71	0.53	-999	-999
LAMOST J064654.93+443926.5	20.27	0.15	19.91	0.10
LAMOST J073406.93+351345.5	22.56	0.33	17.54	0.02
LAMOST J074743.32+173302.0	22.41	0.44	20.64	0.14
LAMOST J083021.22+154319.6	23.08	0.28	22.21	0.17
LAMOST J084906.99+462727.2	22.21	0.16	21.81	0.08
LAMOST J091555.05+043115.6	21.53	0.32	20.42	0.18
LAMOST J093450.24+022355.0	22.35	0.40	21.47	0.22
LAMOST J094634.19+140521.7	24.01	0.30	20.10	0.02
LAMOST J101110.08+285036.0	22.12	0.37	21.24	0.27
LAMOST J101423.40+302200.3	25.20	0.25	21.07	0.01
LAMOST J101946.87+252932.7	22.45	0.41	20.32	0.11
LAMOST J115932.16+014326.9	22.54	0.50	20.90	0.18
LAMOST J130359.18+050938.6	23.74	0.27	21.98	0.07
LAMOST J130824.28+530224.4	23.03	0.20	22.42	0.13
LAMOST J131525.84+062520.9	19.09	0.12	18.61	0.06
LAMOST J133841.23+014523.7	22.89	0.26	21.79	0.15
LAMOST J140953.08-061141.8	21.36	0.33	19.79	0.12
LAMOST J142057.12-031953.2	19.09	0.13	18.66	0.06
LAMOST J154903.86+033253.1	22.38	0.33	22.10	0.18
LAMOST J164420.62+034506.6	19.75	0.12	19.59	0.08
LAMOST J220255.21-010708.3	21.12	0.06	21.00	0.05

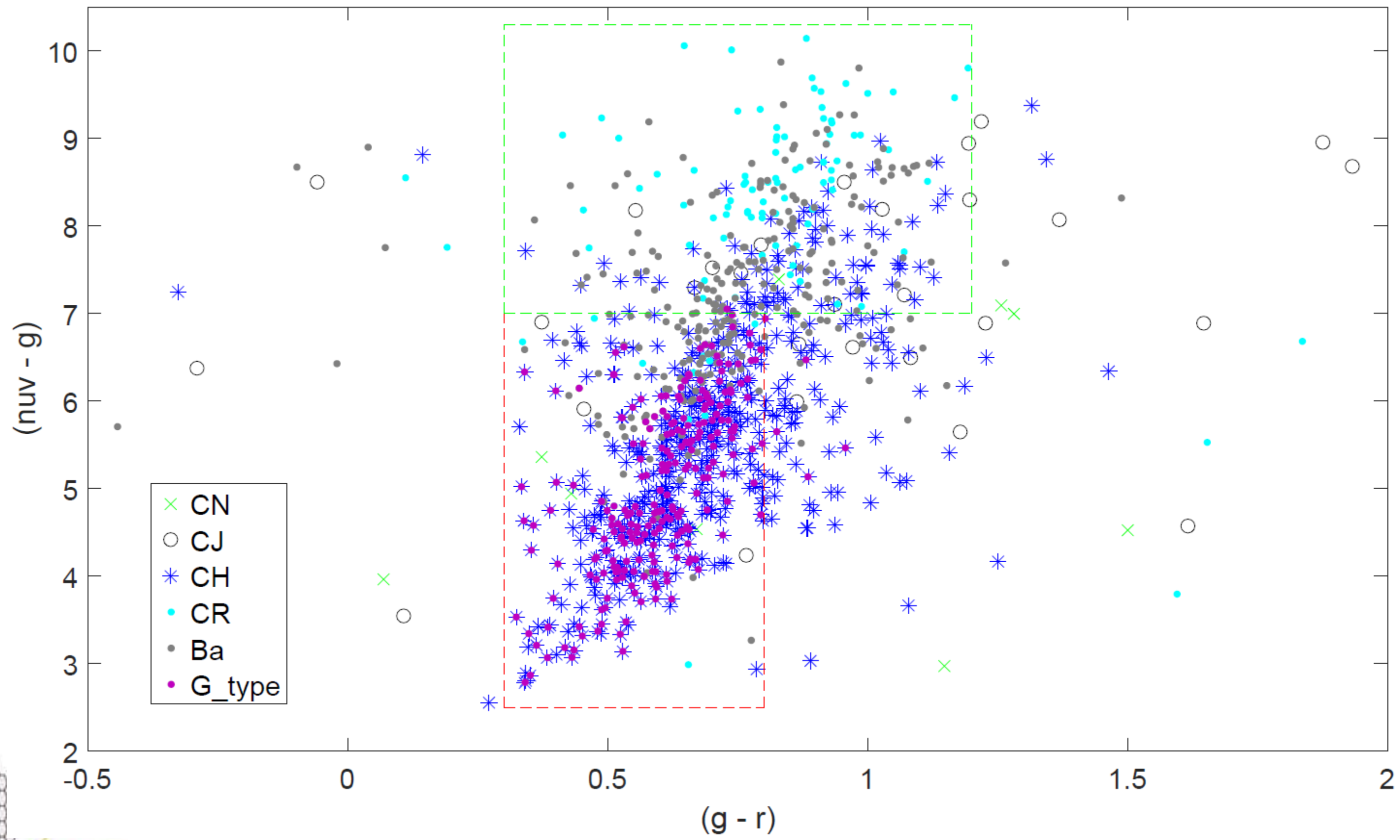
Multiple-wavelength Data

- G-type stars: 0.3 <= (g - r) <= 0.8 and 3 <= (nuv - r) <= 7.5
- Ba stars: 0.3 <= (g - r) <= 1.2 and 7.5 <= (g - r) <= 11



