Principal Component Analysis of Light Curves of Type Ia Supernovae

beyond the “stretch”

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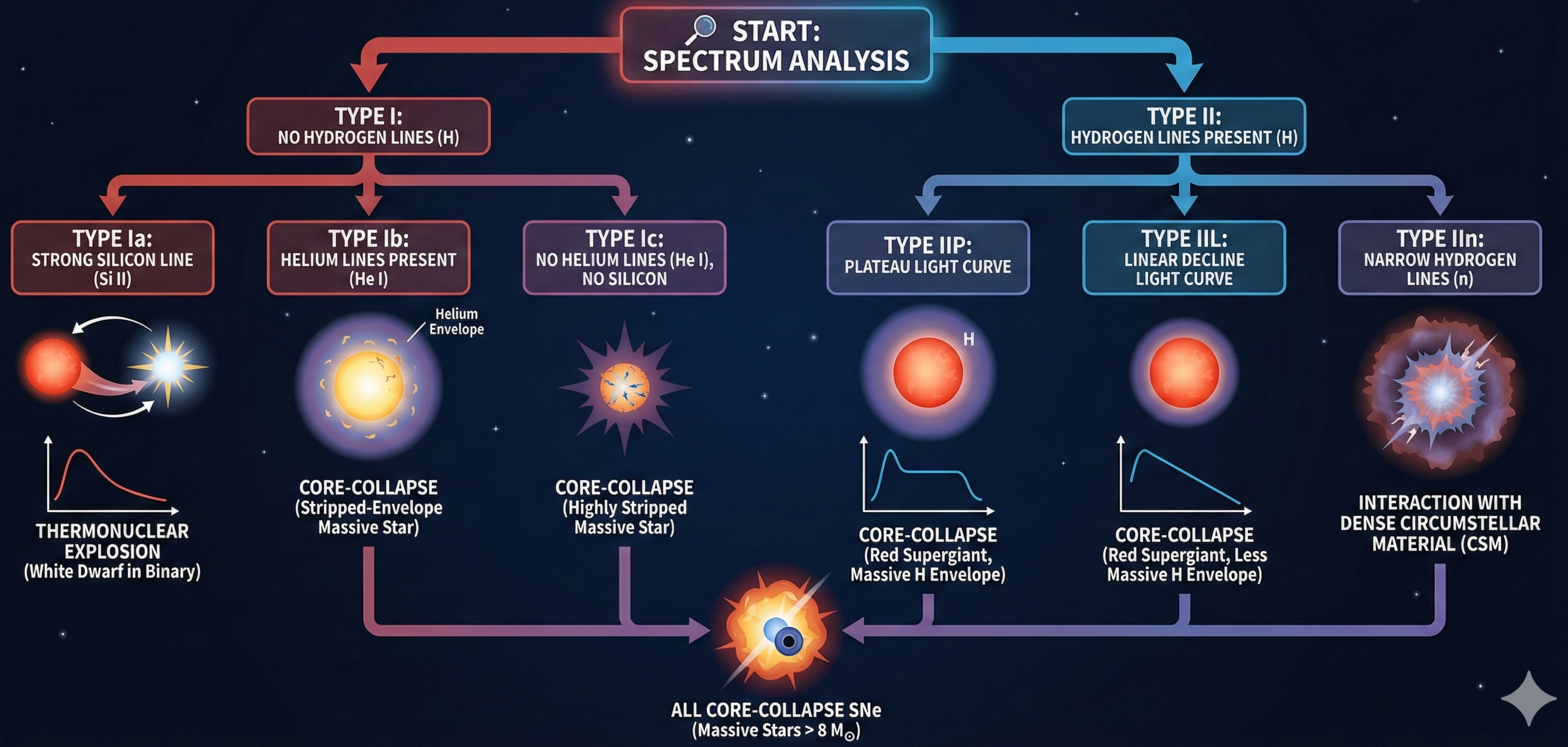
Todays Topics

- Introduction
  - The importance of type Ia supernovae
  - Light curves and spectral features
- Observations and Methods
  - Zwicky Transient Facility
  - GPR
  - PCA
- Results and Discussions
  - PCA result for r-band light curves
  - Correlation between principal components and host galaxy
- Conclusion

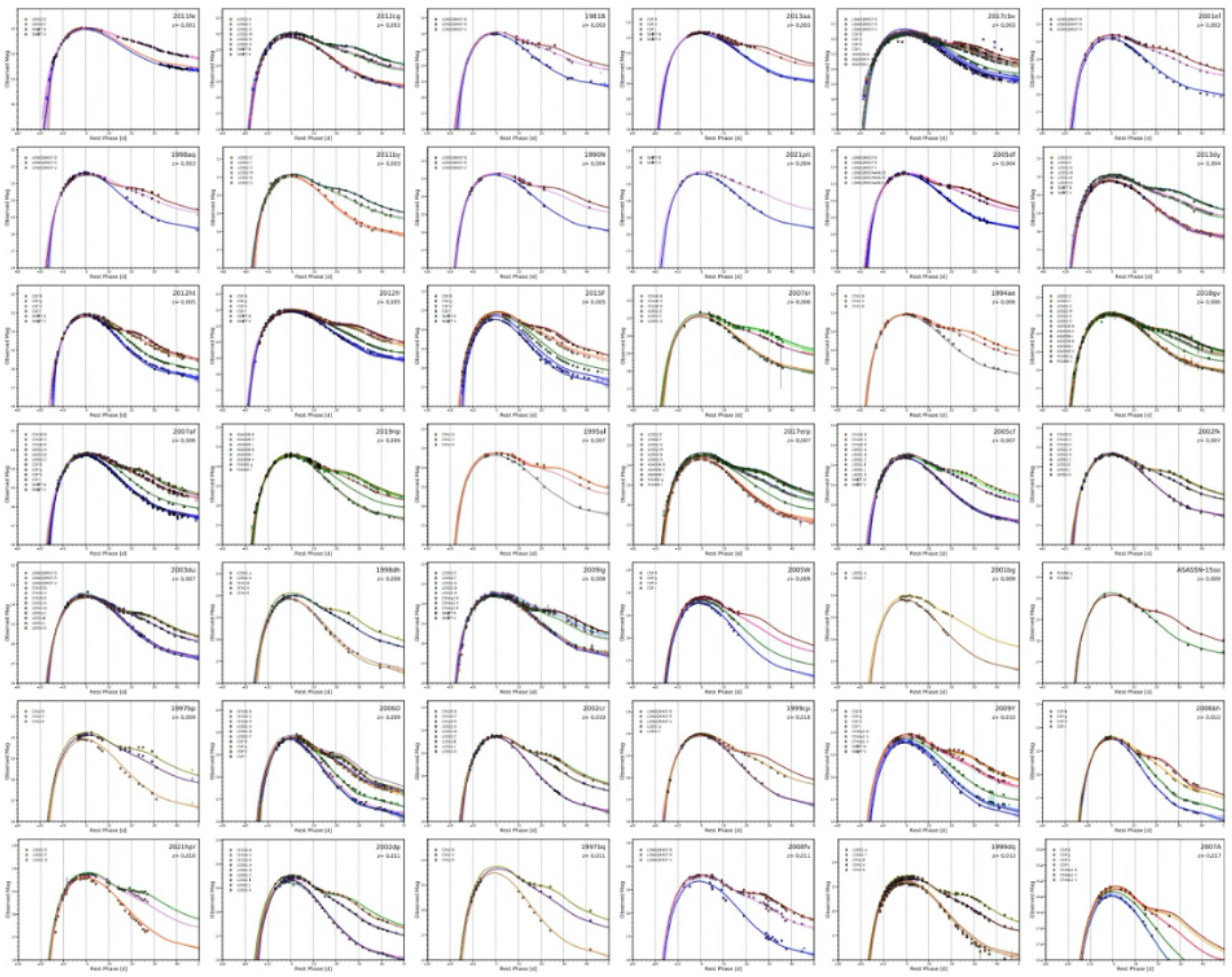
Classification of SNe



SNe Ia as the Standard Candles

- high luminosity
- relatively homogeneous peak luminosities and light-curve shapes

distance indicator
for cosmology



Dan Scolnic+2022

Stretch: the classical parameter

- SNe Ia have a relatively homogeneous peak luminosity, but exhibit an intrinsic scatter of **~0.4 mag**.

Correction with **stretch** and **color**

- Scatter of corrected luminosity: **0.15 mag**
- There are some light curve fitting methods such as SALT2 (Guy+2007), SALT 3 (Kenworthy+2021), SNooPy (Burns+2011).

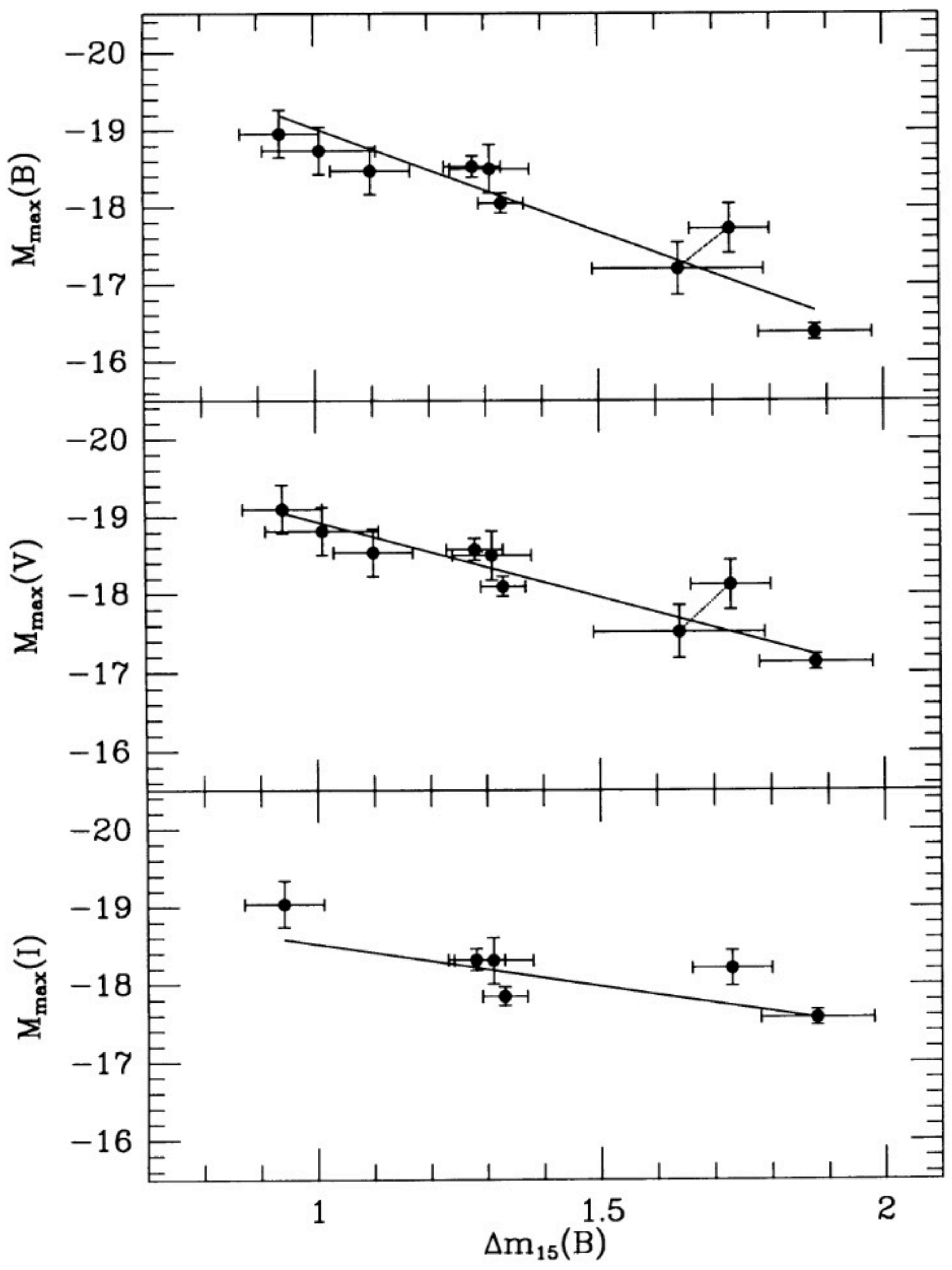


FIG. 1.—Decline rate–peak luminosity relation for the nine best-observed SN Ia's. Absolute magnitudes in *B*, *V*, and *I* are plotted vs. $\Delta m_{15}(B)$, which measures the amount in magnitudes that the *B* light curve drops during the first 15 days following maximum.

