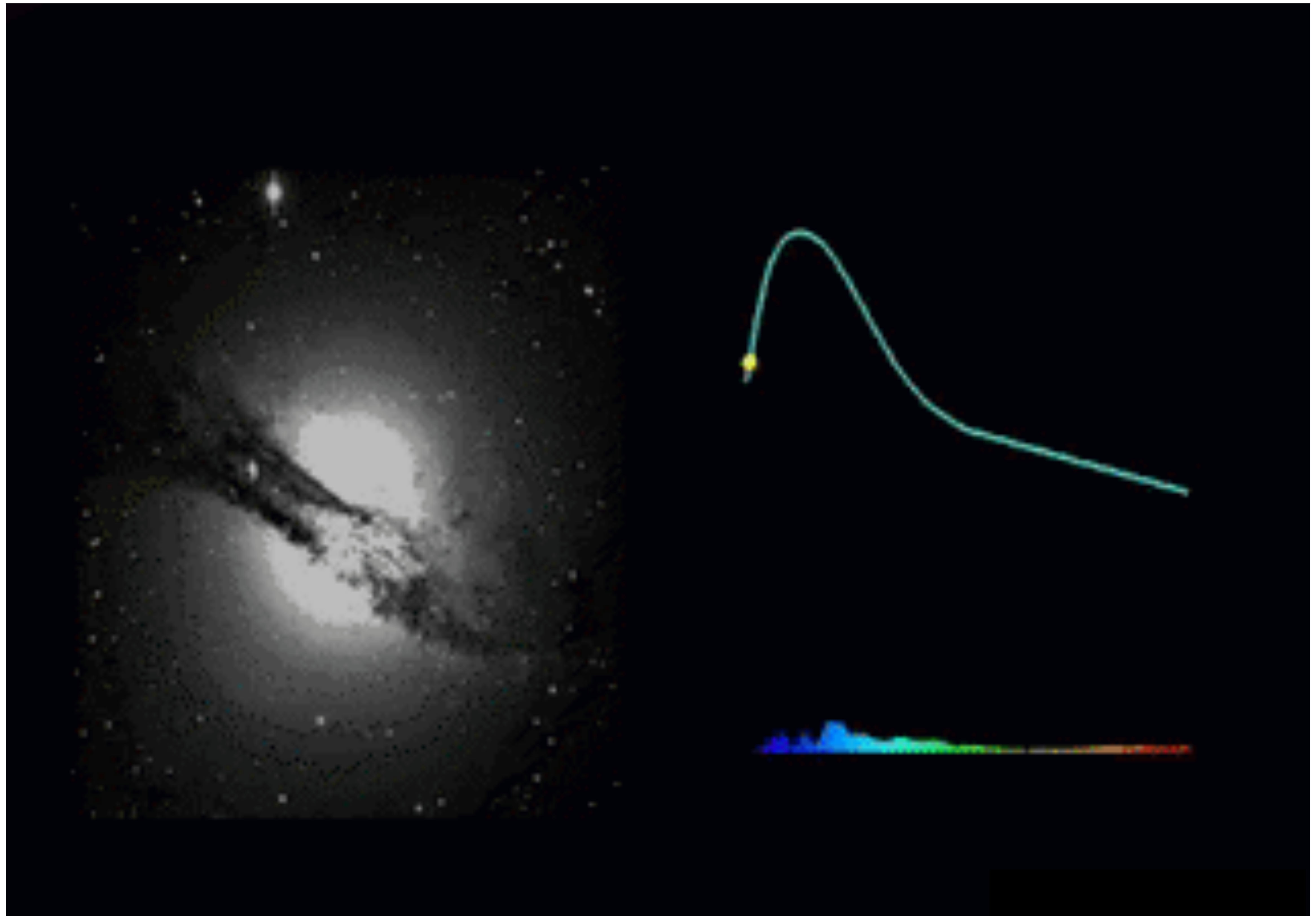
Introduction to type Ia supernova cosmology

Lluís Galbany (RyC fellow, ICE-CSIC)

Grau en matemàtica computacional i analítica de dades, 1 Març 2022

Supernovae

- End points of stellar evolution
- Bright stellar explosions of mag -14 to -22
- Element factories
- Expels material at up to 30000 km/s
- Shock wave into interstellar medium: supernova remnant


Supernova Cosmolgy Project: SN1986G in Centaurus

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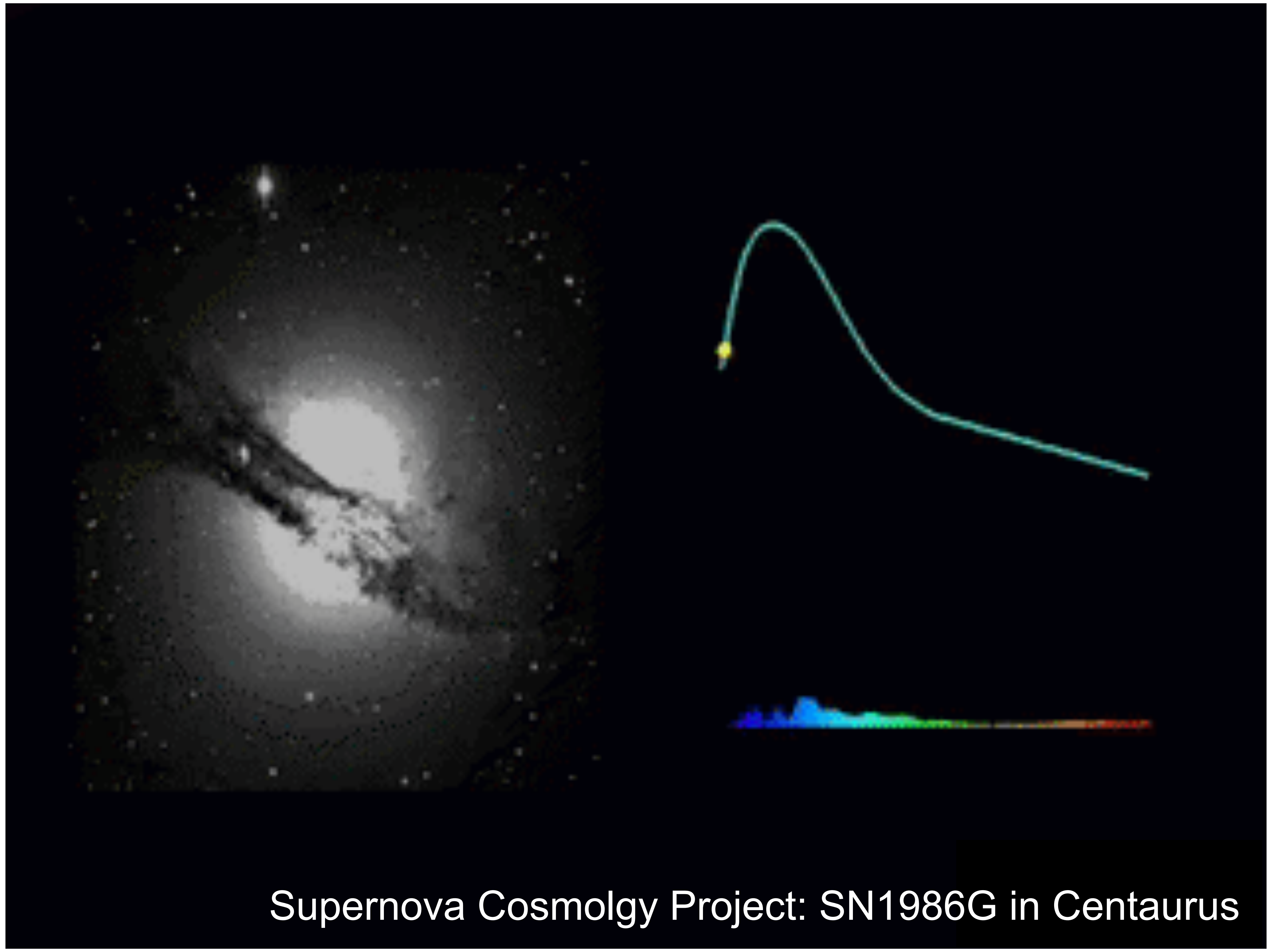

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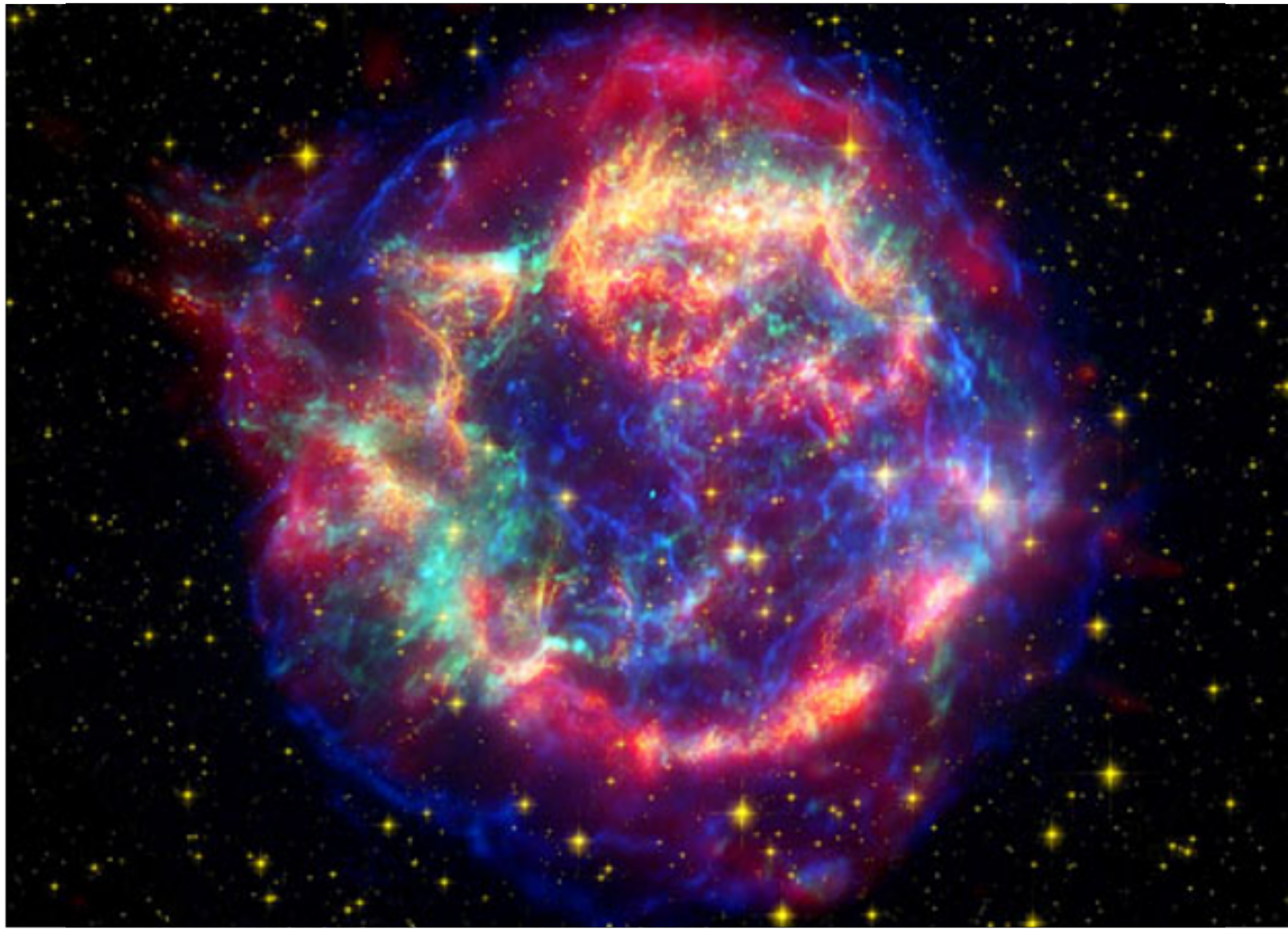
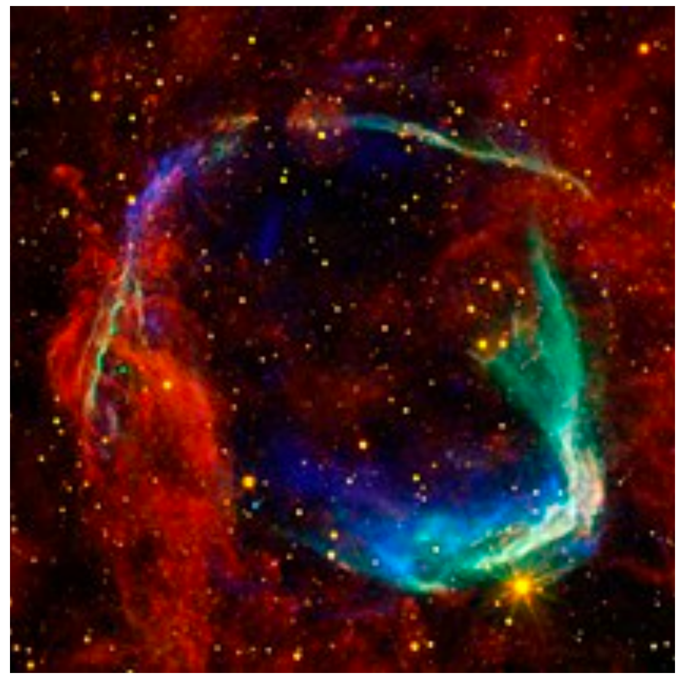
CasA/Chandra