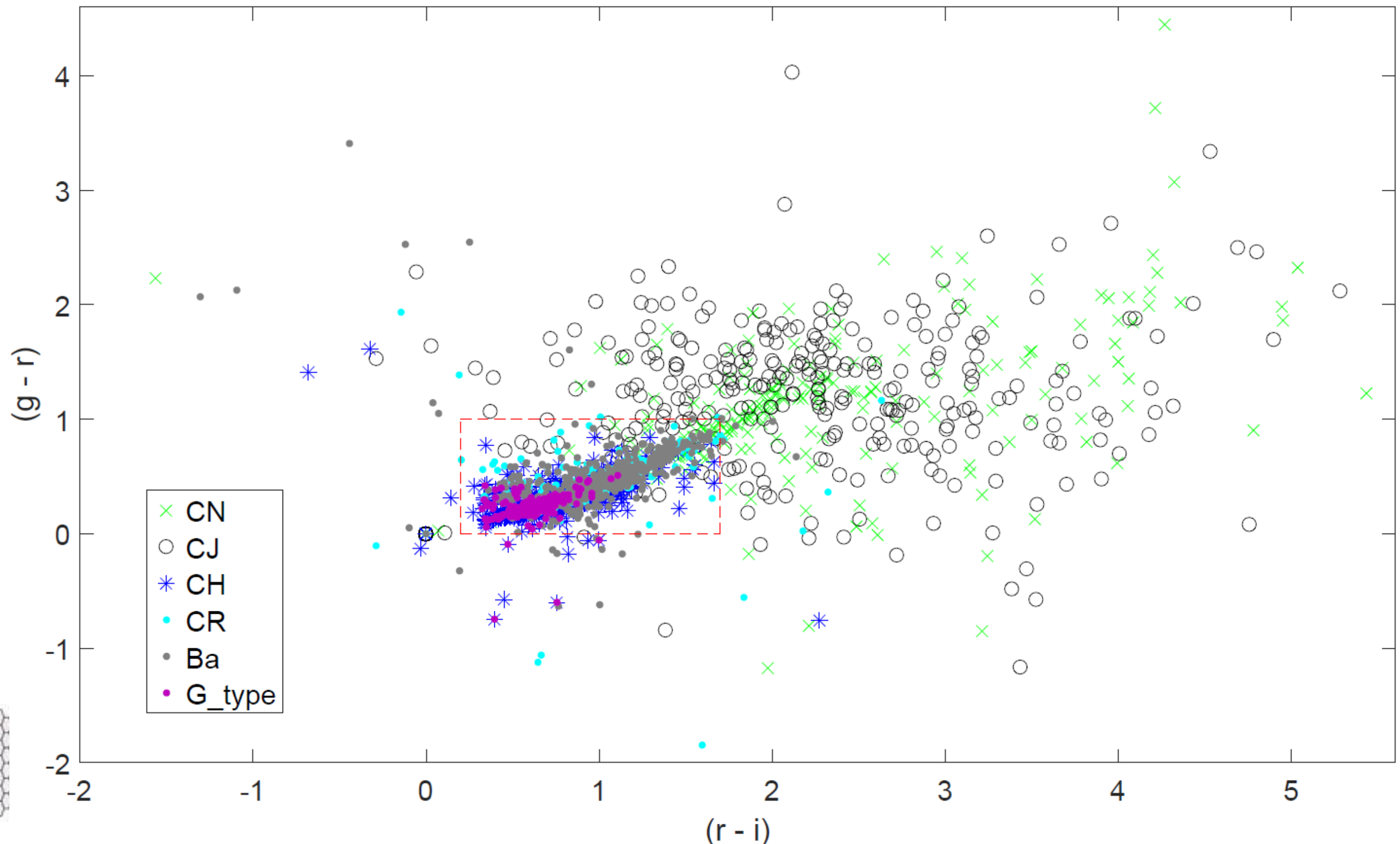
Multiple-wavelength Data

- G-type stars: 0.3 <= (g - r) <= 0.8 and 2.5 <= (nuv - g) <= 7
- Ba stars: 0.3 <= (g - r) <= 1.2 and 7 <= (g - r) <= 10.5