Phillips (1993)

About the SALT2

SALT2 (Spectral Adaptive Lightcurve Template 2) is the standard empirical model allowing us to calculate precise distances. (Guy+2007)

$$F(SN, p, \lambda) = x_0 \times [M_0(p, \lambda) + x_1 M_1(p, \lambda) + \ldots] \times \exp[cCL(\lambda)]$$

p : epoch

λ : wavelength

$$\mu_B = m_B^* - M_0 + \alpha x_1 + \beta c$$

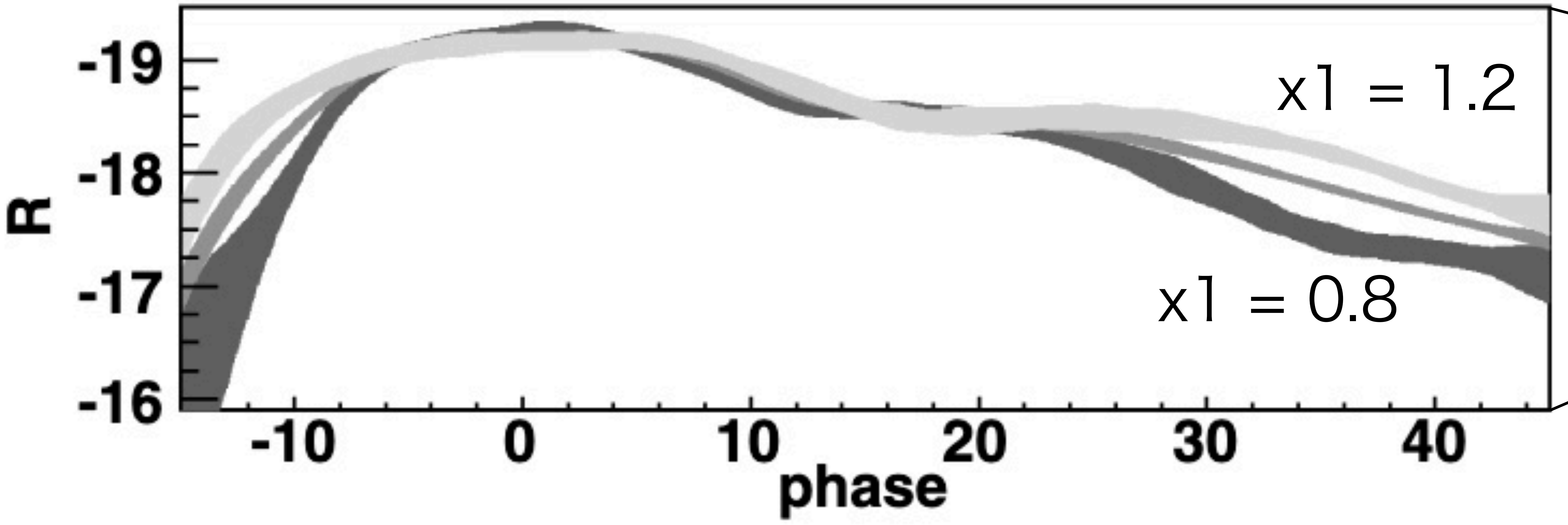
M_0, M_1 and $CL(\lambda)$ are the common values which best explain the scatter of SNe.

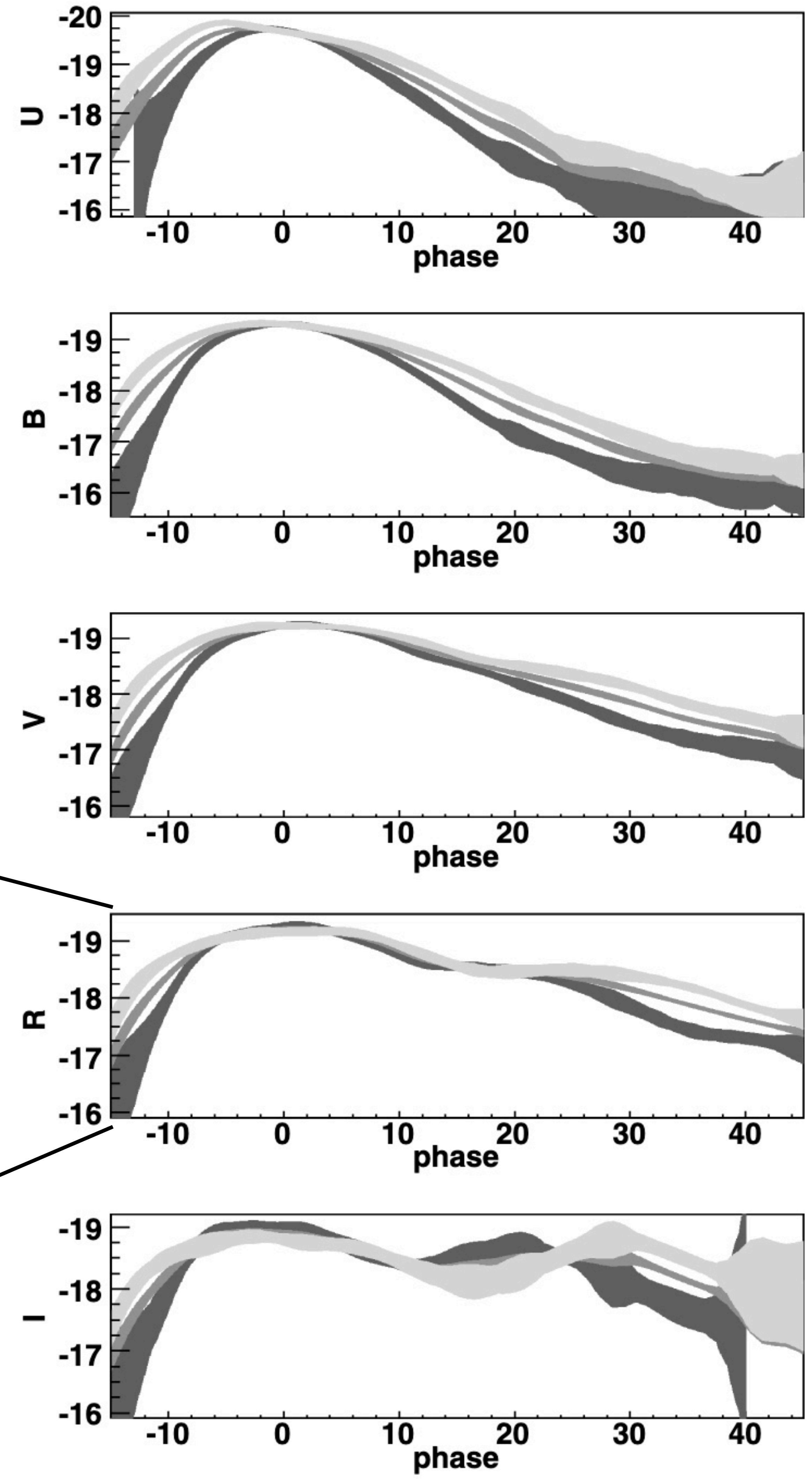
Each SN has individual x_0, x_1 and c values.

About the SALT2

x1 is strongly correlated with stretch.

$$s = 0.98 + 0.091x_1 + 0.003x_1^2 - 0.00075x_1^3$$





Guy+2007

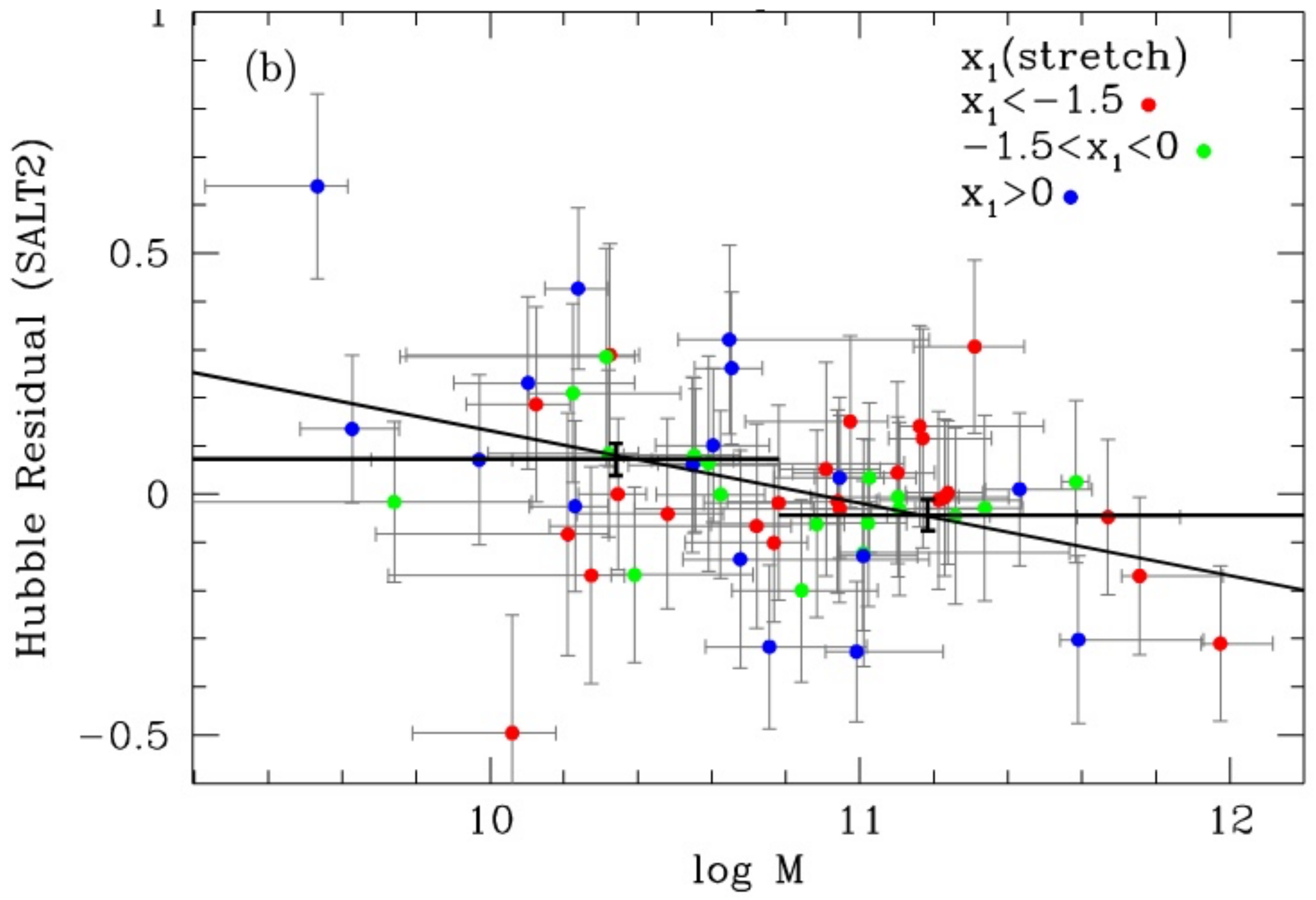
Fig. 2. The U^*UBVRI template light curves obtained after the training phase for values of x_1 of −2, 0, 2 (corresponding to stretches of 0.8, 1.0, and 1.2; dark to light curves) and null B_V color excess. U^* is a synthetic top hat filter in the range 2500–3500 Å. The shaded areas correspond to the one standard deviation estimate as described in Sect. 6.1.

Mass step

- Mass step is an empirical difference:
  high-mass hosts → **brighter** than expected
  low-mass hosts → **fainter** than expected

- The size of this step is typically **0.06 - 0.10** mag.
  (Kelly+2010, Lampeitl+2010)

- In recent study with ZTF data, bigger step
  (**0.12 – 0.14** mag) is reported.(Burgaz+2025)



- It may be caused by dust. (Brout+2021, Popovic+2021)

- But, there is mass step in NIR. (Ponder+2021, Uddin+2020)

- Susceptibility to dust is determined by intrinsic properties.
  (Burgaz+2025)

Spectral Classification of SNe Ia

- Spectral classification
  - Ia-norm
  - 91bg-like
  - 91T-like
- Velocity classifications
  - high velocity / normal velocity (Wang+2009)
  - HVG / LVG / faint (Benetti+2005)
- pEW classification
  - Core-Normal / Broad Line / Cool / Shallow Silicon (Branch+2006)

Light Curve Diversity of SNe Ia

Other than stretch, LCs have some diversity.