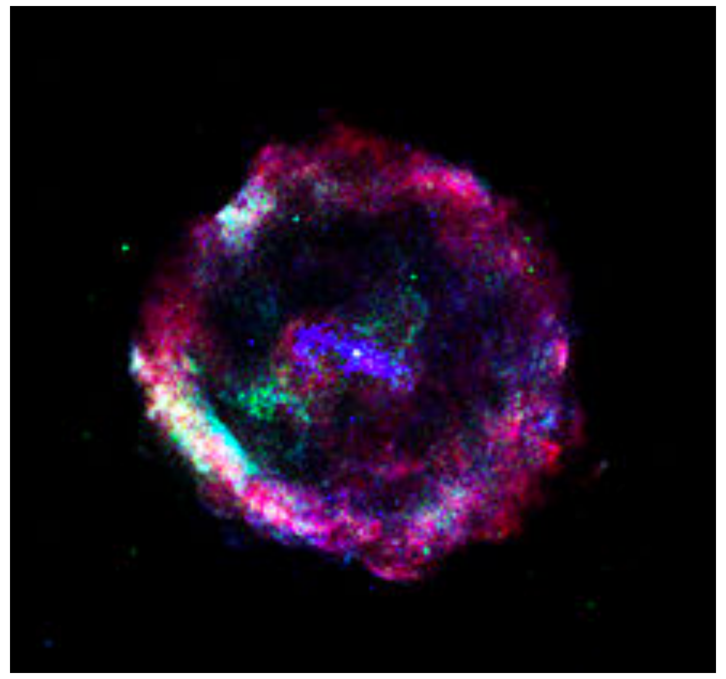


Historical supernovae

- Babylonian, Chinese, Korean, Japanese, Arabic, and European records of supernova discoveries
- Ancient civilizations recorded cyclical phenomena such as eclipses, planetary movements, as well as meteors, comets, and stellar outbursts
- Events used to confirm the power of the ruling king at that time
- Most records incomplete and lost



SN 185



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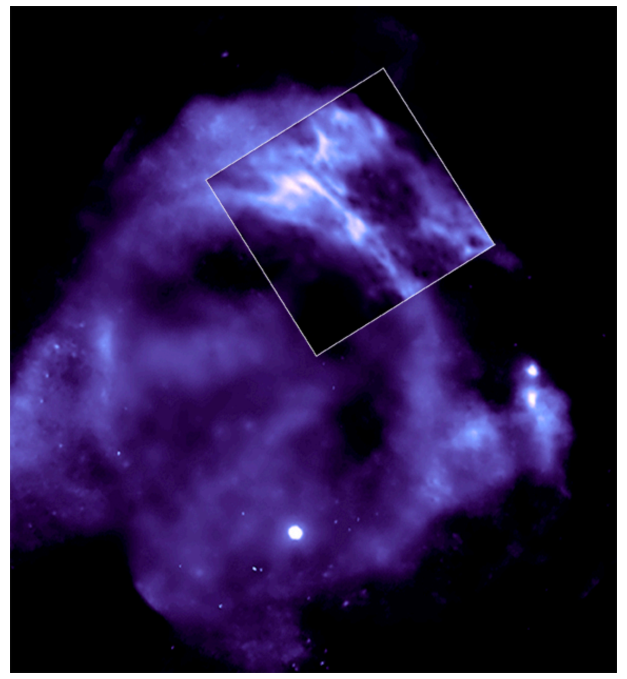
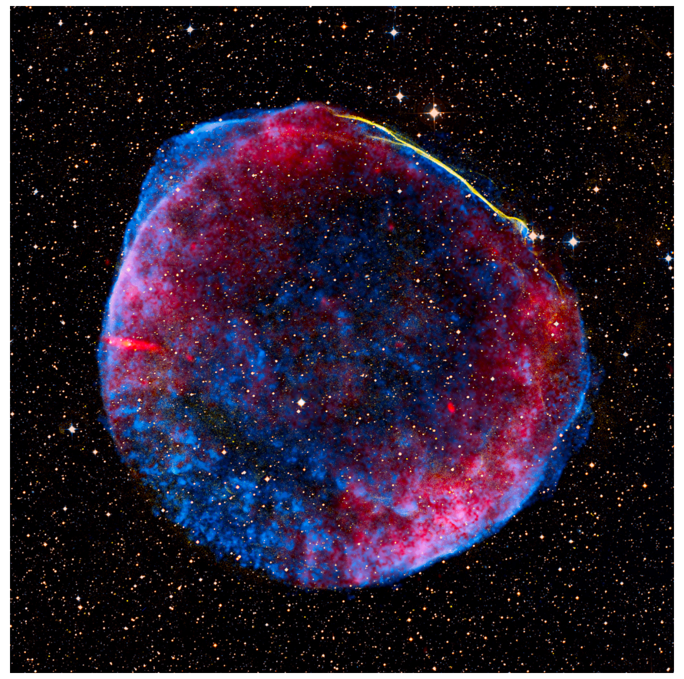