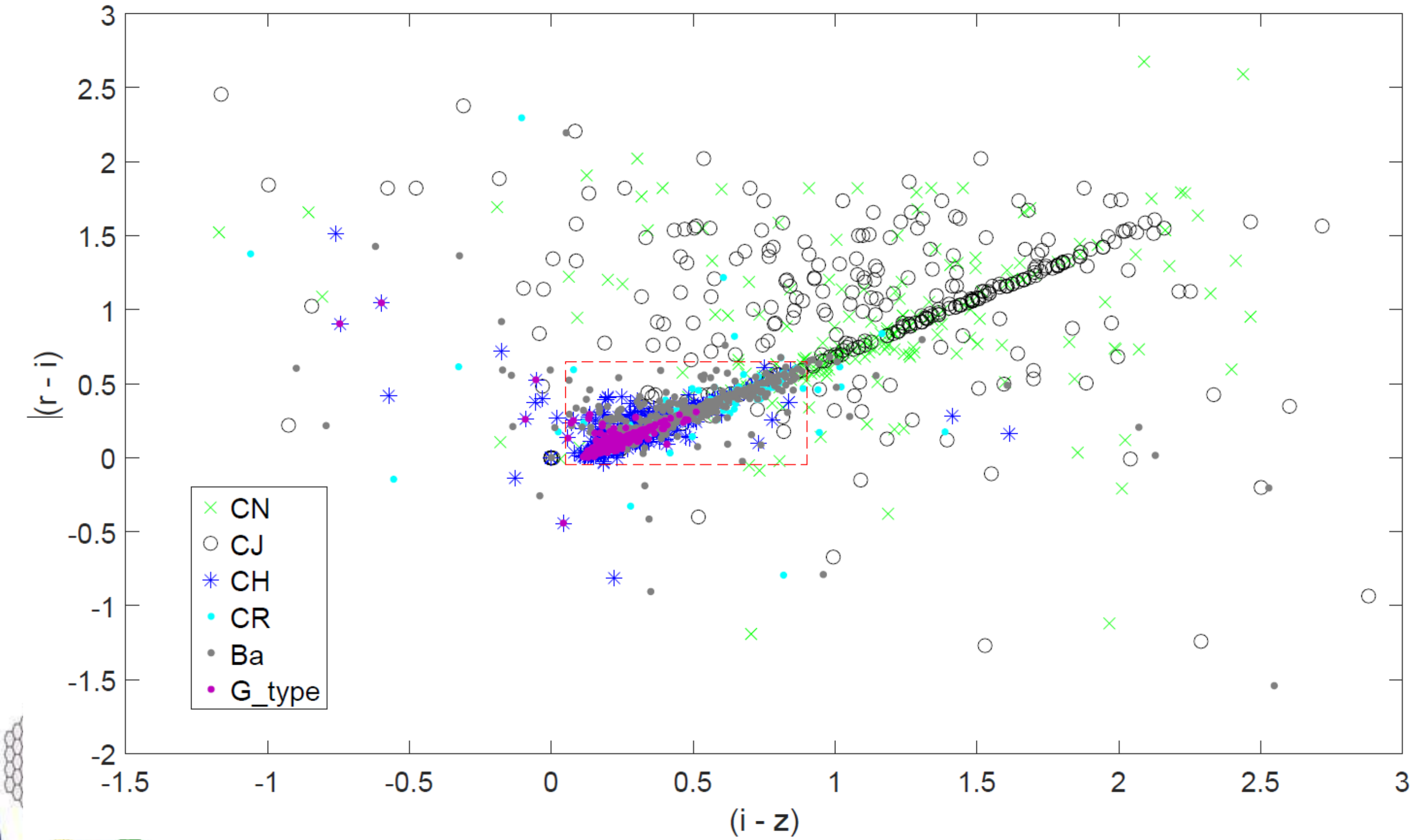
Multiple-wavelength Data

- Hot carbon stars: 0 <= (g - r) <= 1 and 0.2 <= (r - i) <= 1.7
- Cool CJ and CN stars:
  - Most of them: (r - i) > 1.7
  - A small fraction of them: (g - r) > 1.0 and (r – i) <= 1.7