- Rise time which is independent of stretch (Ganeshalingam+2011)
- Early blue excess (Hosseinzadeh+2017, Deckers+2022)
- Secondary maximum in r-, i- band (Kasen+2006, Folatelli+2010, Burgaz+2021)

High velocity SNe may have strong secondary maximum

The strength and timing of the secondary maximum are strongly correlated with the stretch

Research Questions

Unraveling light curve diversity is crucial for constraining progenitor systems and precisely determining the Hubble constant.

- What are the features of light curves of SNe Ia?
- How much does the stretch explain the diversity of r-band light curves?
- Is the r-band secondary maximum independent from the stretch

Zwicky Transient Facility

- The Zwicky Transient Facility (ZTF) is a major optical time-domain astronomical survey currently operating at the Palomar Observatory in California.
- ZTF discovers thousands of SNe Ia per year. Its Data Release 2 (DR2) alone contains over 3,000 spectroscopically confirmed SNe Ia.

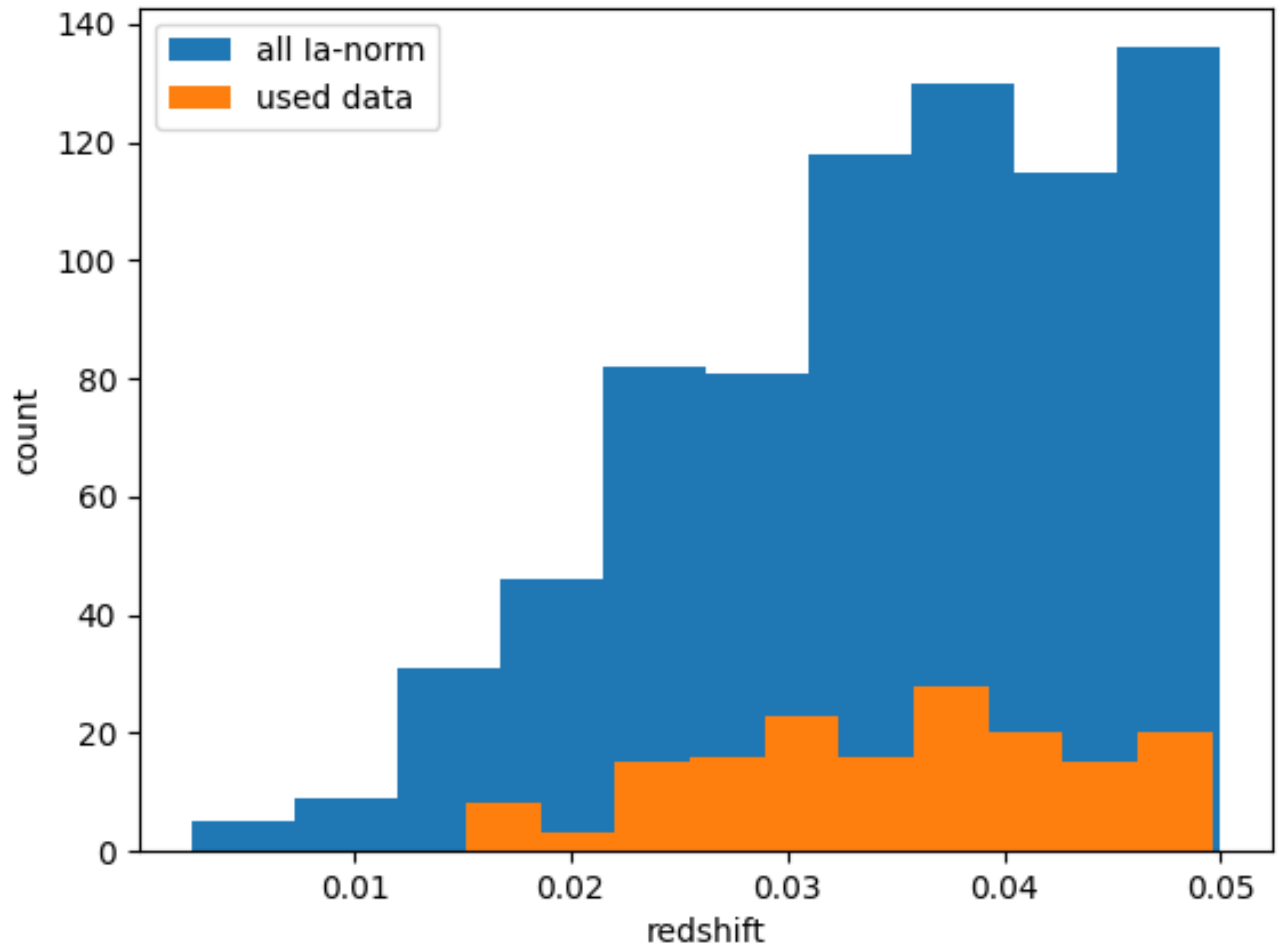
- Telescope: Palomar 1.2m Schmidt
- Field of View: 47 square degrees
- Cadence: every ~2 nights (entire northern sky)

Observations and Sample Selection

- Classified as Ia-norm
- More than 20 data points in the light curve between -20 days before the peak and 60 days after it.
- At least one point before peak.
- Data spanning at least 10 days.

→

- r-band sample: 164
  - HV:11, NV:30
  - early type host: 37, late type host: 60
- g-band sample: 120



K-correction

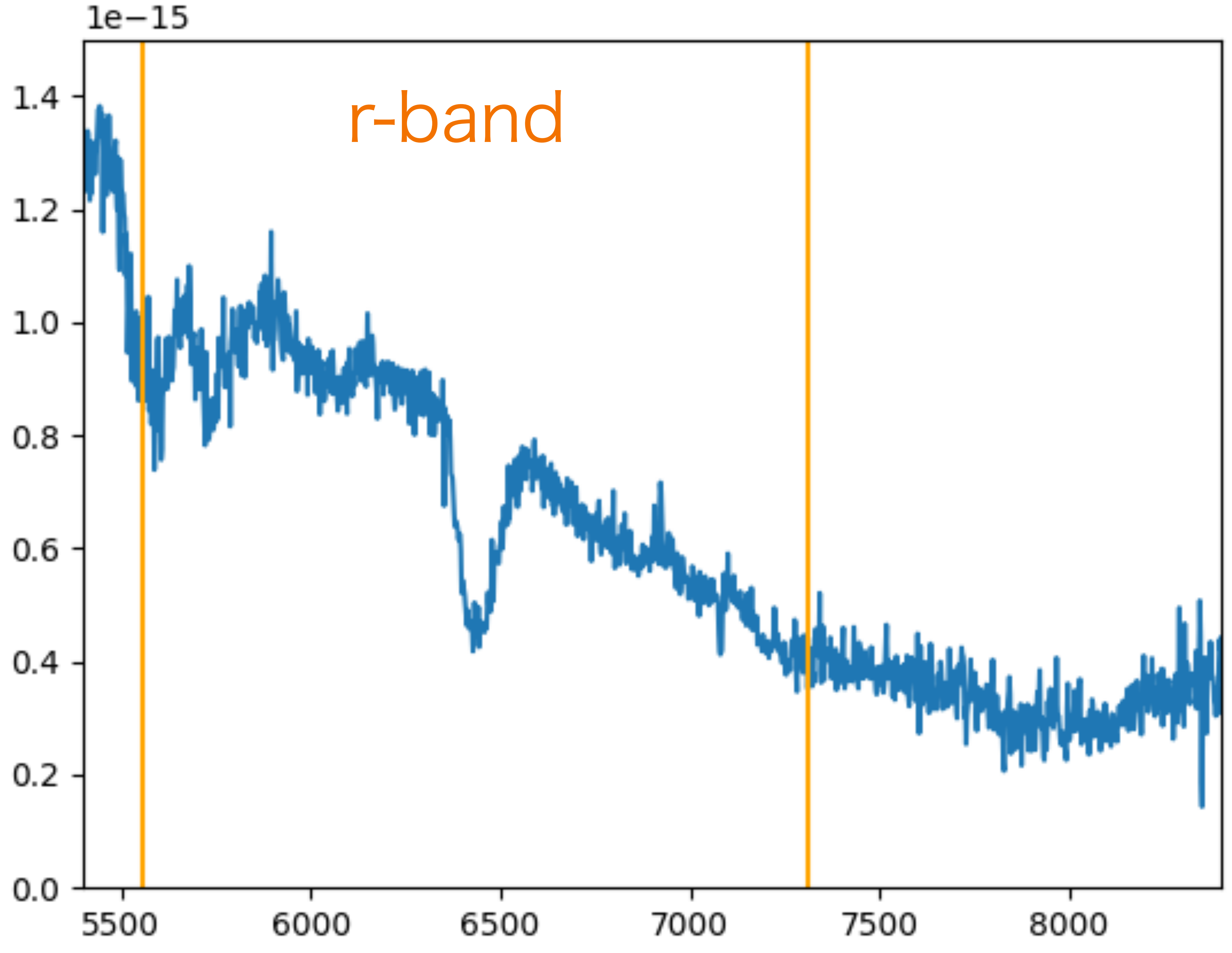
The K correction "corrects" for the fact that sources observed at different redshifts are, in general, compared with standards or each other at different rest-frame wavelengths.

(Hogg+2002)

In SN observations, we also have to consider the effect of ejecta velocity.

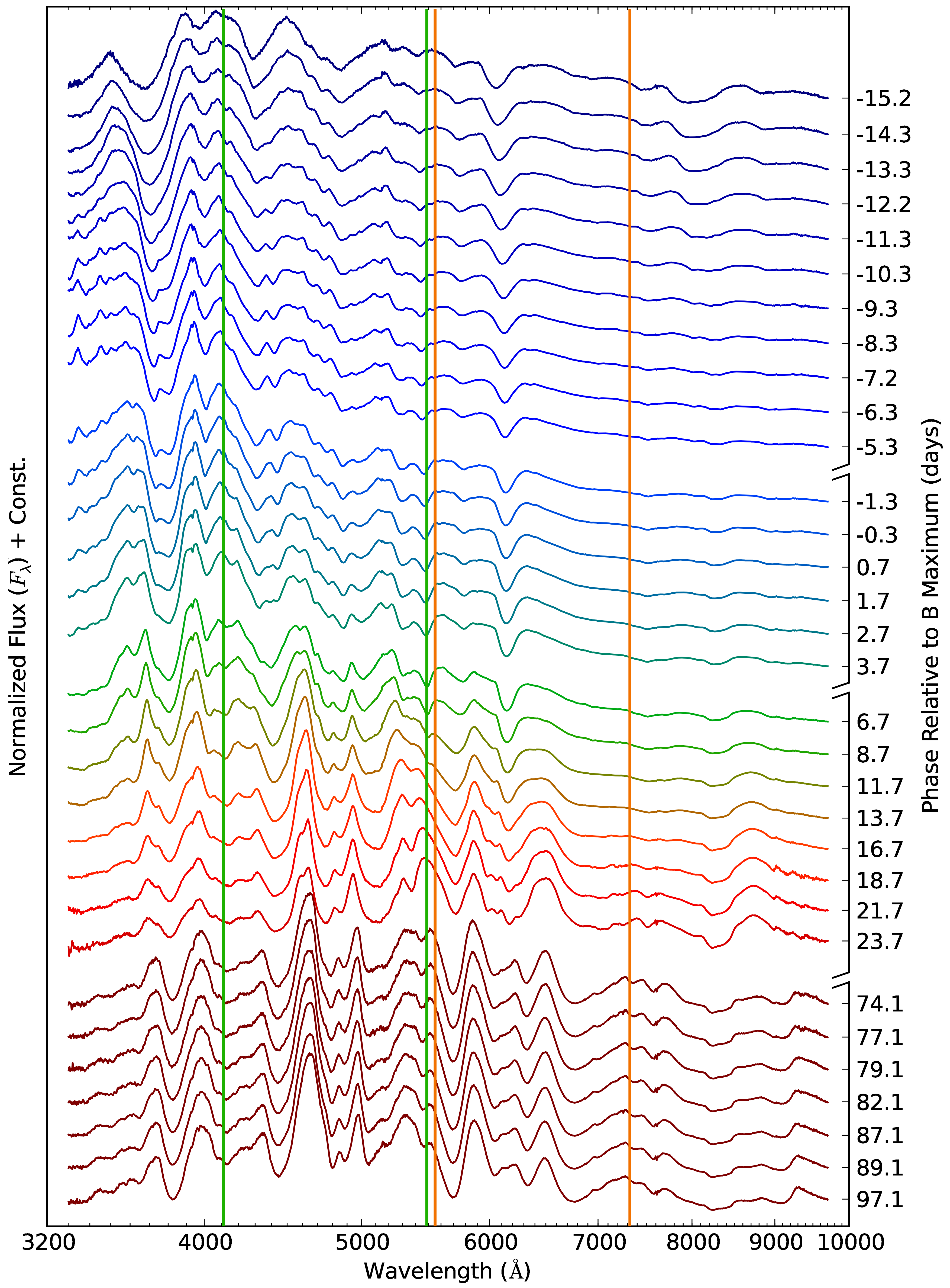
$$m_R = M_Q + \mu + K_{QR}$$

$$K_{QR} = -2.5\log_{10}\left[(1+z)\frac{\int \frac{d\nu_o}{\nu_o} f_\nu(\nu_o)R(\nu_o)\int \frac{d\nu_e}{\nu_e} g_\nu^Q(\nu_e)Q(\nu_e)}{\int \frac{d\nu_o}{\nu_o} g_\nu^R(\nu_o)R(\nu_o)\int \frac{d\nu_e}{\nu_e} f_\nu(\frac{\nu_e}{1+z})Q(\nu_e)}\right]$$