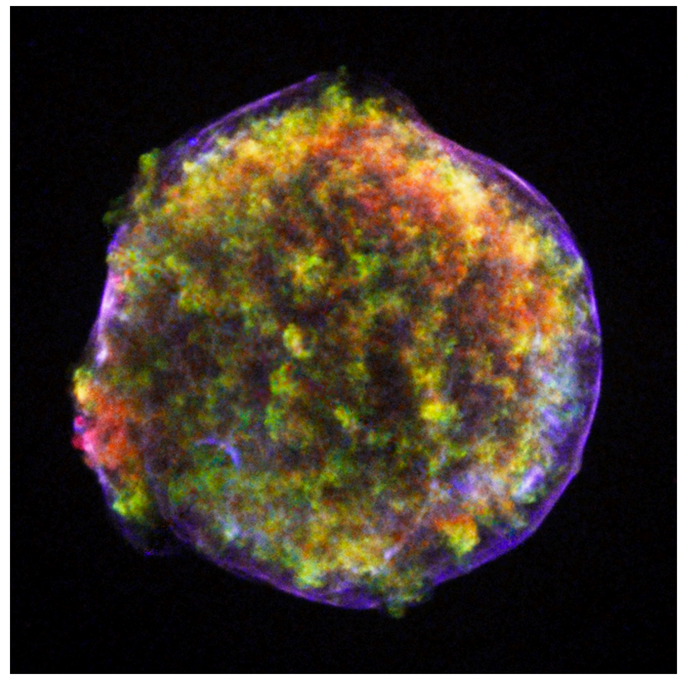
SN 393



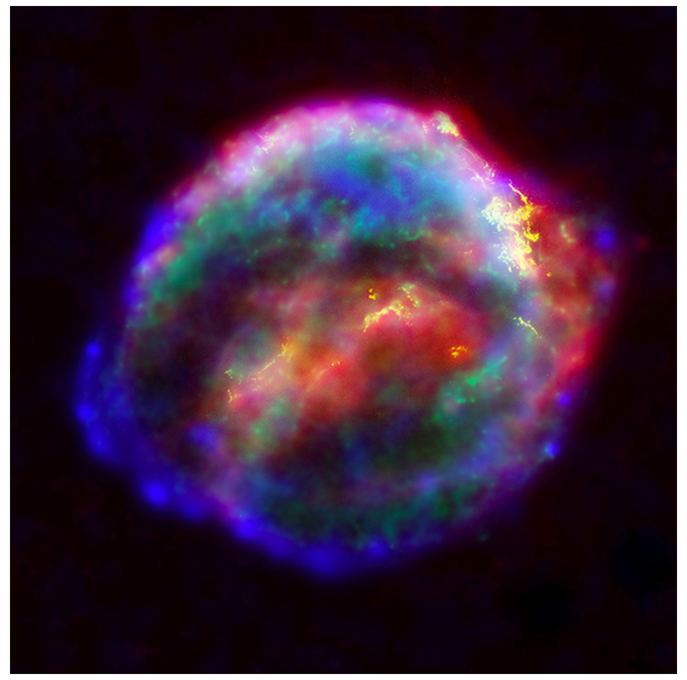
SN 1006

SN 1054

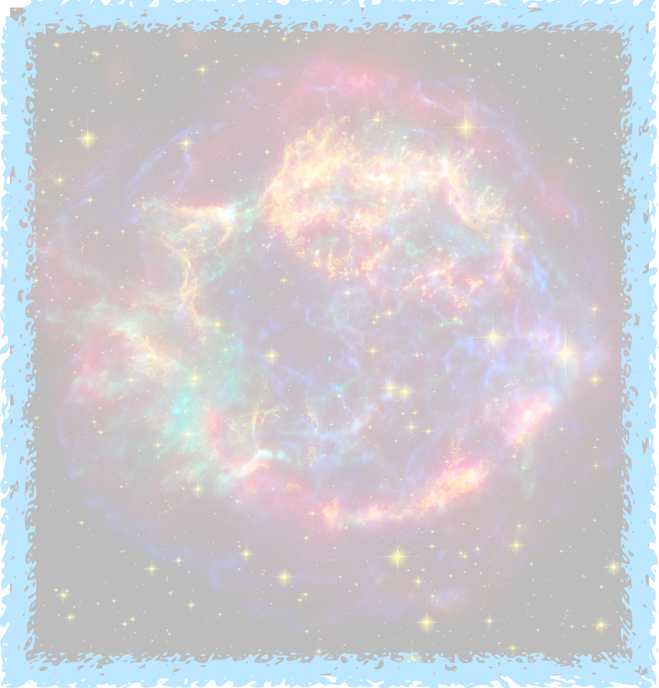
SN 1181



SN 1572



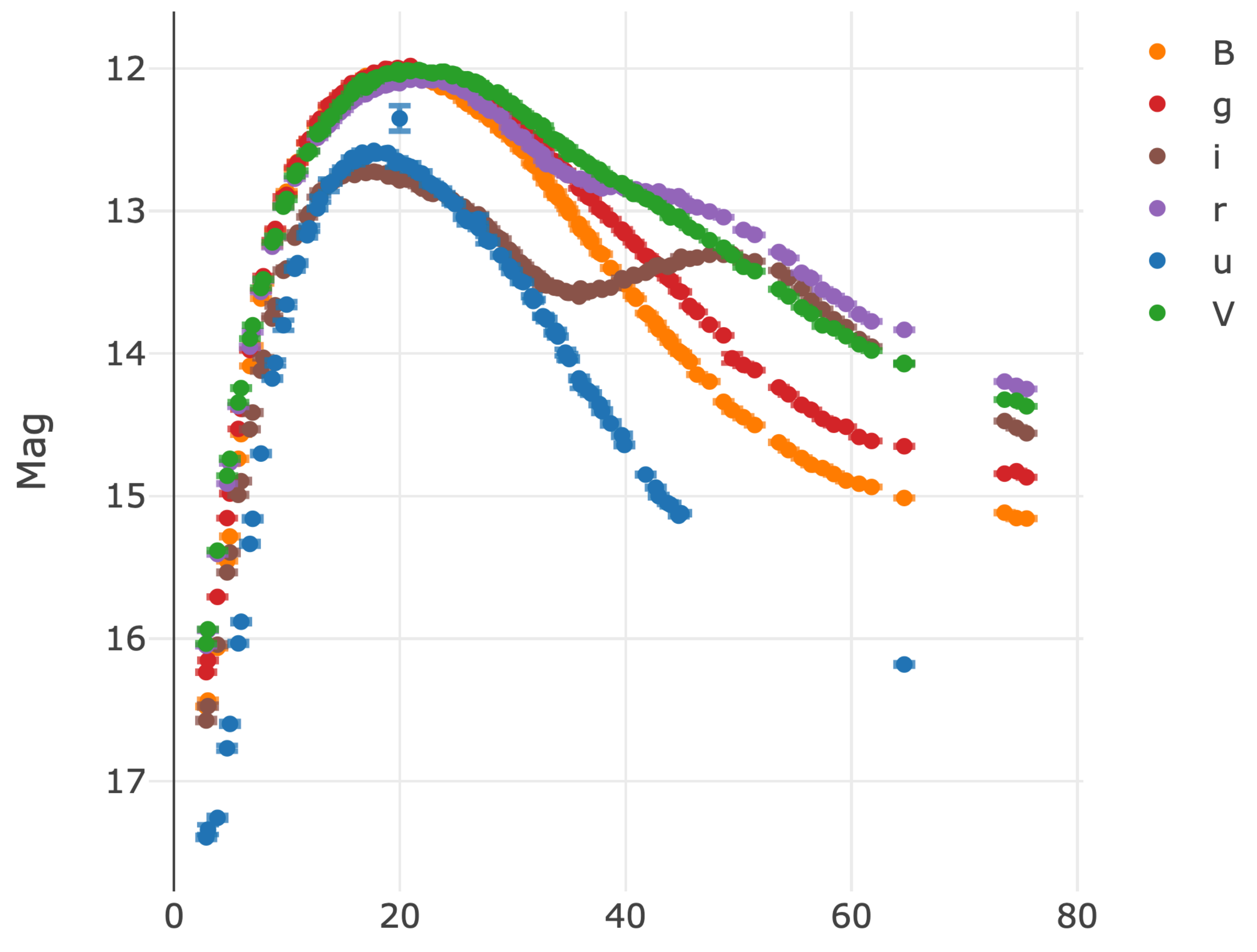
SN 1604

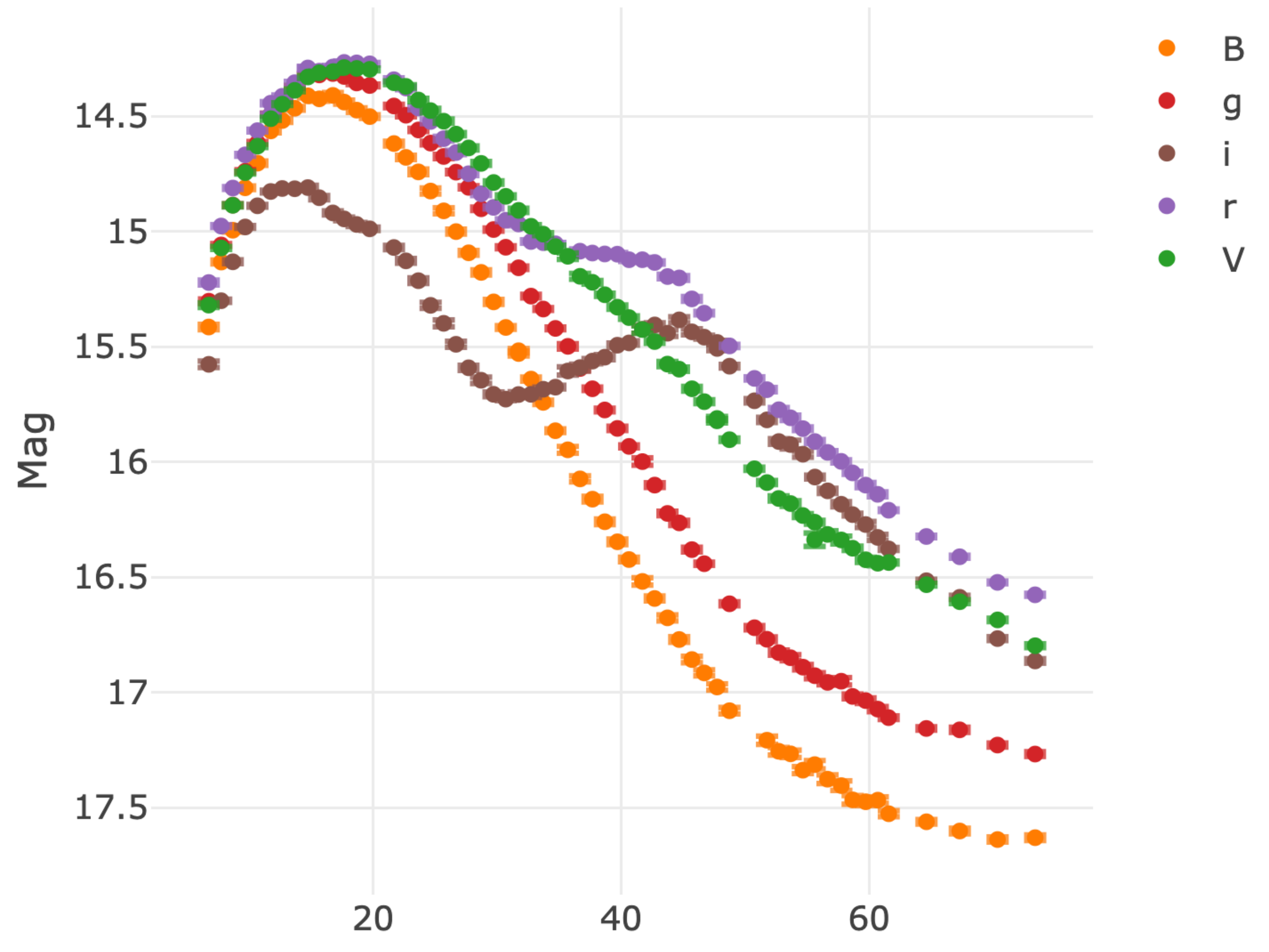


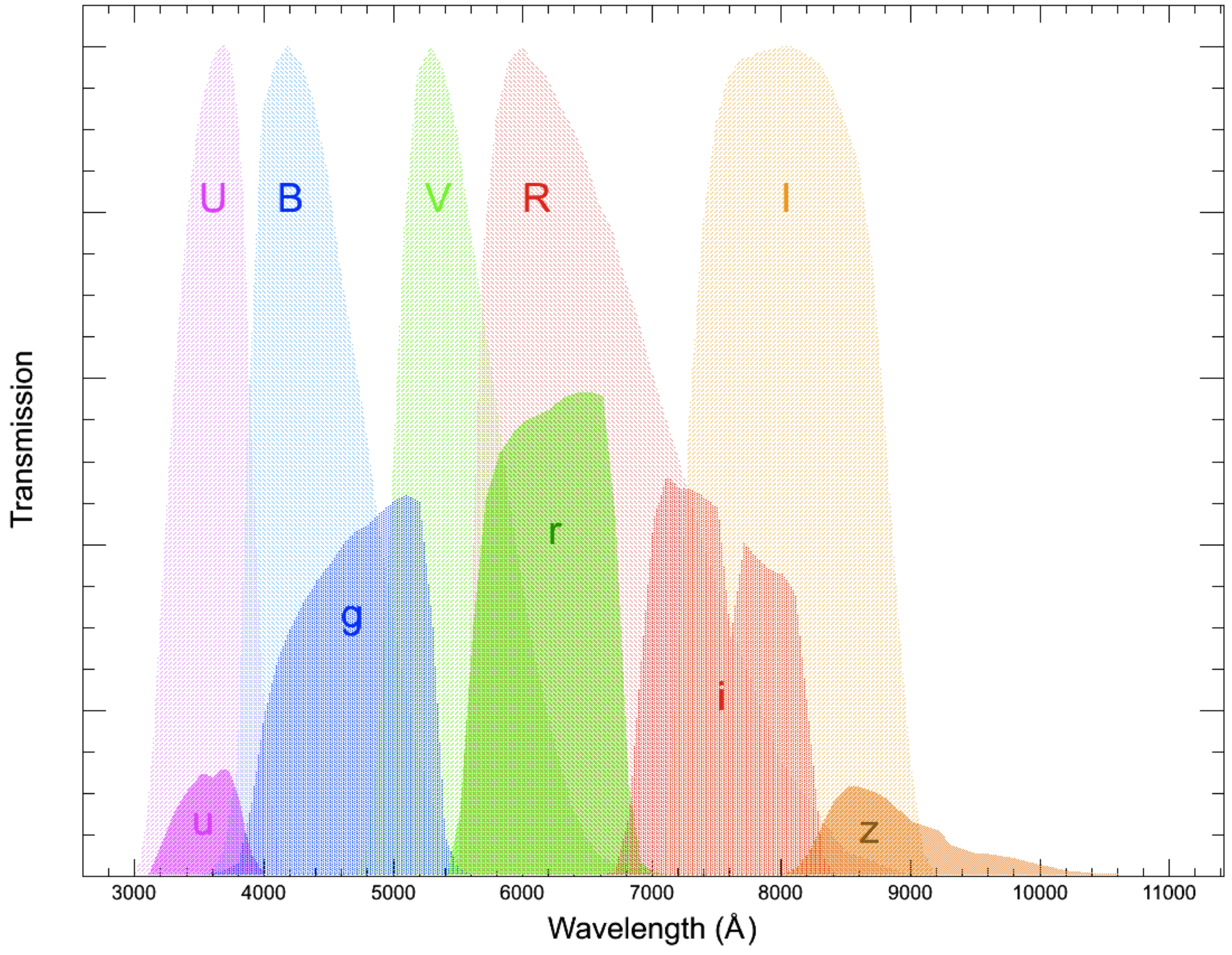
SN 1667 - CasA

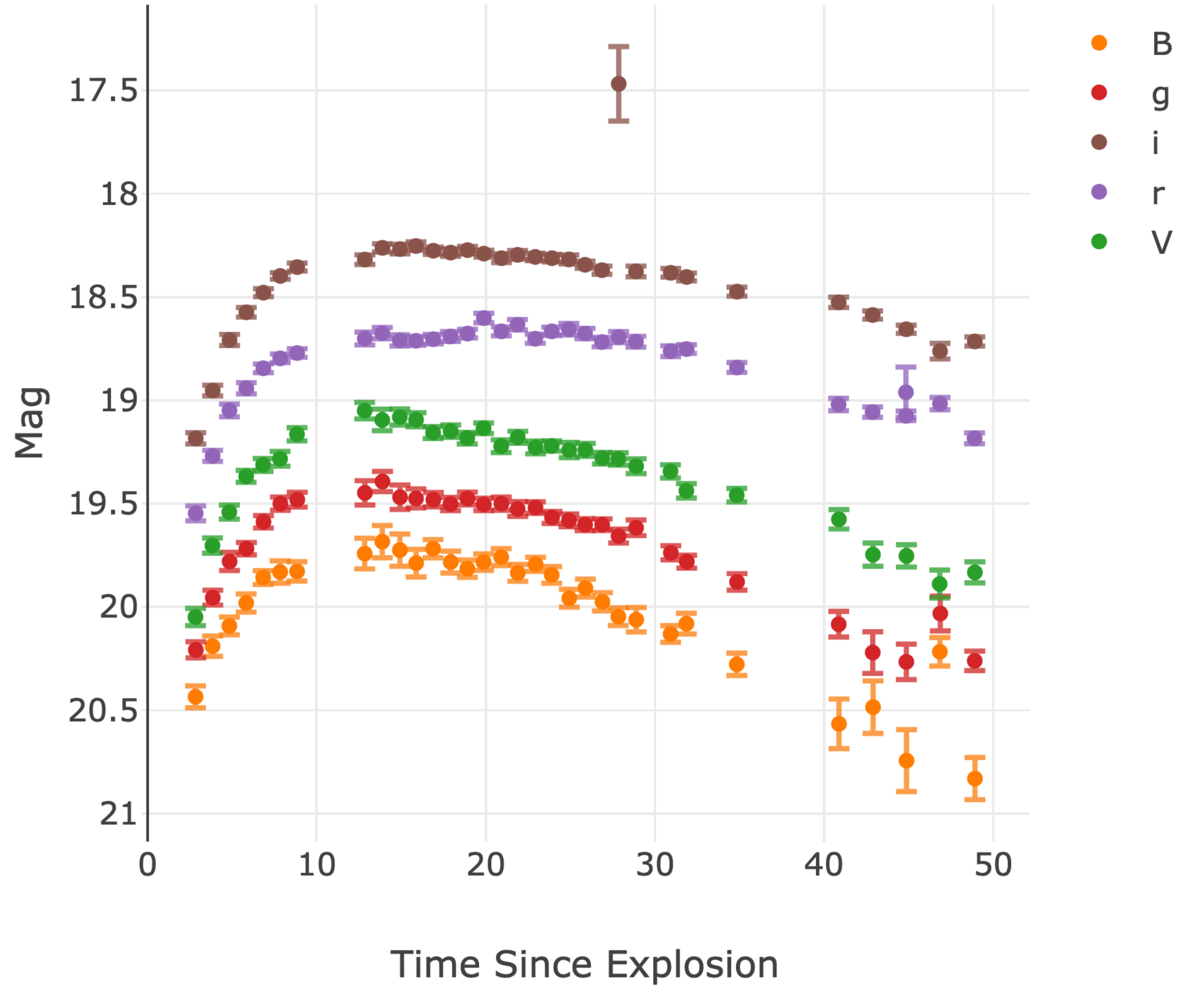
Light curves

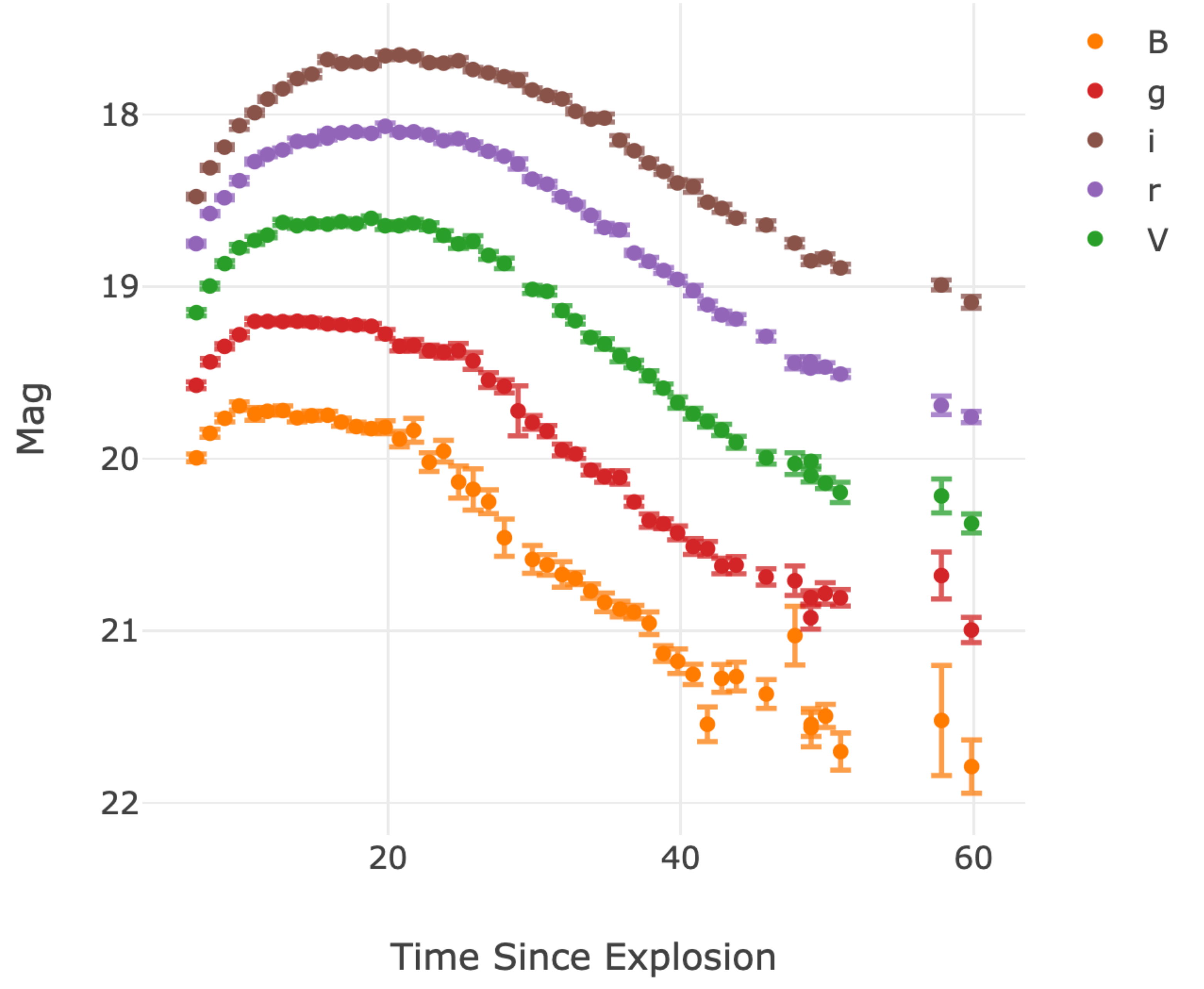
- Brightness
- Evolution
- Color





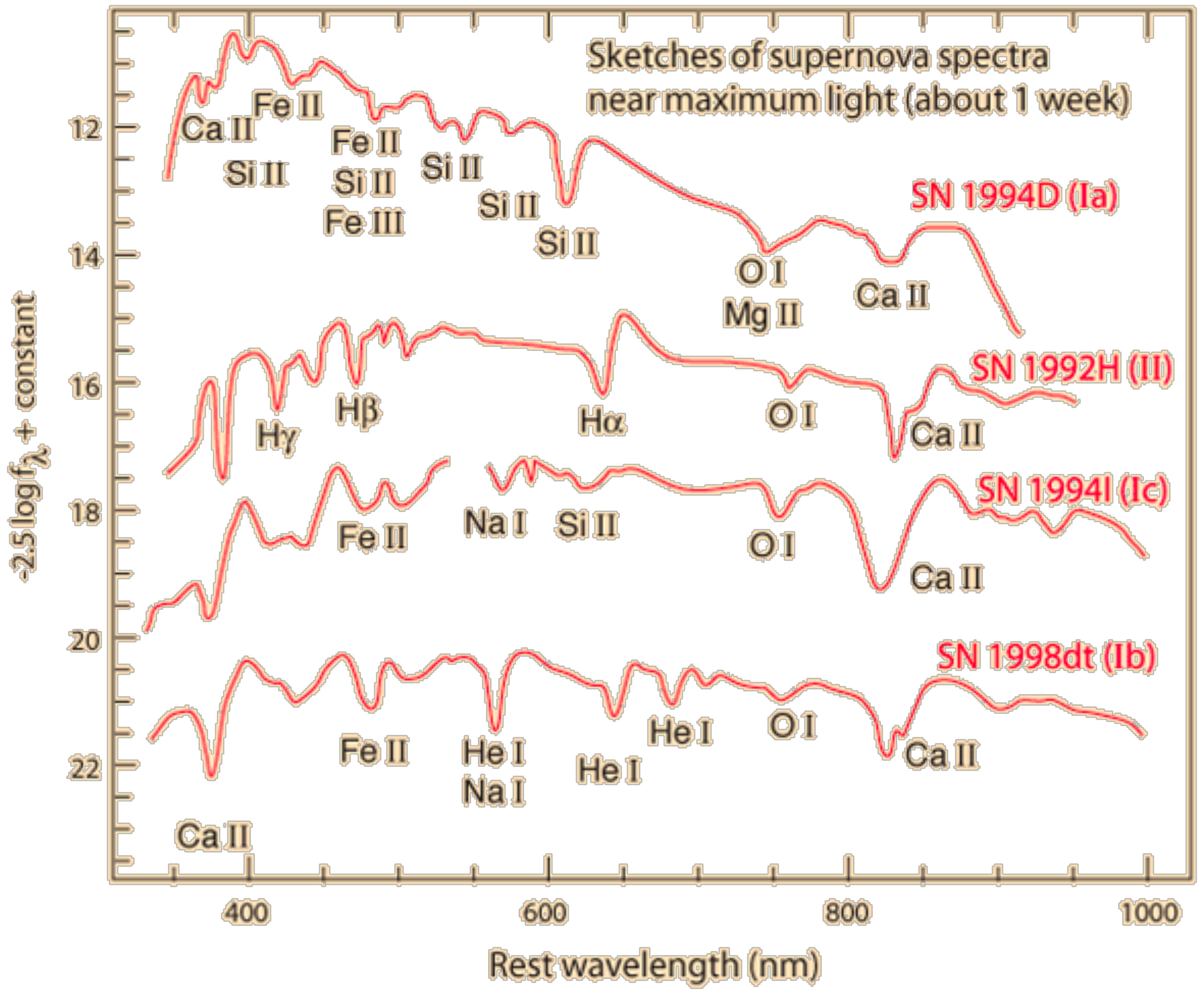


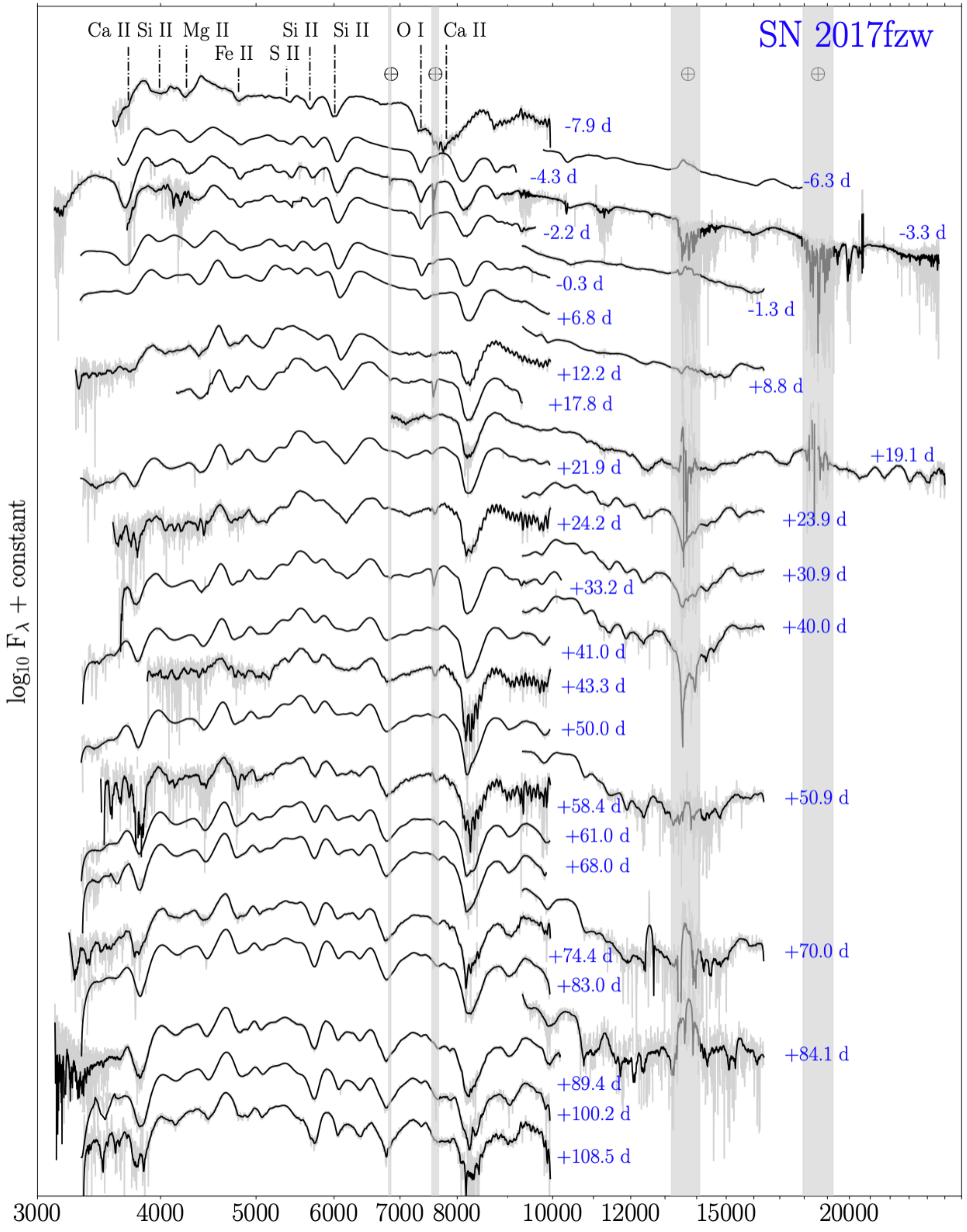




Spectroscopy

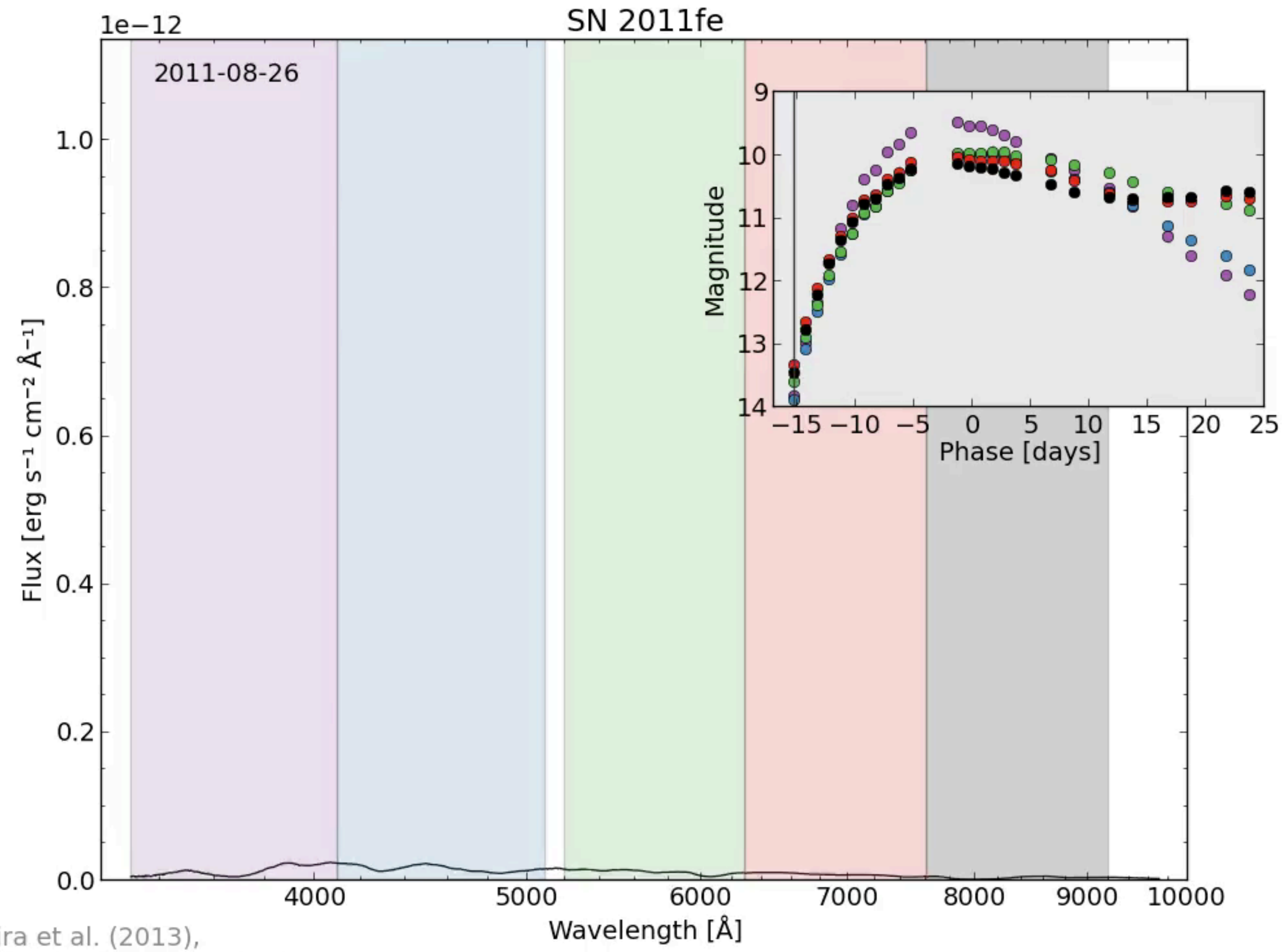
Carroll&Ostile07





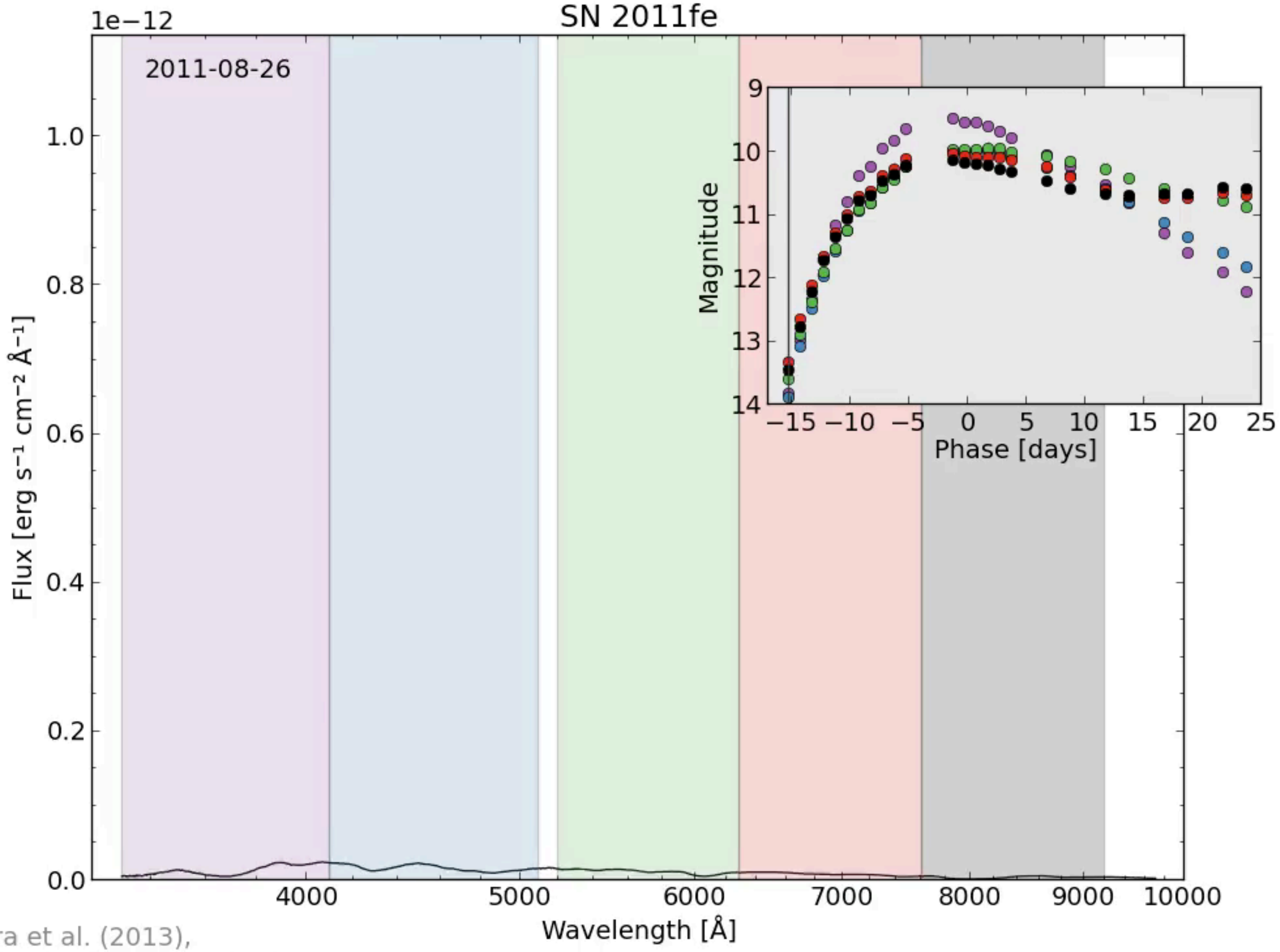
- Composition
- Velocity
- Evolution

Phot&Spec



Pereira et al. (2013),
The Nearby Supernova Factory

Phot&Spec

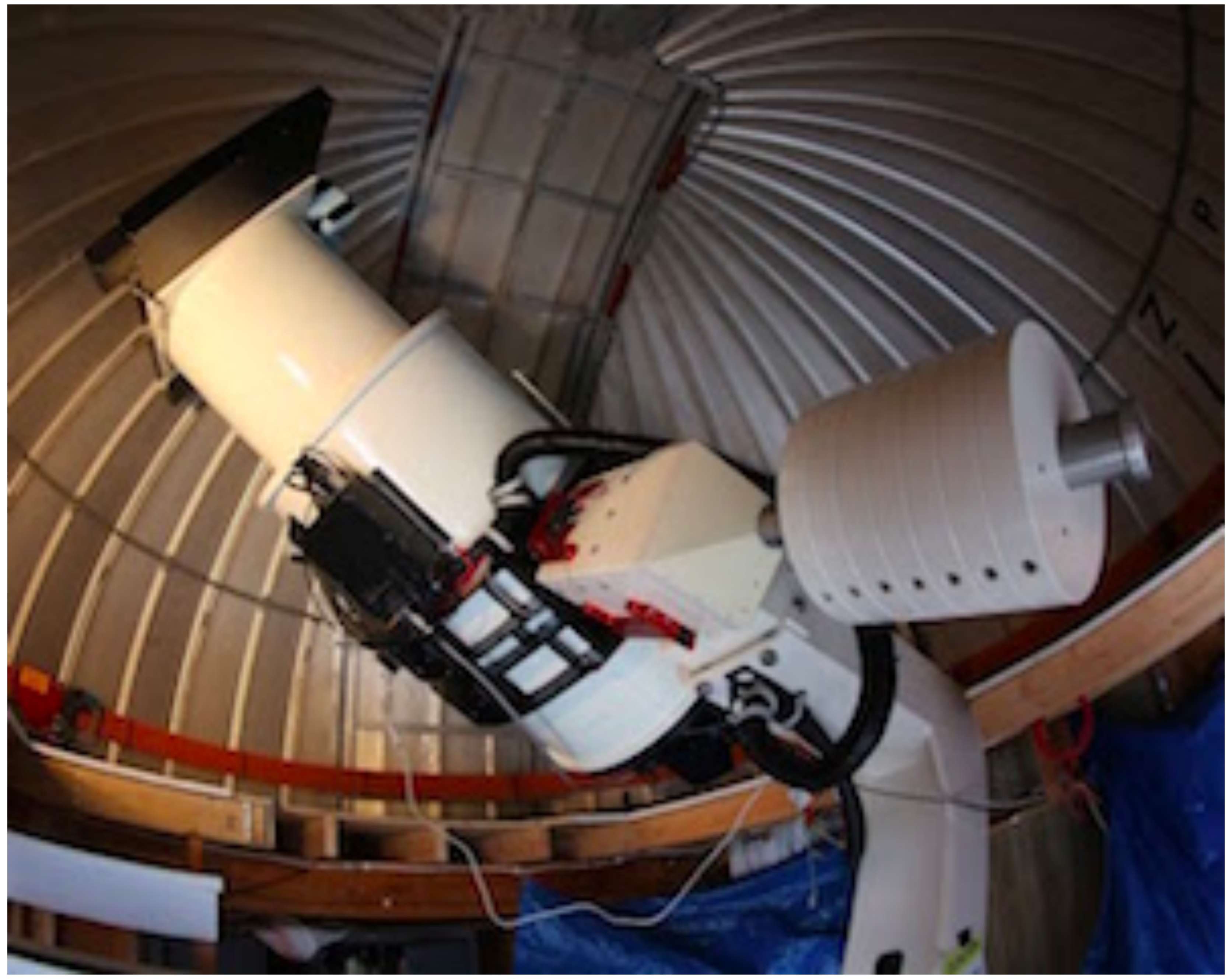


Pereira et al. (2013),
The Nearby Supernova Factory

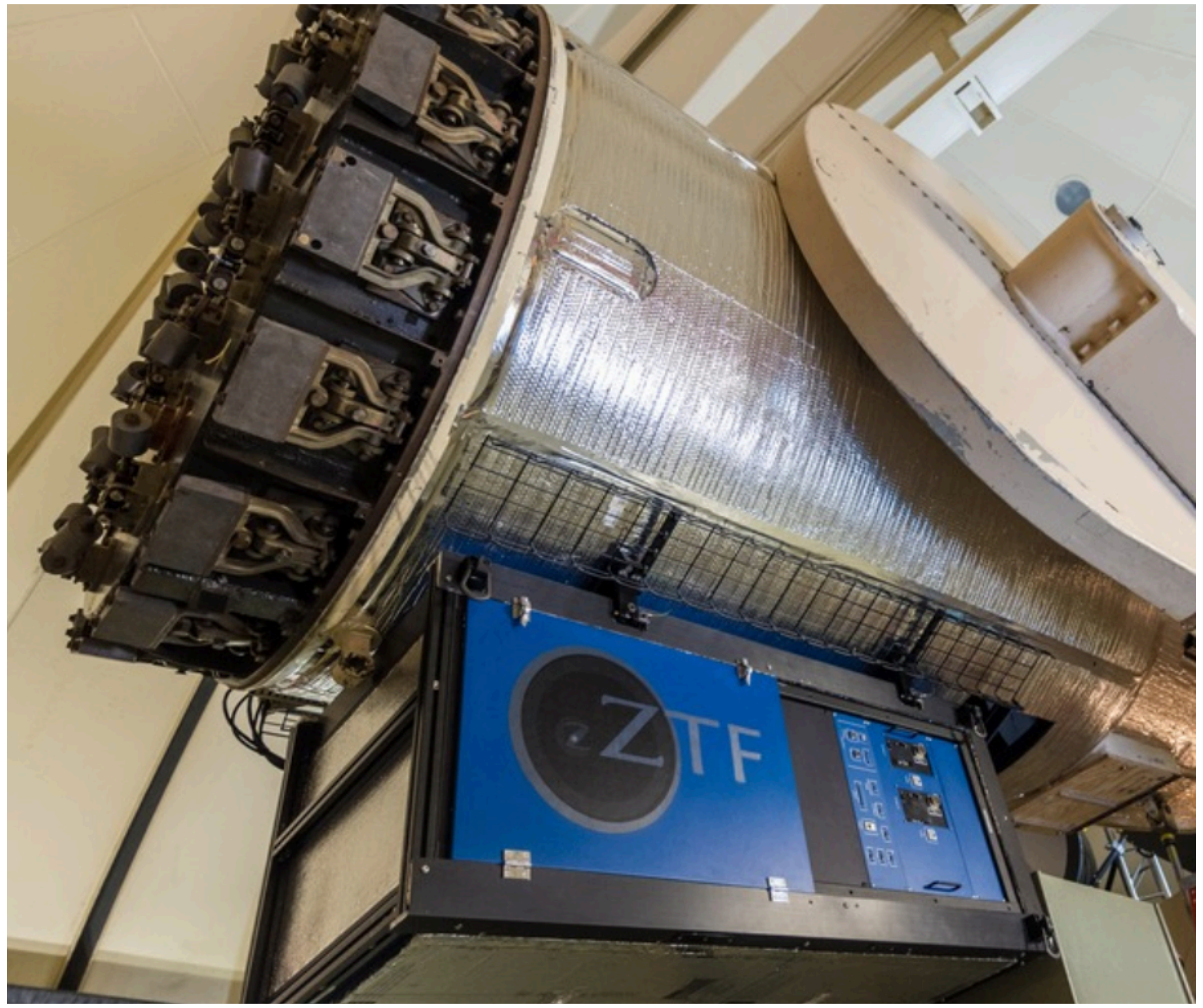
Supernova discoveries

Rolling searches

ASAS-SN



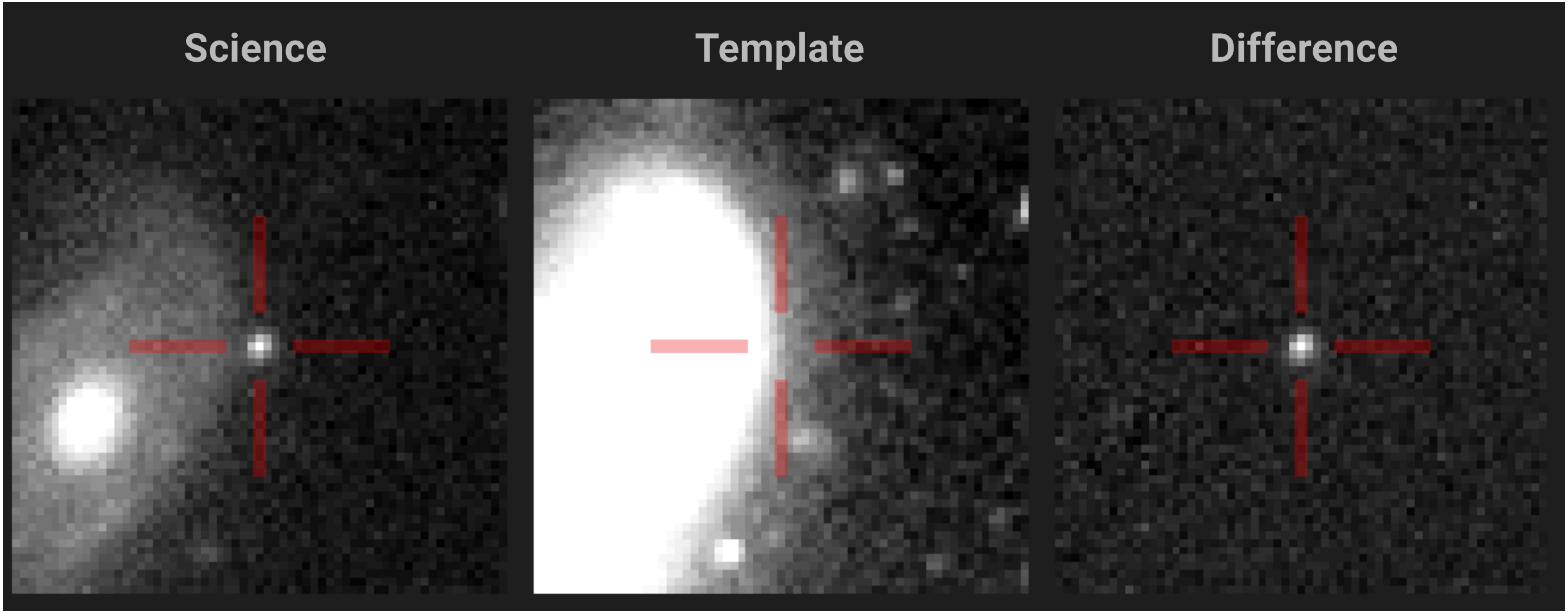
atlas



ZTF

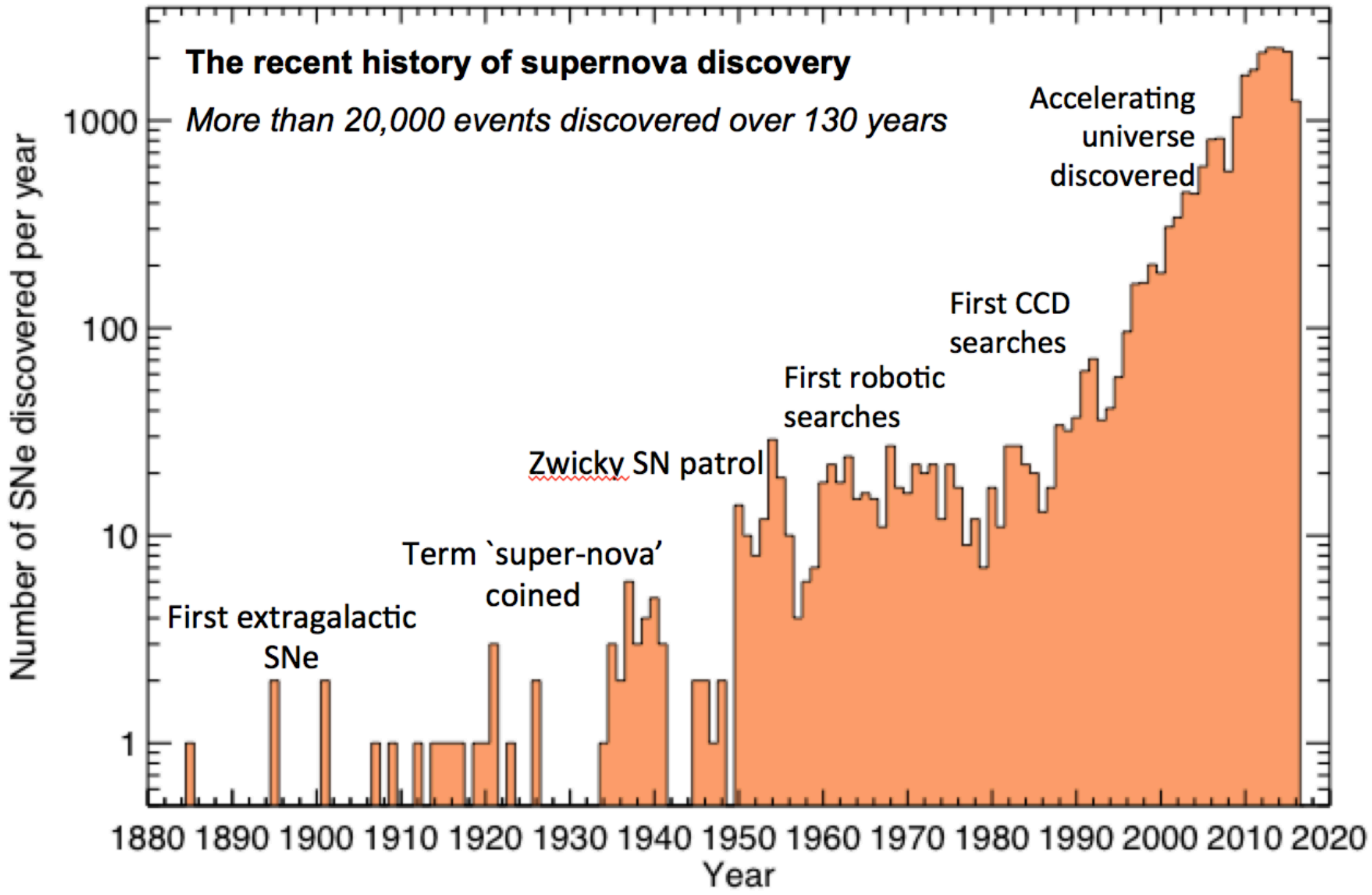