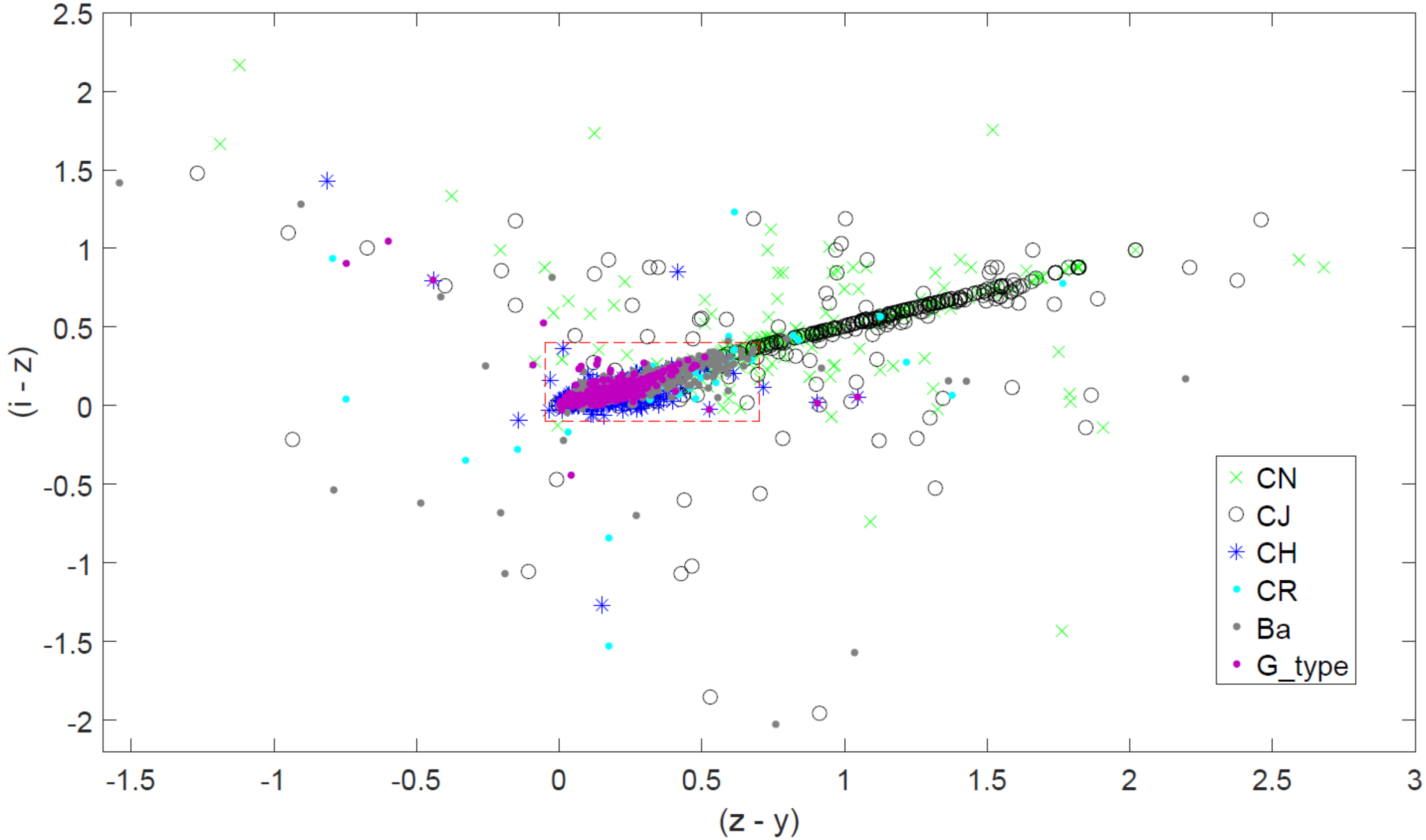
Multiple-wavelength Data

- Hot carbon stars: -0.05 <= (r - i) <= 0.65 and 0.05 <= (i - z) <= 0.9
- Cool CJ and CN stars:
  - Most of them: (i - z) > 0.9
  - A small fraction of them: (r - i) > 0.65 and (i - z) <= 0.9



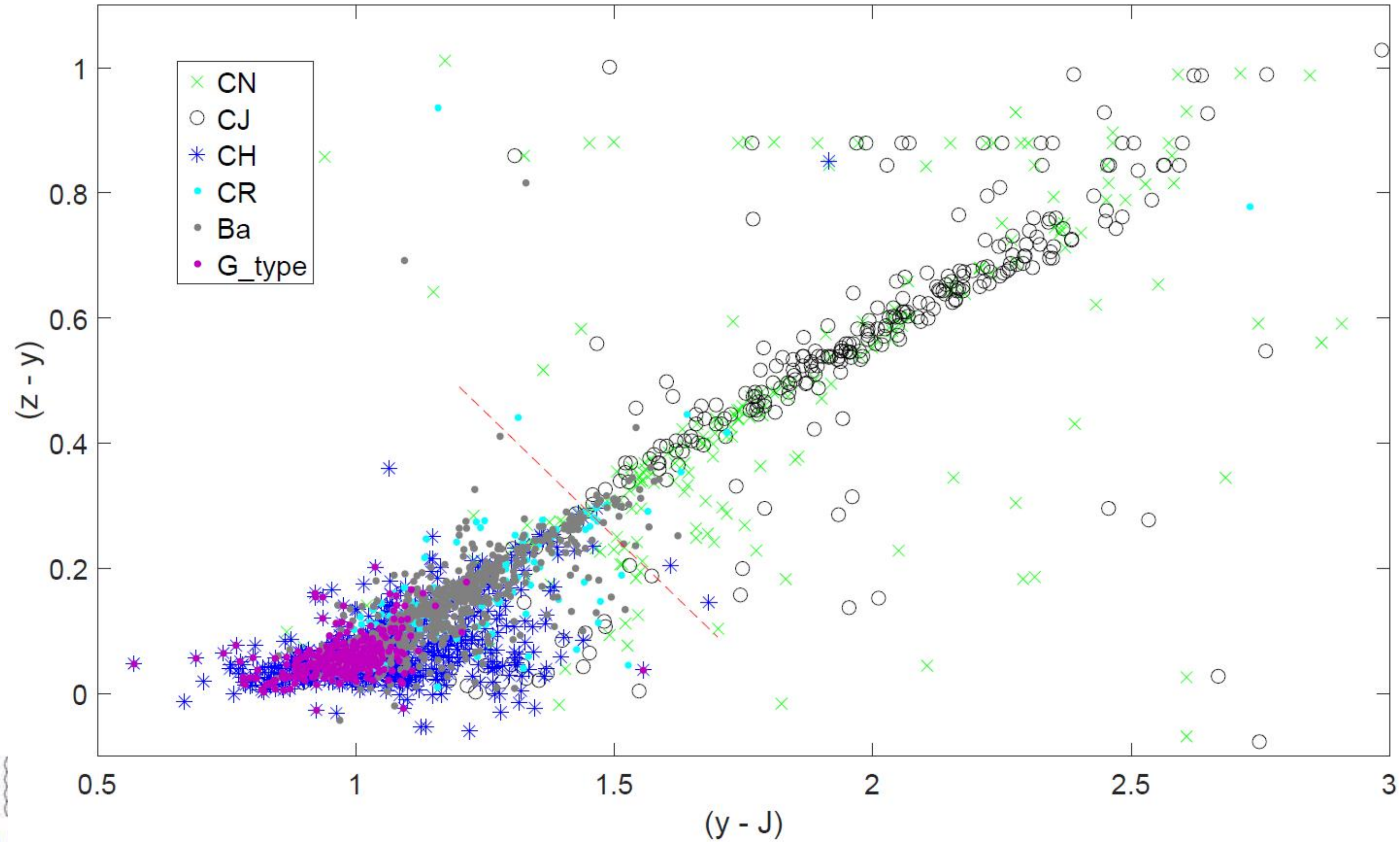
Multiple-wavelength Data

- Hot carbon stars: -0.05 <= (z - y) <= 0.7 and -0.1 <= (i - z) <= 0.4
- Cool CJ and CN stars:
  - Most of them: (z - y) > 0.7
  - A small fraction of them: (i - z) > 0.4 and (i - z) <= 0.7