K-correction

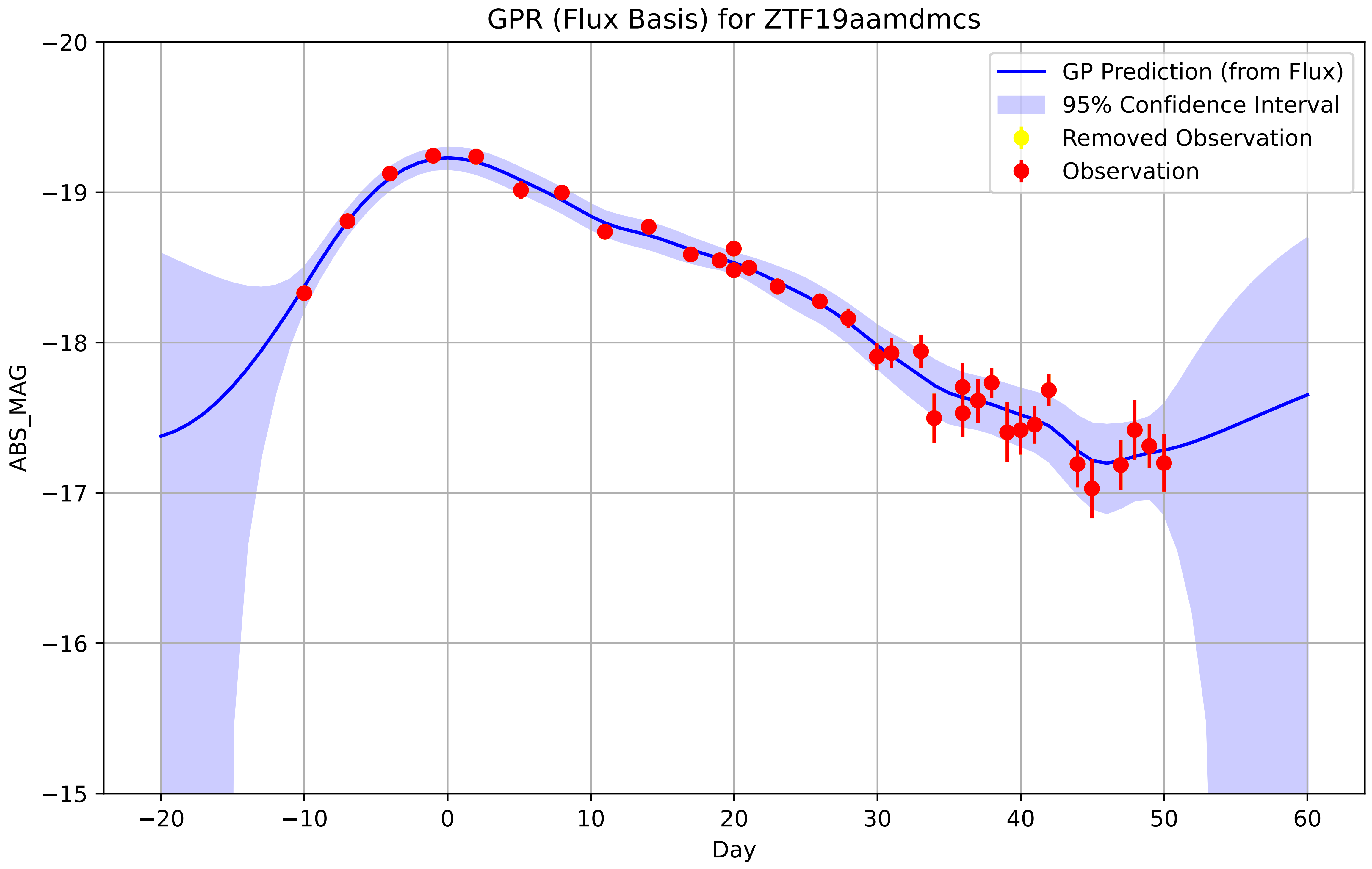
- (Template) spectra are needed for K-correction.
- We don't want to use any assumptions.
- r-band:
  -0.06~0.04
  →It can be neglected.
- g-band:
  -0.10~0.20
  →It cannot be neglected.
- We focus on r-band data.
  We don't use any templates.

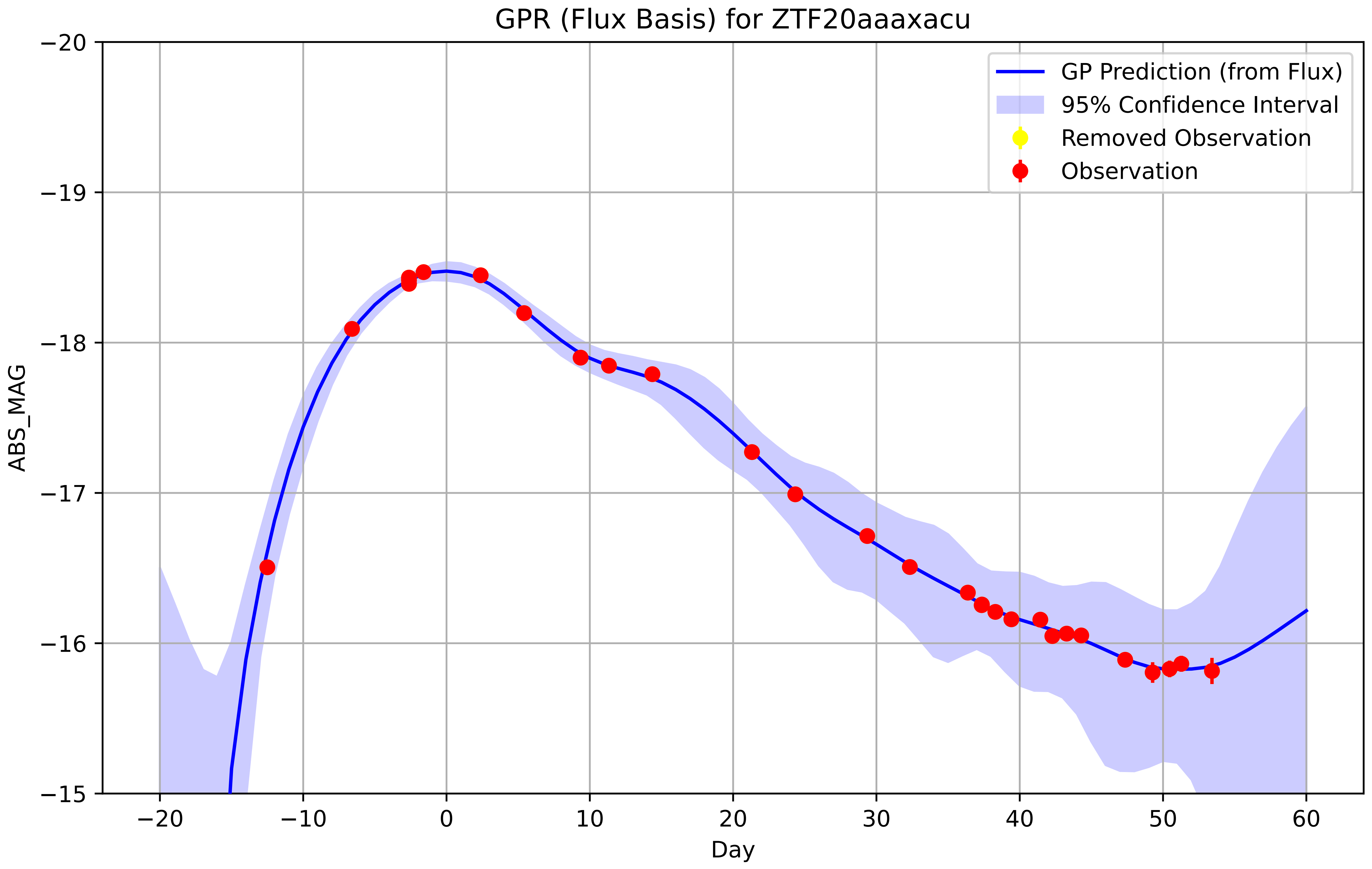


Gaussian Process Regression (GPR)

Gaussian Process Regression is a non-parametric interpolation method.
We incorporate observational uncertainties and reconstruct light curves with confidence intervals.

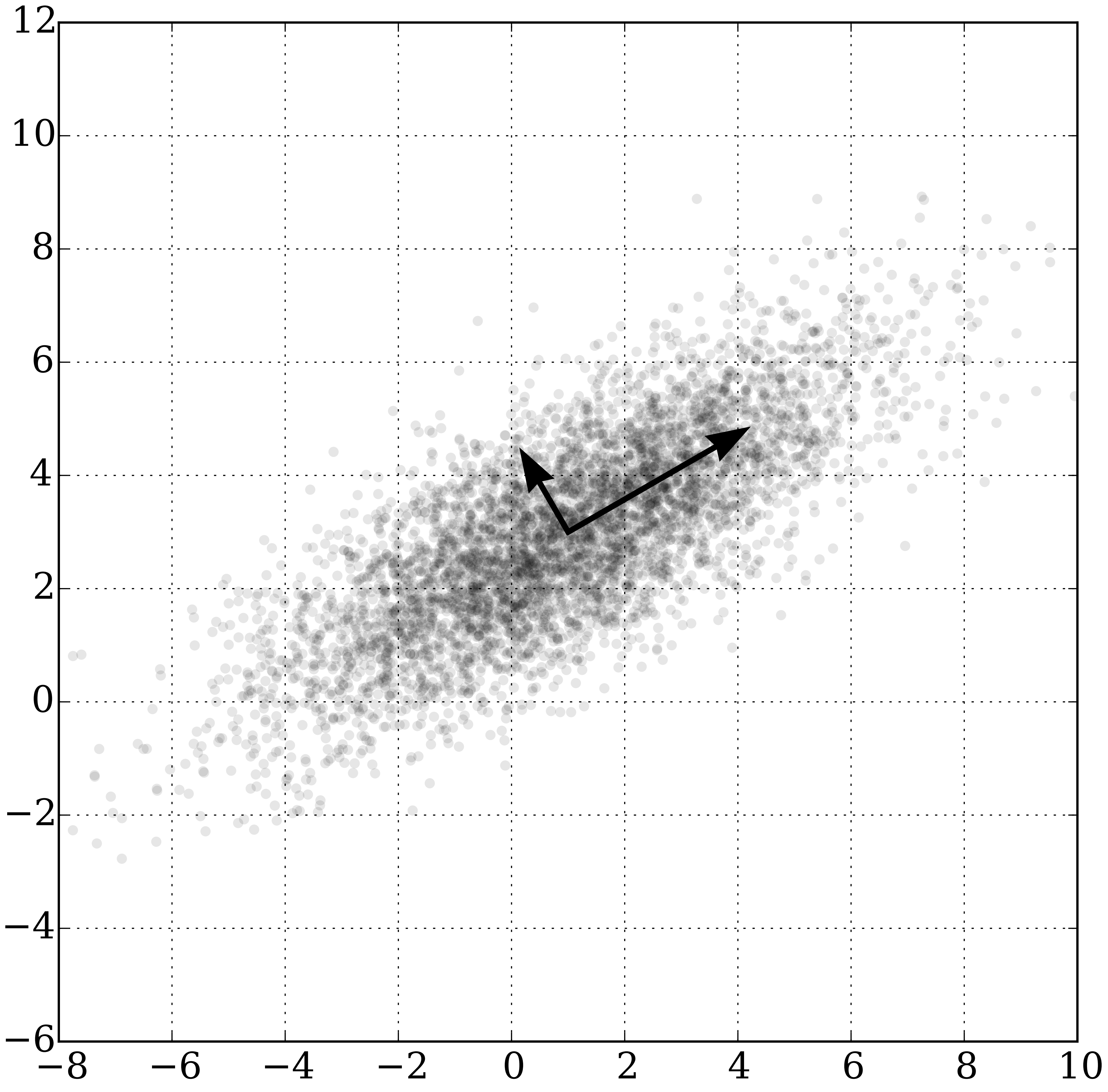
Kernel: Constant(1.0) * RBF(ν=1.0)