Supernova discoveries
Difference imaging

Alerce/ZTF



Supernova discoveries

Sullivan



- First extragalactic SN on 1885
- Baade & Zwicky 1934 coined of the term ‘supernova’
- Emergence of the first robotic searches in the 1960s
- development, implementation and deployment of CCD cameras in the 1980s
- SNe Ia lead to the discovery of the accelerated expansion of the Universe in late 90s
- More than 20,000 SNe discovered until (2018) with 5, on average, being discovered per day
- on-going and new high-cadence searches (ATLAS, ASAS-SN, BlackGem, ZTF) produce thousands of alerts per night.
- LSST is expected to produce 100,000 transient alerts per night, with 10 million supernovae discoveries in 10 years

History of SN Ia cosmology

1941PASP...53..224M

SPECTRA OF SUPERNOVAE

By R. Minkowski

(*Abstract*)

Spectroscopic observations indicate at least two types of supernovae. Nine objects (represented by the supernovae in IC 4182 and in NGC 4636) form an extremely homogeneous group provisionally called "type I." The remaining five objects (represented by the supernova in NGC 4725) are distinctly different; they are provisionally designated as "type II." The individual differences in this group are large; at least one object, the supernova in NGC 4559, may represent a third type or, possibly, an unusually bright ordinary nova.

Spectra of supernovae of type I have been observed from 7 days before maximum until 339 days after. Except for minor differences, the spectrograms of all objects of type I are closely comparable at corresponding times after maxima. Even at the earliest premaximum stage hitherto observed, the spectrum consists of very wide emission bands. No significant transformation of the spectrum occurs near maximum. Spectra of type II have been observed from maximum until 115 days after. Up to about a week after maximum, the spectrum is continuous and extends far into the ultraviolet, indicating a very high color temperature. Faint emission is suspected near *Hα*. Thereafter, the continuous spectrum fades and becomes redder. Simultaneously, absorptions and broad