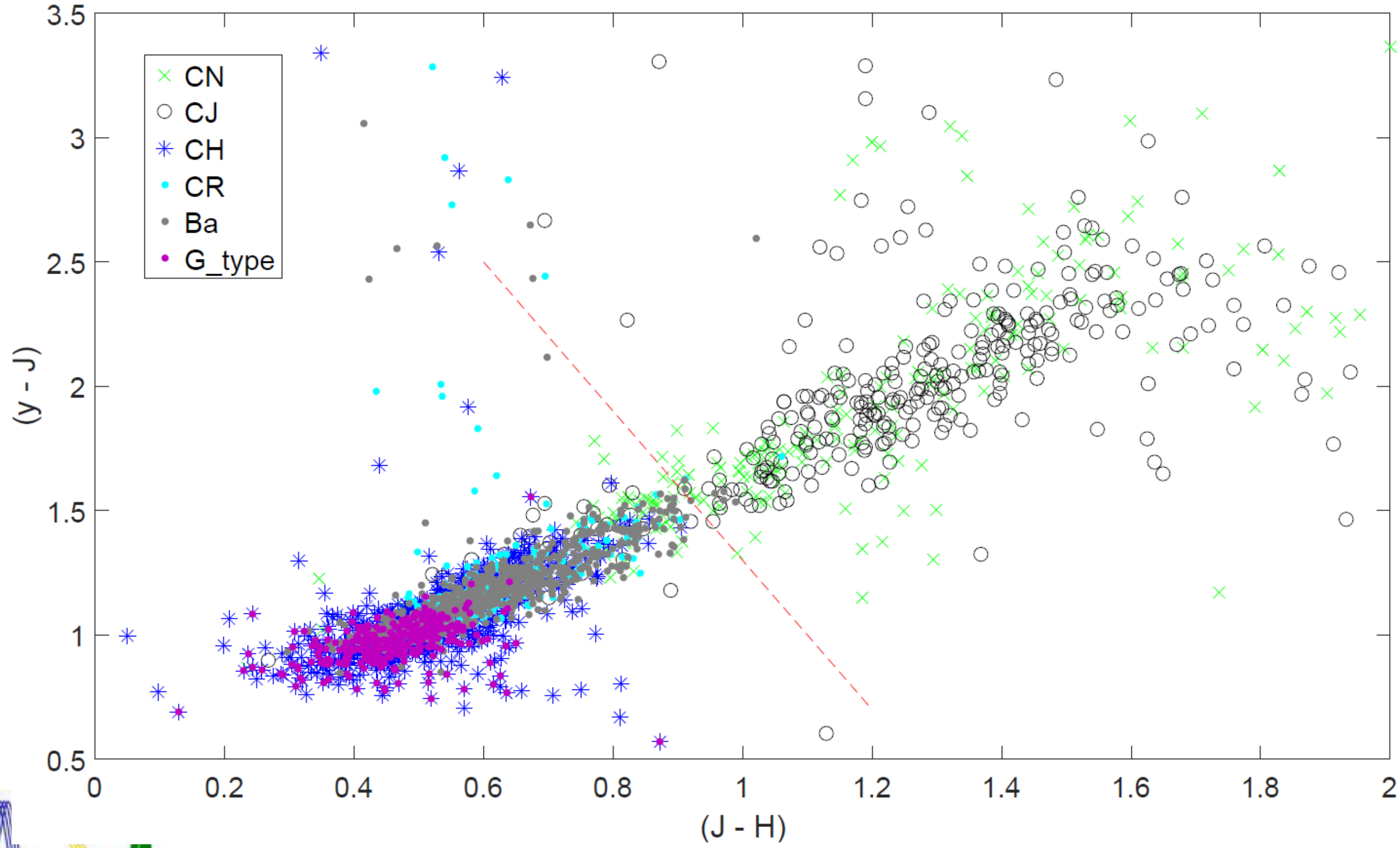
Multiple-wavelength Data

- Hot carbon stars are distinguished from cool CJ and CN stars:
  - $(z-y) \leq -0.8 \times (y-J) + 1.45$
  - Roughly criterion: $(y-J) \geq 1.45$