Principal Component Analysis (PCA)

The data is linearly transformed onto a new coordinate system such that the directions (principal components) capturing the largest variation in the data can be easily identified. (Wikipedia)



Principal Component Analysis (PCA)

$X_1 = (8,10,13,9)$

$X_2 = (10,10,5,11)$

$X_3 = (0,6,9,1)$

$X_4 = (2,6,1,3)$

$X_1 = \text{mean} + (3,2,6,3)$

$X_2 = \text{mean} + (5,2,-2,5)$

$X_3 = \text{mean} + (-5,-2,2,-5)$

$X_4 = \text{mean} + (-3,-2,-6,-3)$

$\text{mean} = (5,8,7,6)$

Principal Component Analysis (PCA)

$$X_1 = \text{mean} + (3,2,6,3)$$

$$X_2 = \text{mean} + (5,2,-2,5)$$

$$X_3 = \text{mean} + (-5,-2,2,-5)$$

$$X_4 = \text{mean} + (-3,-2,-6,-3)$$

$$X_1 = \text{mean} + 2\sqrt{10}\boldsymbol{v_1} + 3\sqrt{2}\boldsymbol{v_2}$$

$$X_2 = \text{mean} + 2\sqrt{10}\boldsymbol{v_1} - 3\sqrt{2}\boldsymbol{v_2}$$

$$X_3 = \text{mean} - 2\sqrt{10}\boldsymbol{v_1} + 3\sqrt{2}\boldsymbol{v_2}$$

$$X_4 = \text{mean} - 2\sqrt{10}\boldsymbol{v_1} - 3\sqrt{2}\boldsymbol{v_2}$$

principal components

basis vectors:

$$\boldsymbol{v_1} = \frac{1}{\sqrt{10}}(2,1,1,2)$$

$$\boldsymbol{v_2} = \frac{1}{3\sqrt{2}}(-1,0,4,-1)$$

Principal Component Analysis (PCA)

$$X_1 = (f^1_{peak}, f^1_{+1d}, f^1_{+2d}, \ldots, f^1_{+40d})$$

$$X_2 = (f^2_{peak}, f^2_{+1d}, f^2_{+2d}, \ldots, f^2_{+40d})$$

…

$$X_N = (f^N_{peak}, f^N_{+1d}, f^N_{+2d}, \ldots, f^N_{+40d})$$

$$X_1 = \text{mean} + k^1_1 \mathbf{v_1} + k^1_2 \mathbf{v_2} + \ldots$$

$$X_2 = \text{mean} + k^2_1 \mathbf{v_1} + k^2_2 \mathbf{v_2} + \ldots$$

…

$$X_N = \text{mean} + k^N_1 \mathbf{v_1} + k^N_2 \mathbf{v_2} + \ldots$$

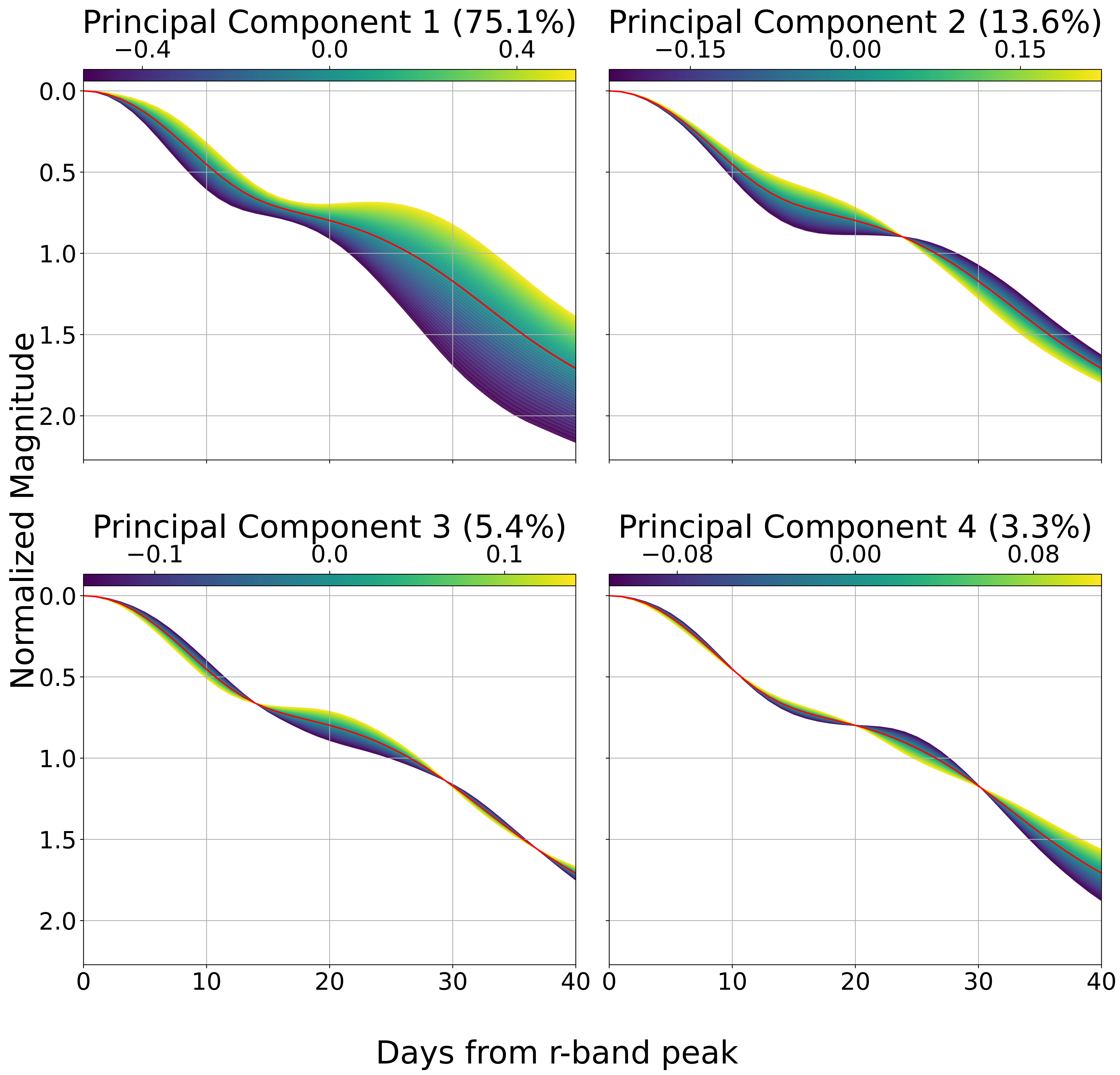
The basis vectors capture the dominant modes of light curve variability.

Correlating these principal components with other observables allows us to constrain the physics of Type Ia supernovae and refine the determination of the Hubble Constant.

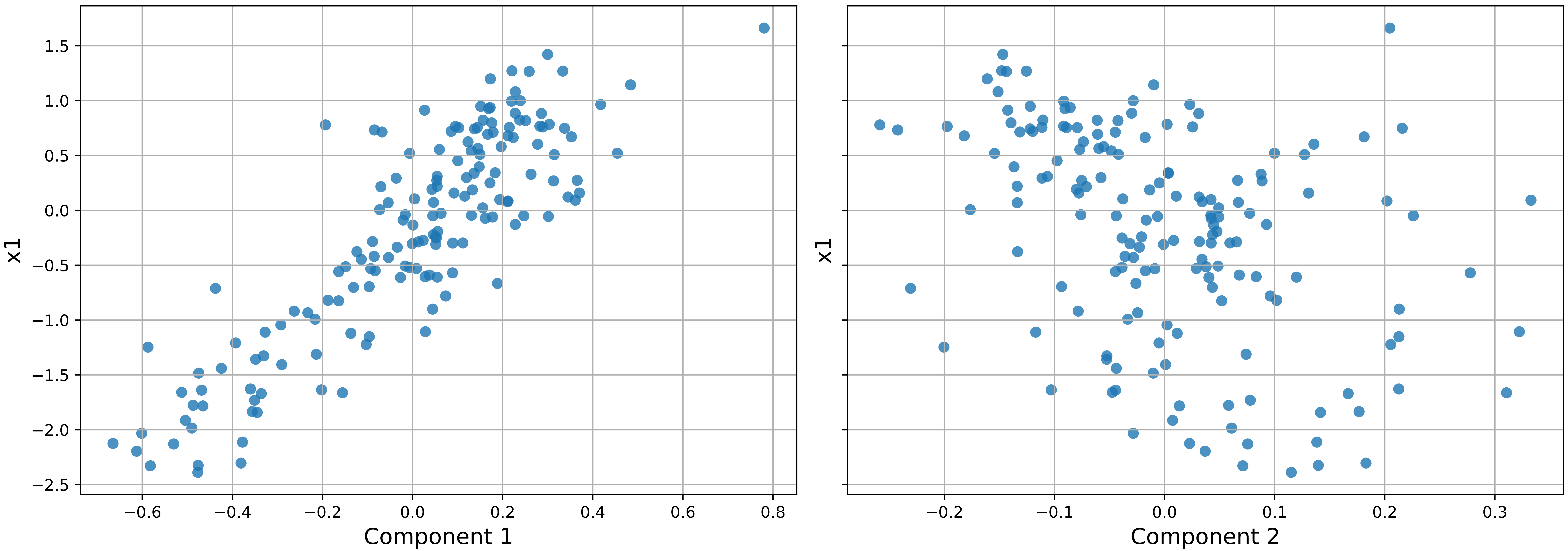
PCA Result for r-band Light Curves

- First component:
  - Correspond to **stretch**.
  - The larger the stretch, the stronger and later the secondary maximum appears.