emission bands are developed. The spectrum as a whole resembles that of normal novae in the transition stage, although the hydrogen bands are relatively faint and forbidden lines are either extremely faint or missing. The supernova in NGC 4559, while generally similar to the other objects in this group, shows multiple absorptions of *H* and *Ca* II; the emission bands are fainter than in the other objects.

No satisfactory explanation for the spectra of type I has been proposed. Two [*O* I] bands of moderate width in the later spectra of the supernova in IC 4182 are the only features satisfactorily identified in any spectrum of type I. They are, at the same time, the only indication of the development of a nebular spectrum for any supernova. The synthetic spectra by Gaposchkin and Whipple disagree in many details with the observed spectra of type I. However, these synthetic spectra agree better with spectra of type II and provide a very satisfactory confirmation of the identifications which, in this case, are already suggested by the pronounced similarity to the spectra of ordinary novae. As compared with normal novae, supernovae of type II show a considerably earlier type of spectrum at maximum, hence a higher surface temperature (order of 40,000°), and the later spectrum indicates greater velocities of expansion (5000 km/sec or more) and higher levels of excitation. Supernovae of type II differ from those of type I in the presence of a continuous spectrum at maximum and in the subsequent transformation to an emission spectrum whose main constituents can be readily identified. This suggests that the supernovae of type I have still higher surface temperature and higher level of excitation than either ordinary novae or supernovae of type II.

Carnegie Institution of Washington
Mount Wilson Observatory

1941: Minkowski classified 14 events, 9 homogeneous were of Type I, the other 5 as Type II (all with H)

History of SN Ia cosmology

1968AJ.....73.1021K

1968AJ.....73.1021K

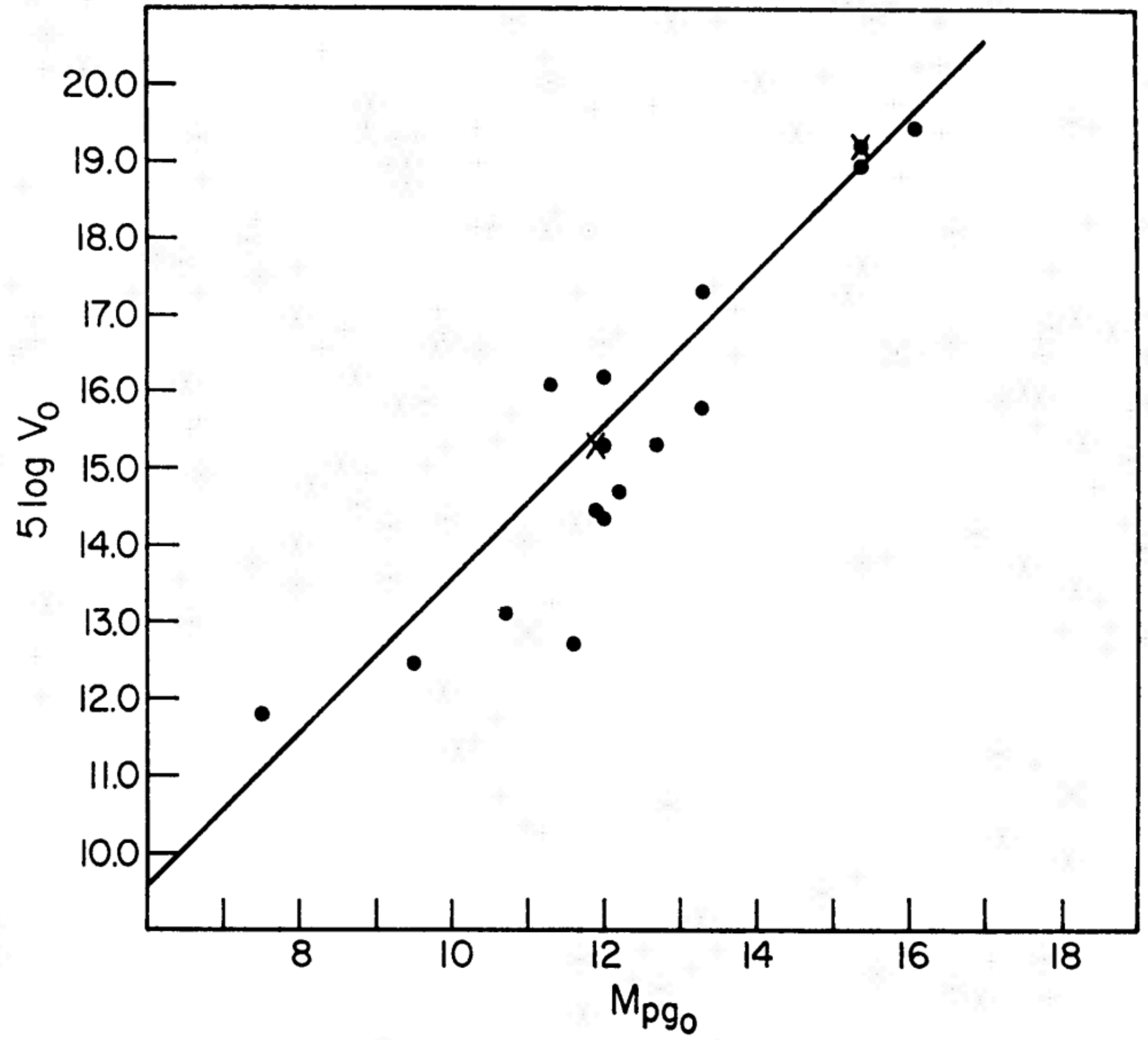
THE ASTRONOMICAL JOURNAL VOLUME 73, NUMBER 10, PART 1 DECEMBER 1968