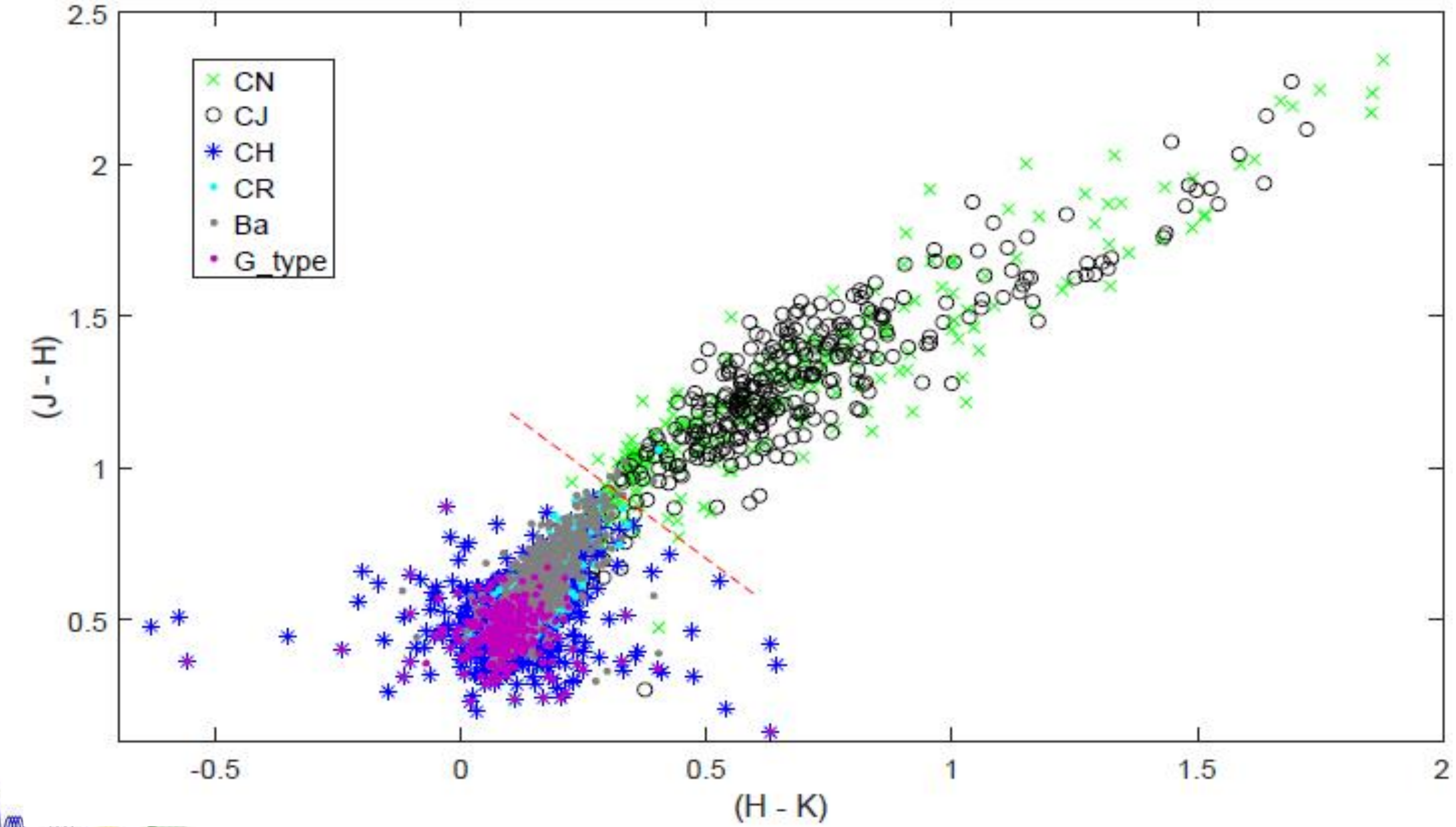
Multiple-wavelength Data

- Hot carbon stars are distinguished from cool CJ and CN stars:
  - $(y-J) \le -3 \times (J-H) + 4.3$
  - Roughly criterion: $(J-H) \ge 0.93$