- Second component:
  - Correspond to the strength of **secondary maximum**.
  - Explained variance ratio: **13.6%**



PCA Result for r-band Light Curves

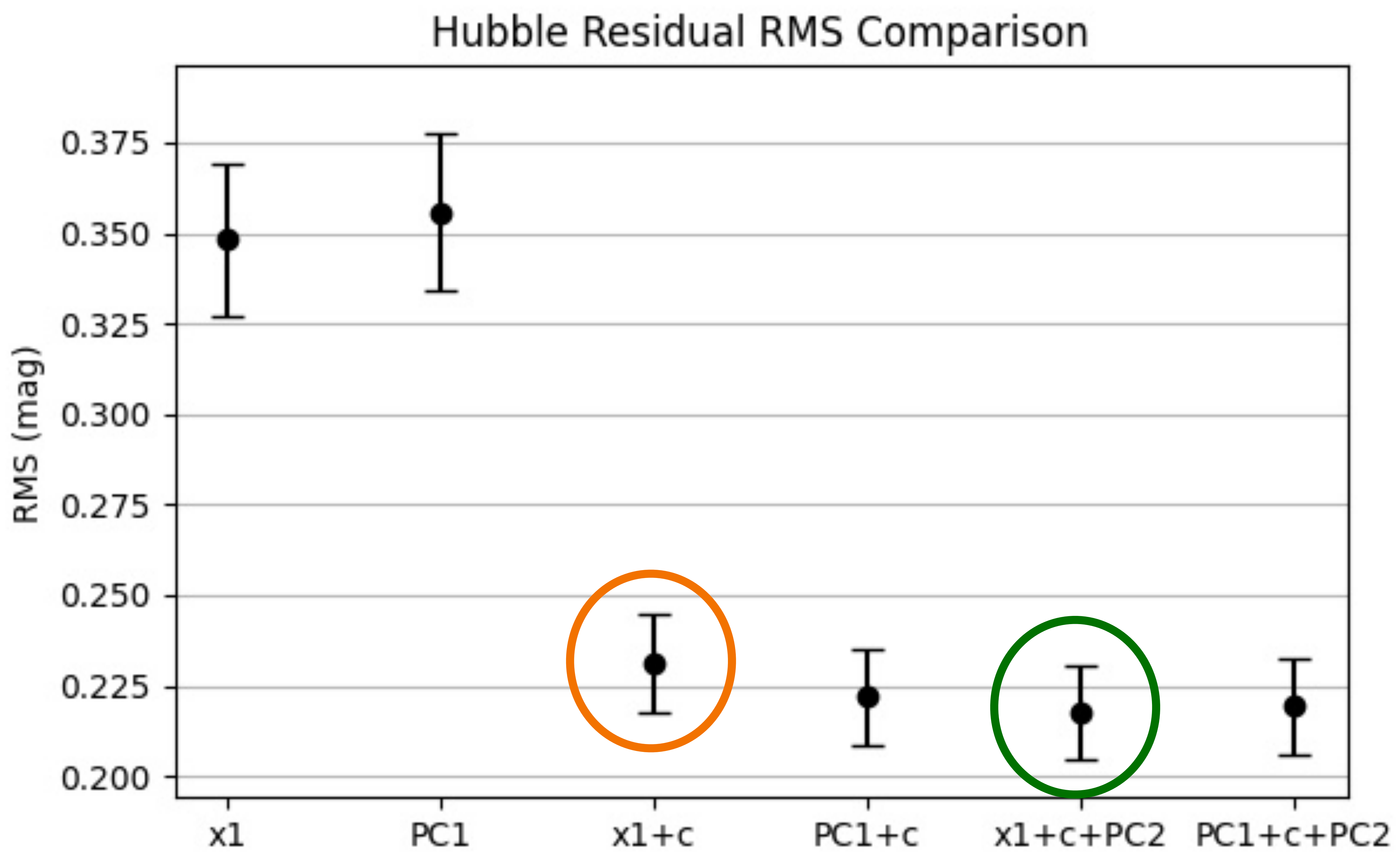


- 1st component is strongly correlated with x1. (r = 0.87)
- 2nd component is slightly correlated with x1. (r = -0.40)

PCA Result for r-band Light Curves

- Second component explains 13.6% variance of LC scatter, and it contributes modestly to peak-luminosity standardization.
- Including PC2 provides a slight statistical improvement (based on AIC/BIC).

	Hubble residual	AIC	BIC
x1 + c	0.231±0.014	-398	-390
x1 + c + PC2	0.217±0.013	-413	-401



PCA Result for r-band Light Curves

- What is the features of light curves of SNe Ia?
- How much does the stretch explain the diversity of r-band light curves?

  →1st component is strongly correlated with SALT2 x1 and stretch.
  →Stretch best explains the diversity of LCs of SNe Ia.

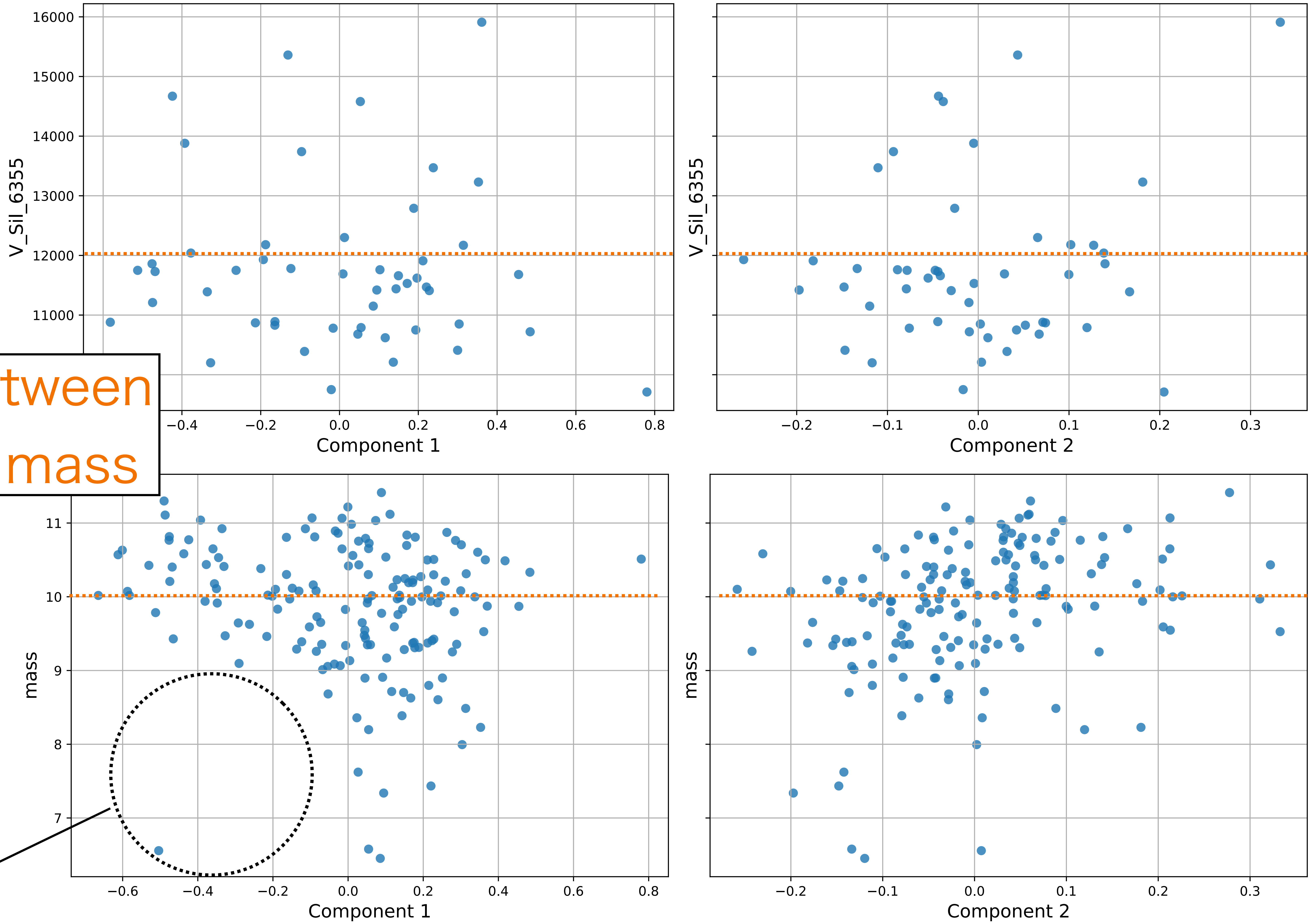
- Is the secondary maximum independent from the stretch?

  →While correlated with stretch, the secondary maximum also has an independent component (PC2), though its impact on Hubble residuals is limited.

PCs vs. Si II velocity and Host mass

Si II velocity

host mass



No strong relationship between PCs and velocity or host mass

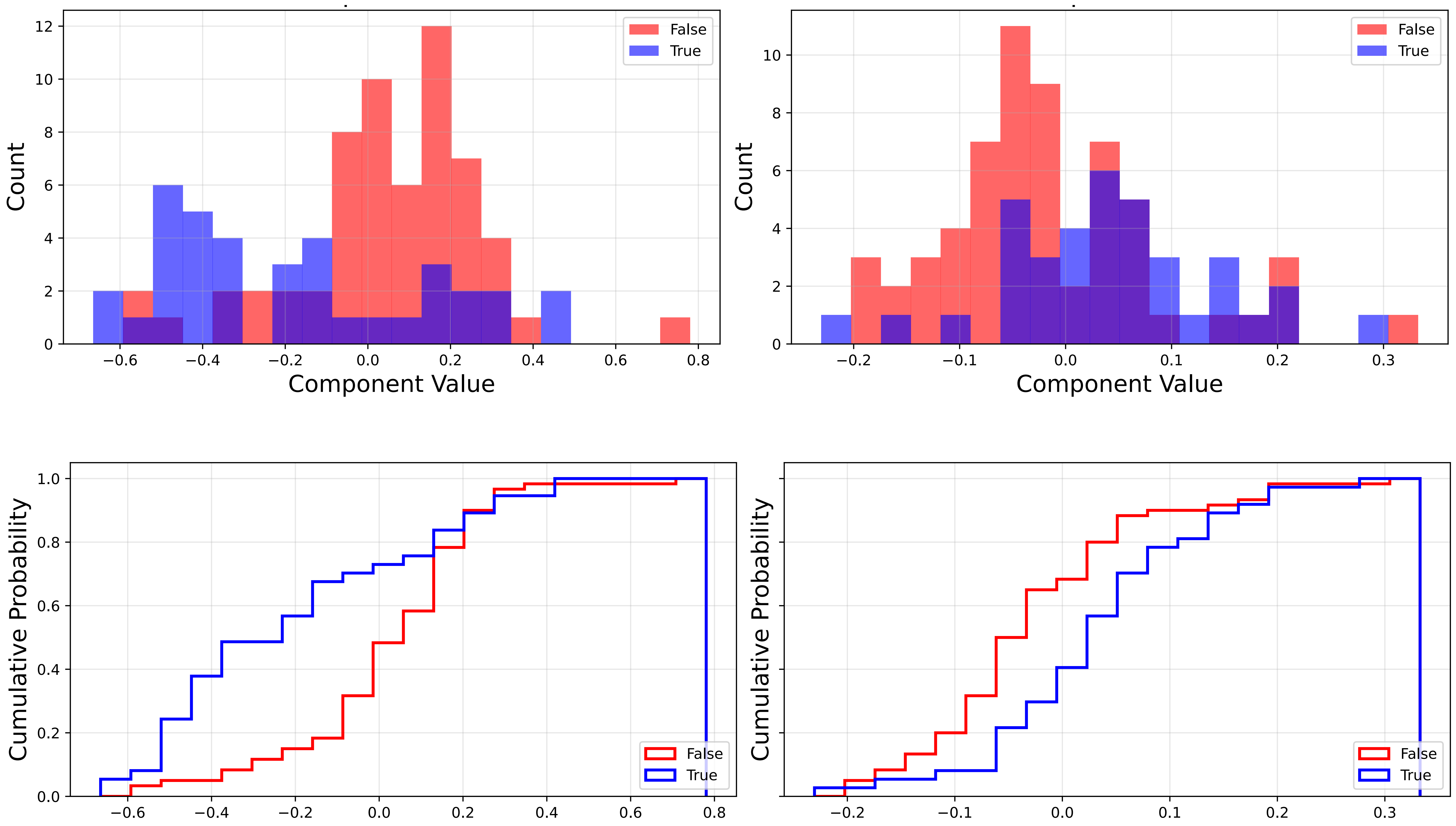
PCs vs. host morphology

- High-luminosity (large stretch) SNe prefer late-type (low-mass) hosts.
  This is consistent with prior research.