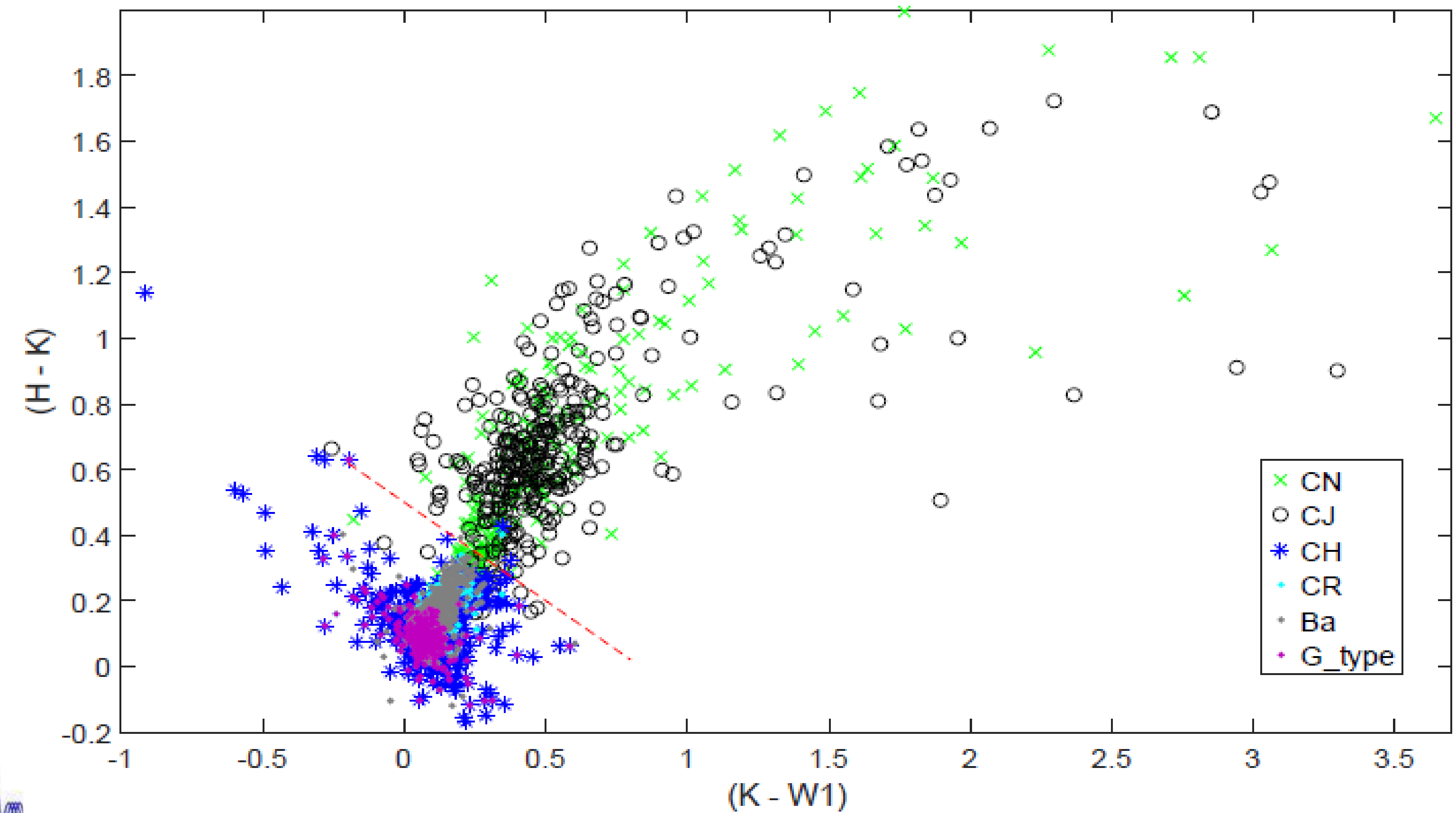
Multiple-wavelength Data

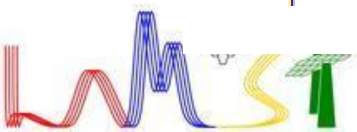
- Hot carbon stars are distinguished from cool CJ and CN stars:
  - $(J - H) \leq -3 \times (H - K) + 4.3$
  - Roughly criterion: $(H - K) \geq 0.35$ and $(J - H) \geq 1.0$



Multiple-wavelength Data

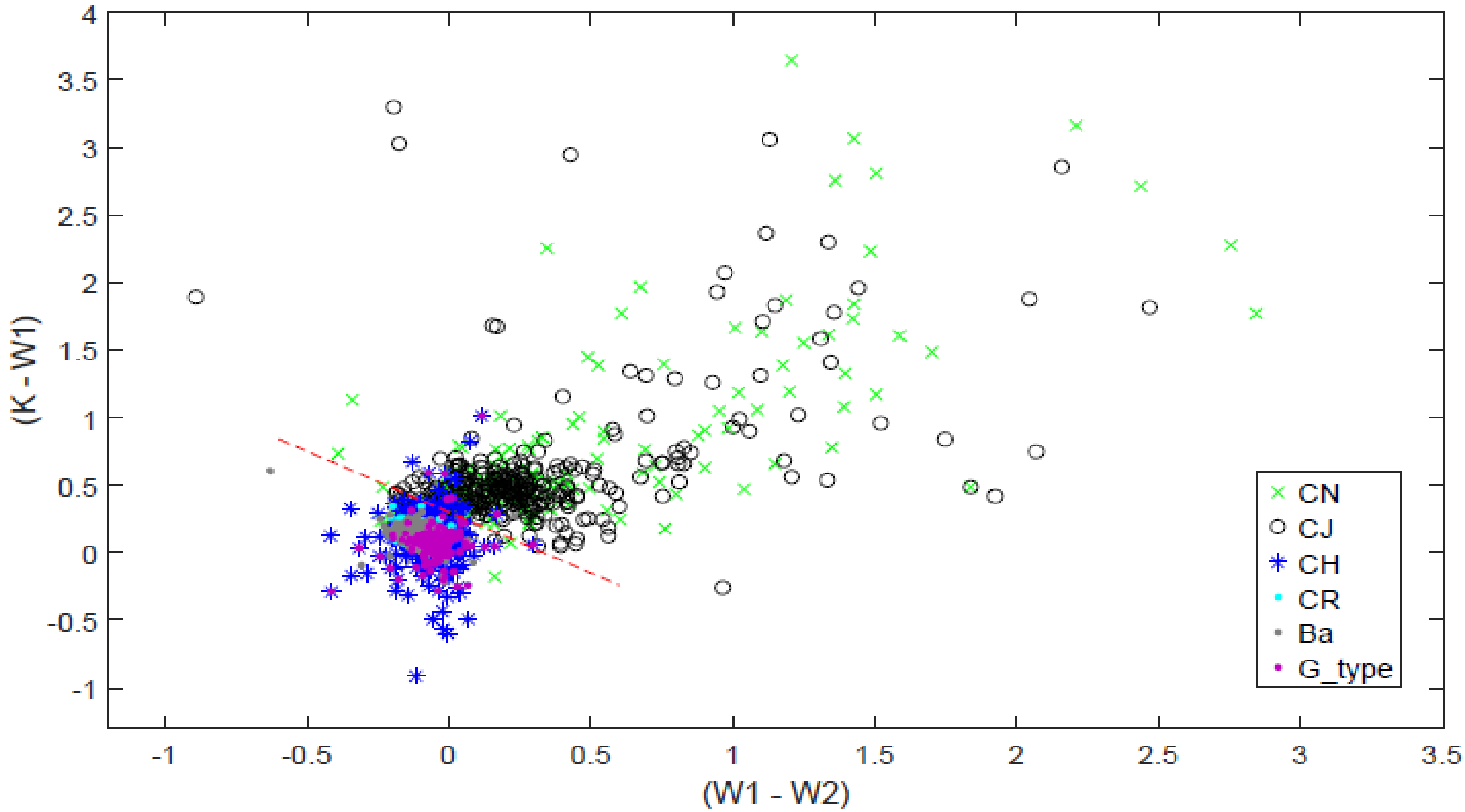
- Hot carbon stars are distinguished from cool CJ and CN stars:
  - $(H-K) \leq -0.6 \times (K-W1)+0.5$