- SNe in **late-type hosts** tend to have a **strong secondary maximum**.

red: late type

blue: early type



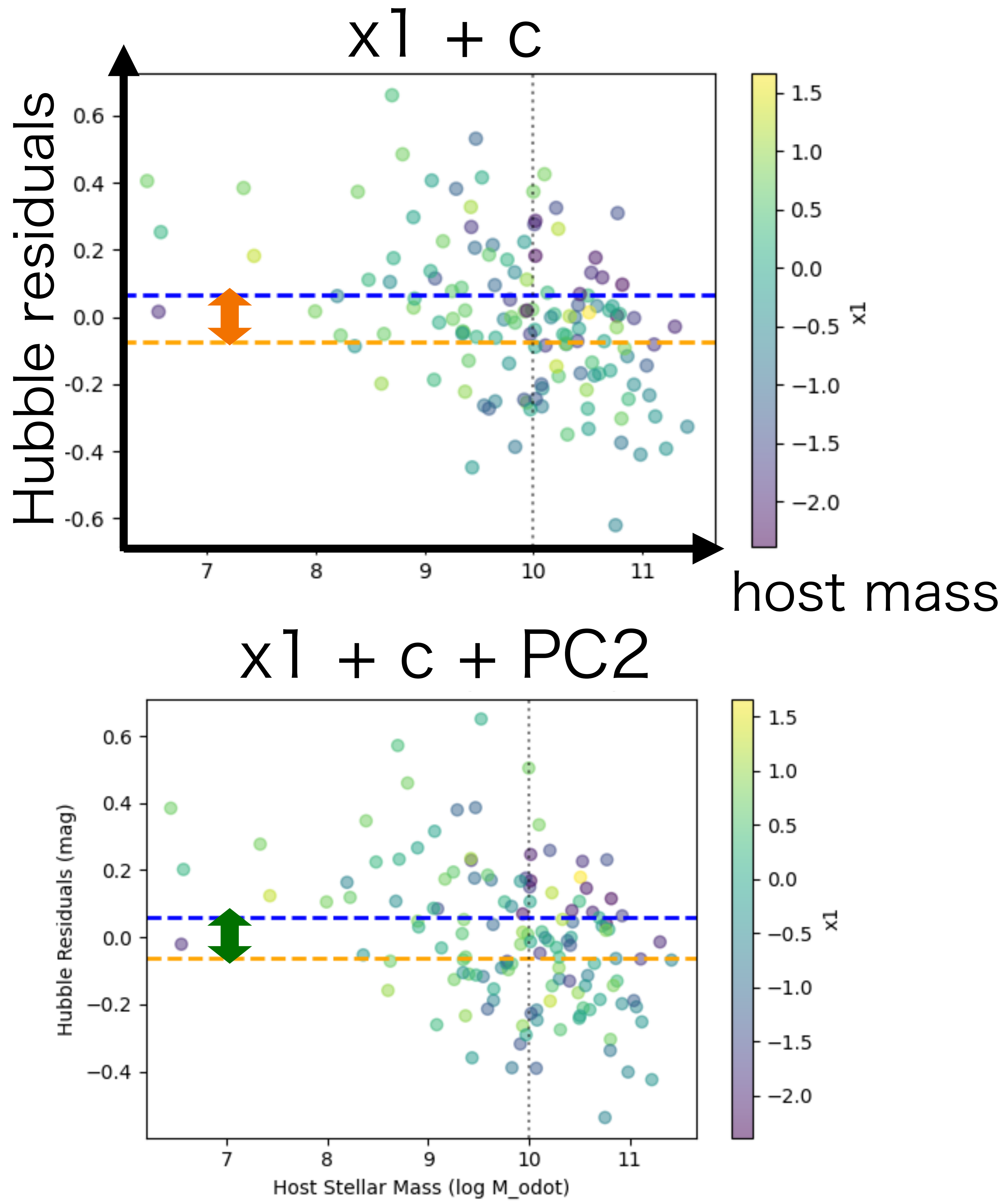
1st component
KS-p: 2.4×10^{-6}

2nd component
KS-p: 1.2×10^{-3}

Mass step

- x1+c: 0.14 ± 0.04 mag
- x1+c+PC2: 0.12 ± 0.03 mag

- **PC2 cannot explain mass step.**
- This indicates that light-curve shape diversity alone is insufficient to explain the mass step, favoring extrinsic effects such as dust.



Origin of 2nd component

2nd component is independent of 1st component (stretch / ^{56}Ni mass).

What governs 2nd component?

- Stronger mixing leads to earlier/broader secondary maximum (Kasen+2006).
- Higher progenitor metallicity increases stable iron abundance, enhancing opacity and fluorescence, which leads to a more prominent secondary maximum (Timmes+2003).
- Higher central density of the progenitor WD promotes electron capture, increasing neutron-rich stable isotopes (e.g., ^{54}Fe, ^{58}Ni) and enhancing the secondary maximum (Lesaffre+2006; Krueger+2012).
- Asymmetries in the ejecta could introduce scatter in timing and strength of secondary maximum.

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- Asymmetries in the ejecta could introduce scatter in timing and strength of secondary maximum.

consistent??

2nd component correlate with host morphology.

bumpy ⟷ late type host

Future works

- Investigate the physical origin of PC2:
    - Correlate PC2 with local metallicity and spectral features (e.g., equivalent widths).
    - Compare with simulations to understand the secondary maximum diversity.
- Apply to future large datasets:
    - Extend this PCA method to upcoming surveys like LSST (Rubin Observatory) to utilize larger statistics and higher redshift samples.
    - Roman Space Telescope will provide the large NIR data, which is less affected by dust.

Conclusion

Quantified the diversity of ZTF SNe Ia r-band light curves using GPR and PCA.

- 1st component: Strongly correlated with stretch (x1), corresponding to the conventional standardization parameter.
- 2nd component: Represents the strength, independent of stretch.
  - Including 2nd component in distance estimation reduced the Hubble residual RMS by ~9%.
  - The mass step remained unresolved even with 2nd component.

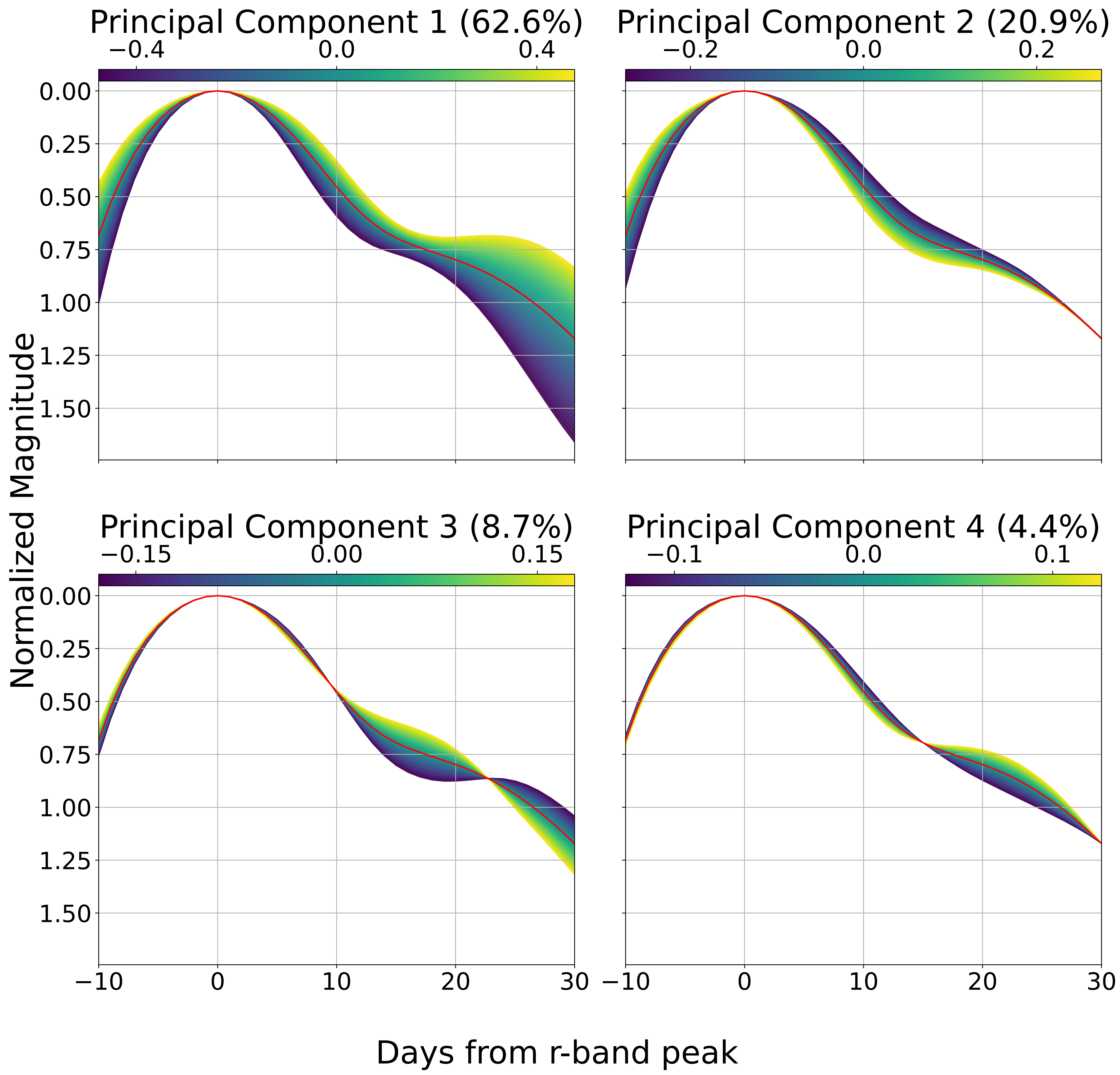
    This supports the scenario where the Mass Step is driven by extrinsic factors (e.g., dust) rather than intrinsic properties that affect light curve shapes.
  - SNe Ia in late-type hosts tend to exhibit a stronger secondary maximum (excess relative to stretch).

    This is consistent with higher central densities of progenitors in late-type hosts.

Appendix

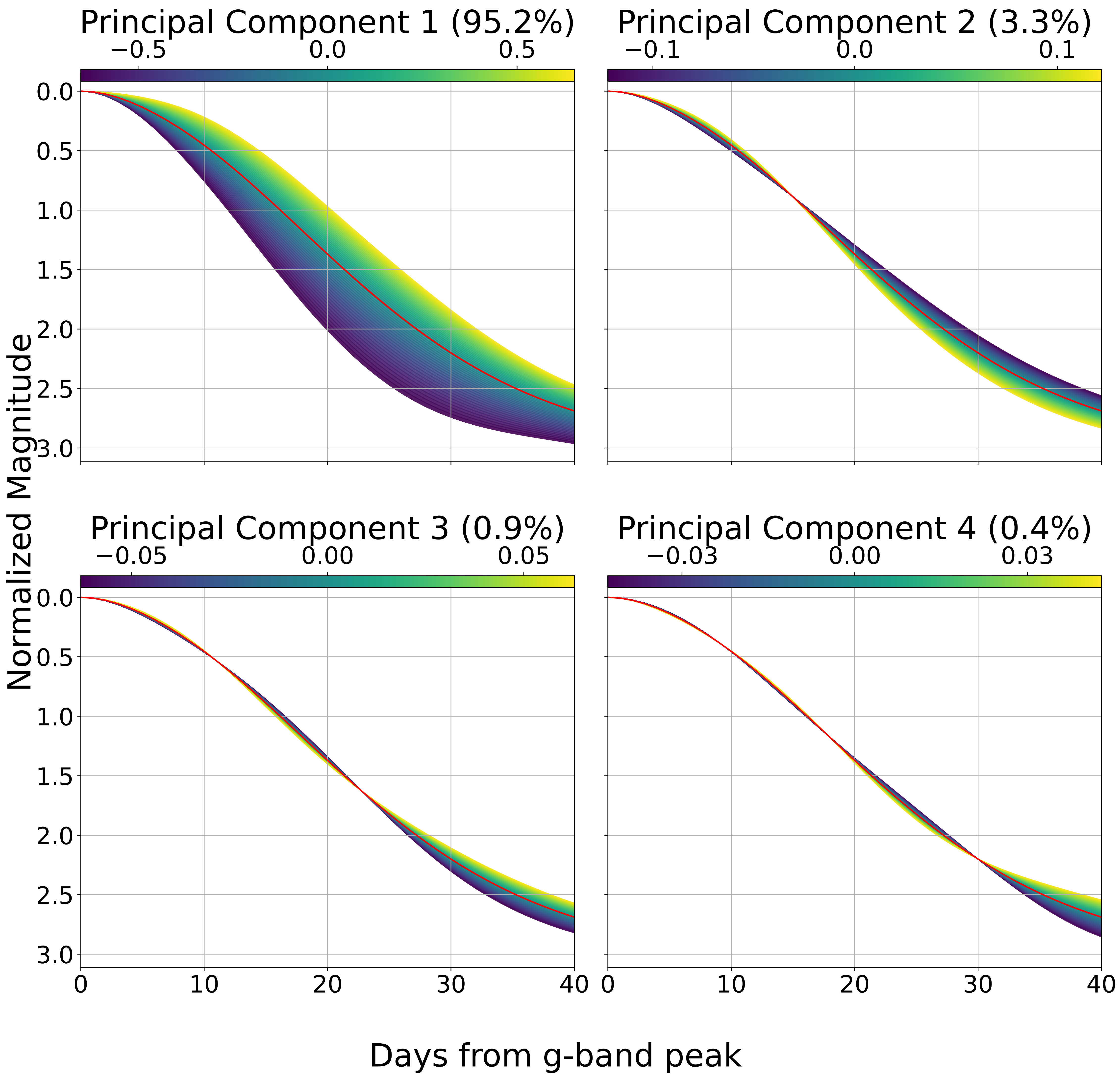
PCA Result for r-band Light Curves

- First component:
  - Correspond to **stretch**.
  - The larger stretch, the bigger and later secondary maximum.
- Second component:
  - Correspond to difference between **brightening** and extinction speed.
- Third component:
  - Correspond to the strength of **secondary maximum**.