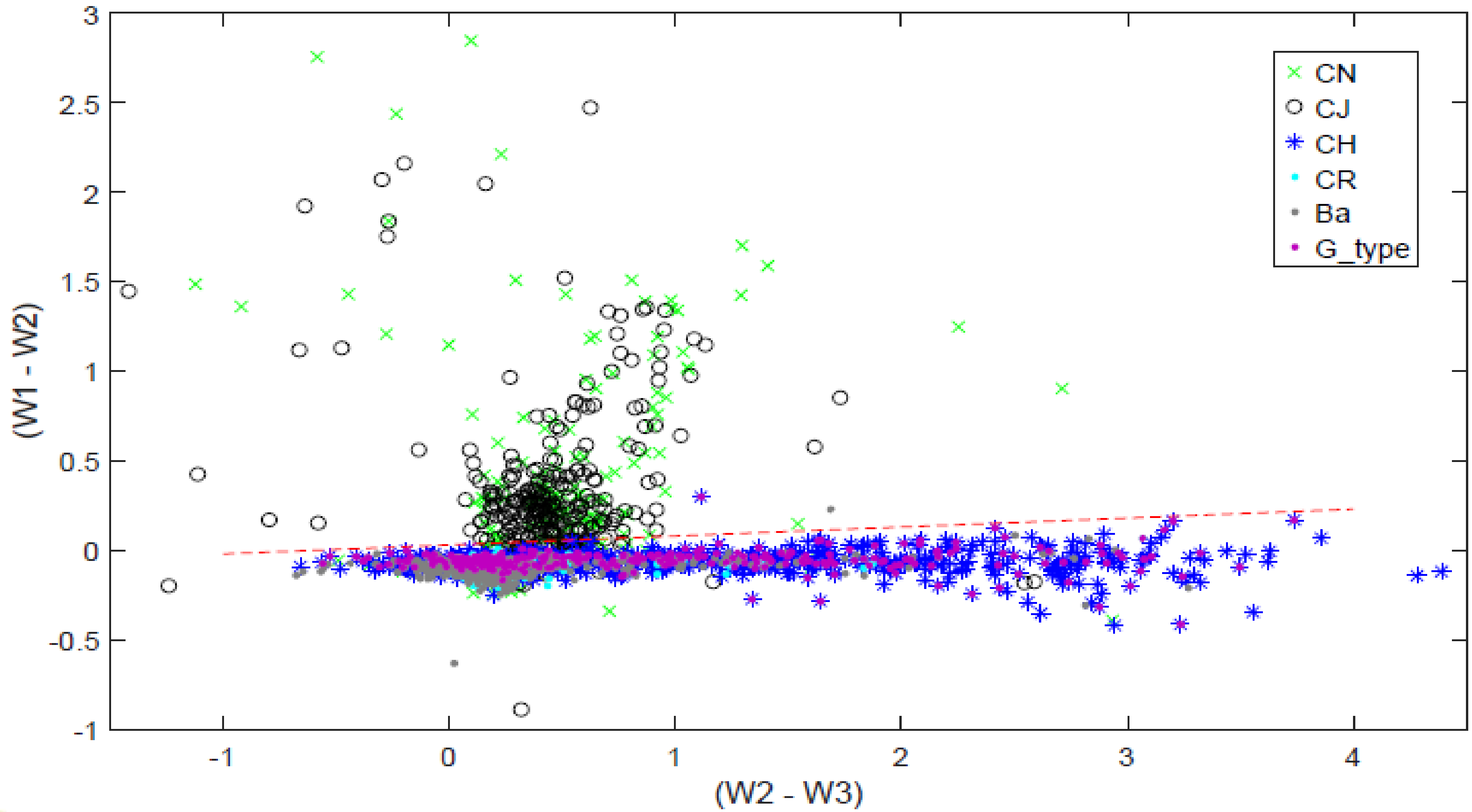
Multiple-wavelength Data

- Hot carbon stars are distinguished from cool CJ and CN stars:
  - $(K-W1) \leq -0.9 \times (W1-W2)+0.3$



Multiple-wavelength Data

- Hot carbon stars are distinguished from cool CJ and CN stars:
  - $(W1 - W2) \leq 0.05 \times (W2 - W3) + 0.03$



Multiple-wavelength Data

- Conclusion
  - It is difficult to distinguish three type hot stars with colors we used.
  - It is also difficult to distinguish cool CJ(N) and CN stars with colors we used.
  - J - H and H – K are the best colors to distinguish cool and hot carbon stars.
  - G-type and CR stars can be roughly isolated from nuv – r and g – r colors.
  - G-type is the hottest stars, and is hotter than CR and Ba stars.
- Questions
  - What else can we do with these multiple-wavelength data ?

Compared with Previous Work

- ApJS, 2016, 226, 1 (894 carbon stars from LAMOST DR2)
  - 5 stars with low quality spectra are not in our catalog
  - Our 575 DR2 carbon stars not in this catalog
    - 122 are test targets
    - 453 are science targets
- RAA, 2015, 15, 1671 (183 carbon stars from LAMOST Pilot Survey)
  - 4 stars with low quality spectra are not in our catalog

Step	Criteria	Abandoned carbon stars
1	S/N(i) $>$ 10 and leave only one epoch for multiply observed stars	32
2	no radial velocitiy	25
3	Equations (2), (3), (4)	138
3	CN7065 $\geq$ 4 or CN7820 $\geq$ 8 CN7065 $<$ 4 and CN7820 $<$ 8 with S/N(g) $>$ 20 and S/N(i) $>$ 20	113
4	CN7065 $\geq$ 2 and $C_2 \geq -13$	54
5	$K_s < 14.5$ and $J - K_s > 0.45$	41

Thank you for your attention !