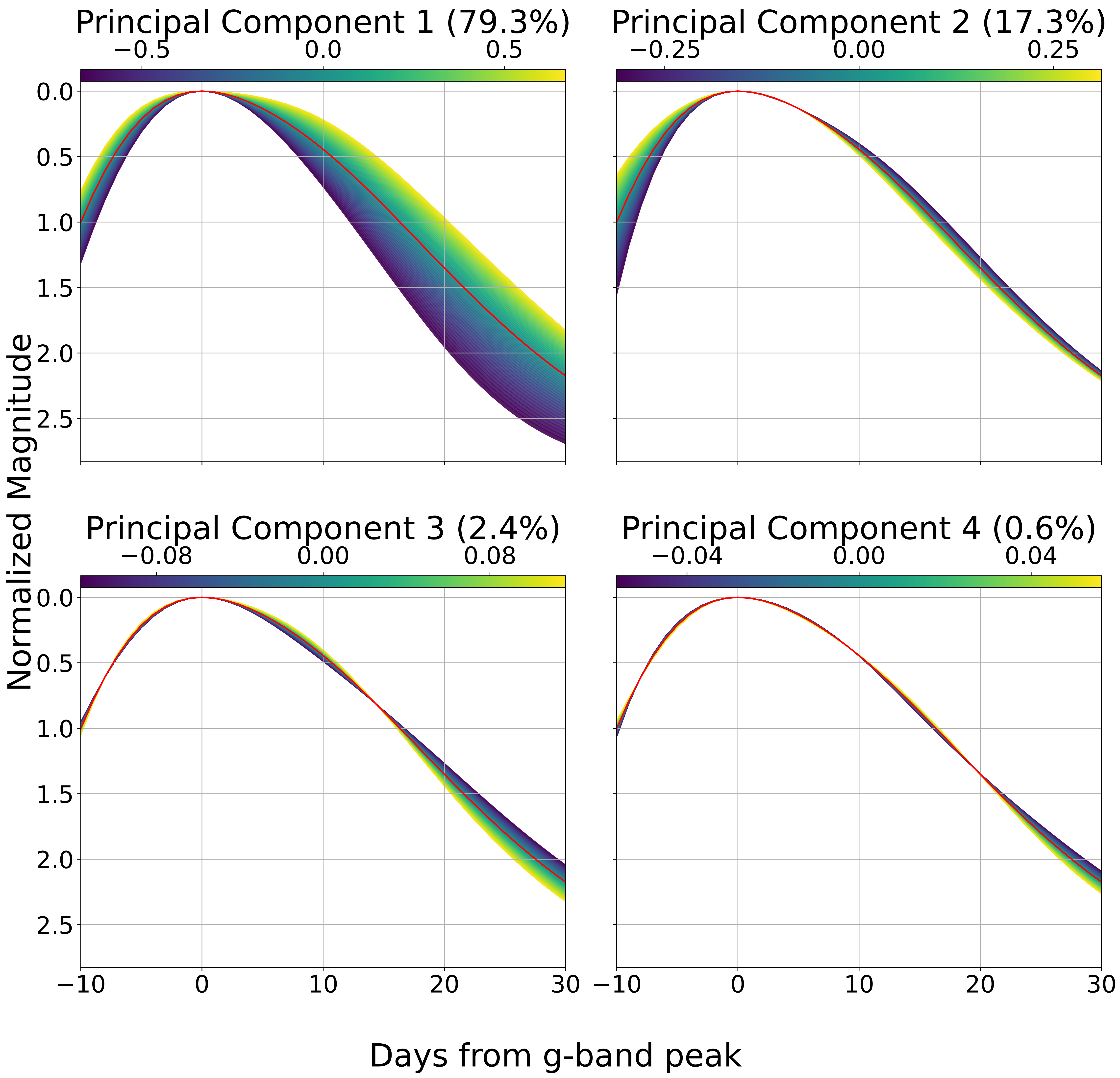
PCA Result for g-band Light Curves

- First component:
  - correspond to stretch
- Other components:
  - not important



PCA Result for g-band Light Curves

- First component:
  - correspond to stretch
- Second component:
  - correspond to brightening speed



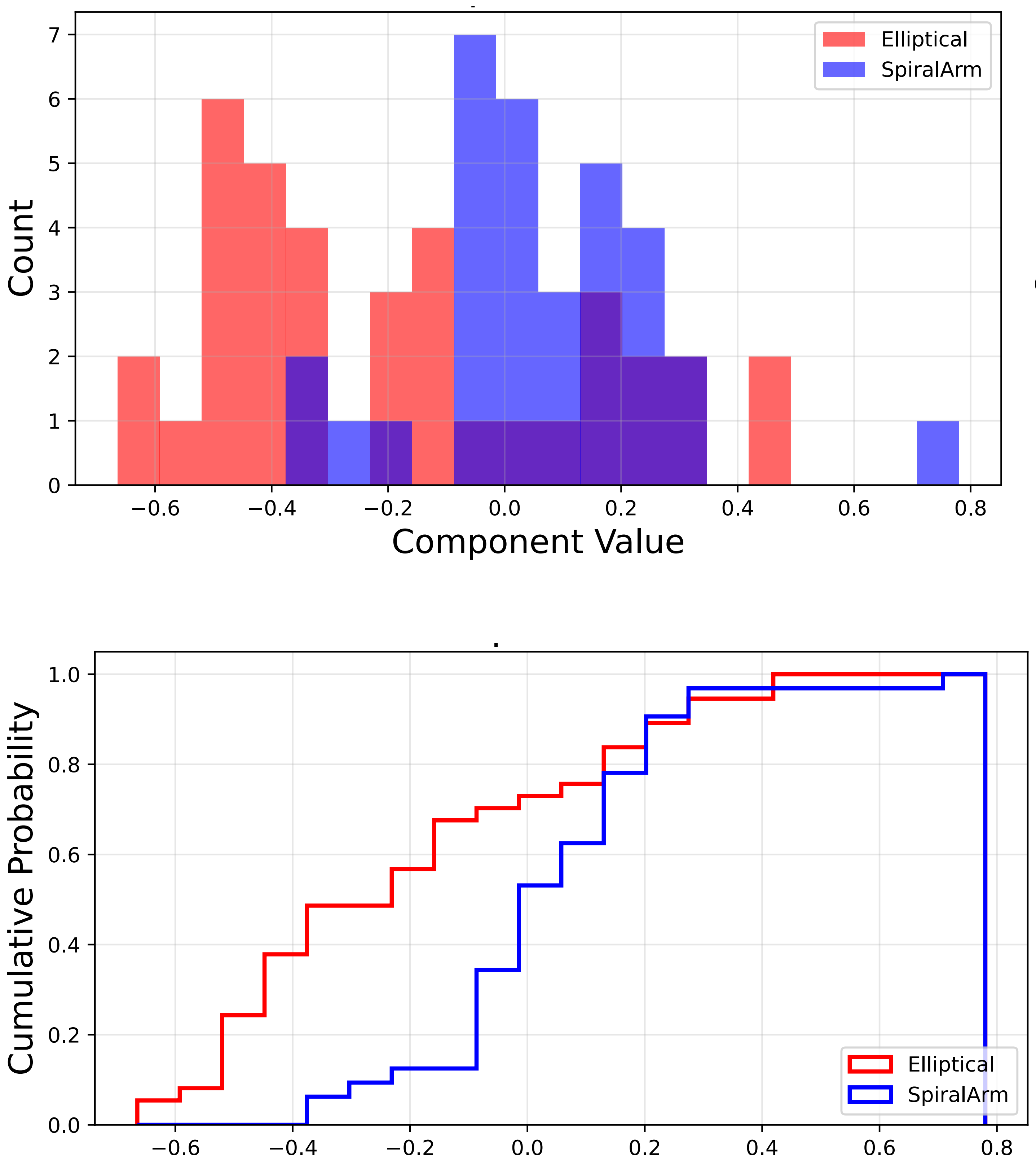
PCs vs. host morphology

- High-luminosity (large stretch) SNe prefer spiral arms rather than early type hosts.
  This is consistent with prior research.

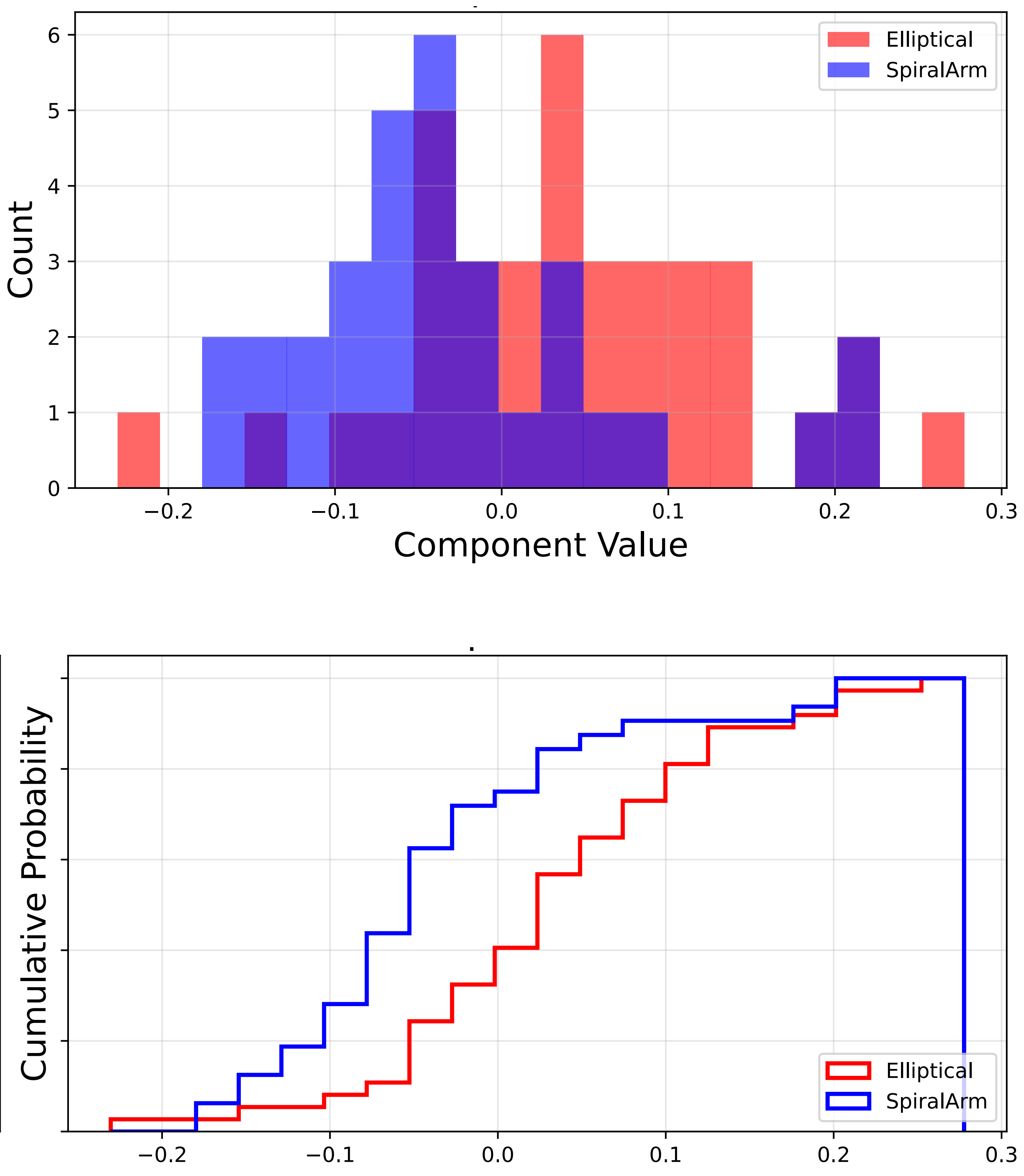
- SNe in **star forming region** tend to have a **strong secondary maximum**.

red: early type host

blue: spiral arm



1st component
KS-p: 7.6×10^{-6}



2nd component
KS-p: 1.4×10^{-3}

ET and LT host SNe on PC plot

- Correlation coefficient is not significant (6.8%)