Absolute Magnitudes of Supernovae

CHARLES T. KOWAL
Mt. Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology

(Received 24 June 1968; revised 29 July 1968)

The maximum indicative absolute magnitudes of 33 supernovae are derived. For supernovae of type I, the average absolute magnitude is $M_{pg} = -18.6 + 5\log(H/100)$. For type II, the average is $M_{pg} = -16.5 + 5\log(H/100)$. These values are lower limits, which neglect the effects of absorption within the parent galaxies. The redshift–magnitude relation for type I supernovae is shown, and the usefulness of these supernovae as distance indicators is discussed.



Kowal 1968: 22 Type I SNe

“With a scatter of 0.6mag it is obvious that Type I supernovae can exceedingly be useful distance indicators.”

History of SN Ia cosmology

1973A&A....25..241B

1973A&A....25..241B

Astron. & Astrophys. 25, 241—248 (1973)

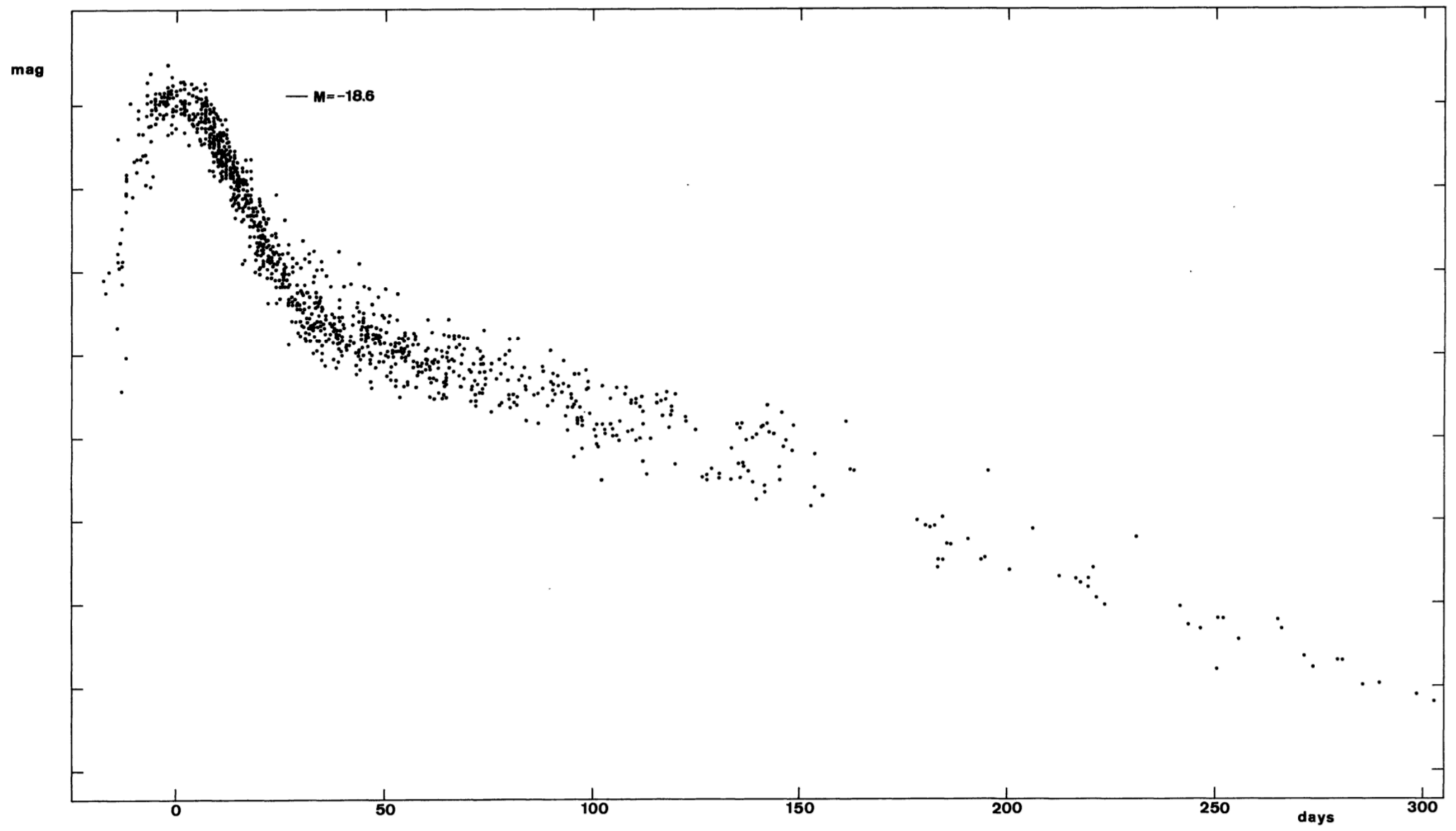
On the Light Curve and Properties of Type I Supernovae

R. Barbon, F. Ciatti and L. Rosino
Asiago Astrophysical Observatory, University of Padova

Received January 24, 1973

Summary. By the best fitting of all available light curves of type I supernovae an average curve, representative of the class, has been drawn. Due to the strong similarity of the light curves, the dispersion of the points is relatively small. From the analysis of the average curve some general properties of the SN-I can be derived. The occurrence of type I supernovae in different types of galaxies and the possibility of a further subdivision in two groups are discussed.

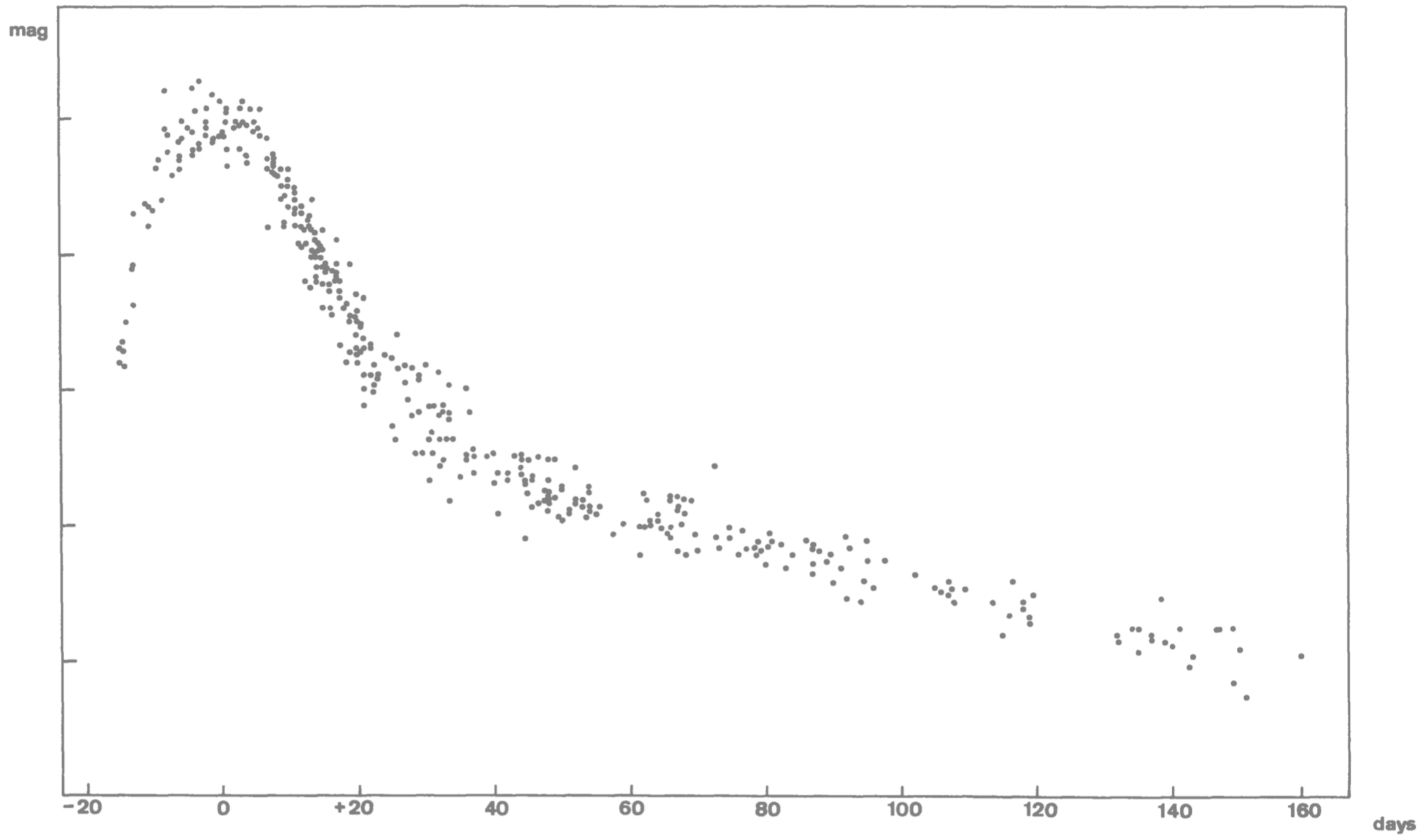
Key words: supernovae – galaxies – photometry – distance indicators



All available data of Type I supernovae

Two subclasses "*fast*" (SNIa) and "*slow*" (SNIb)

"The fact that *fast* and *slow* SNe occur with different frequency in different types of galaxies seems to show that discrimination between type Ia and Ib has a physical meaning"



History of SN Ia cosmology

1973A&A....25..241B

1973A&A....25..241B

Astron. & Astrophys. 25, 241—248 (1973)

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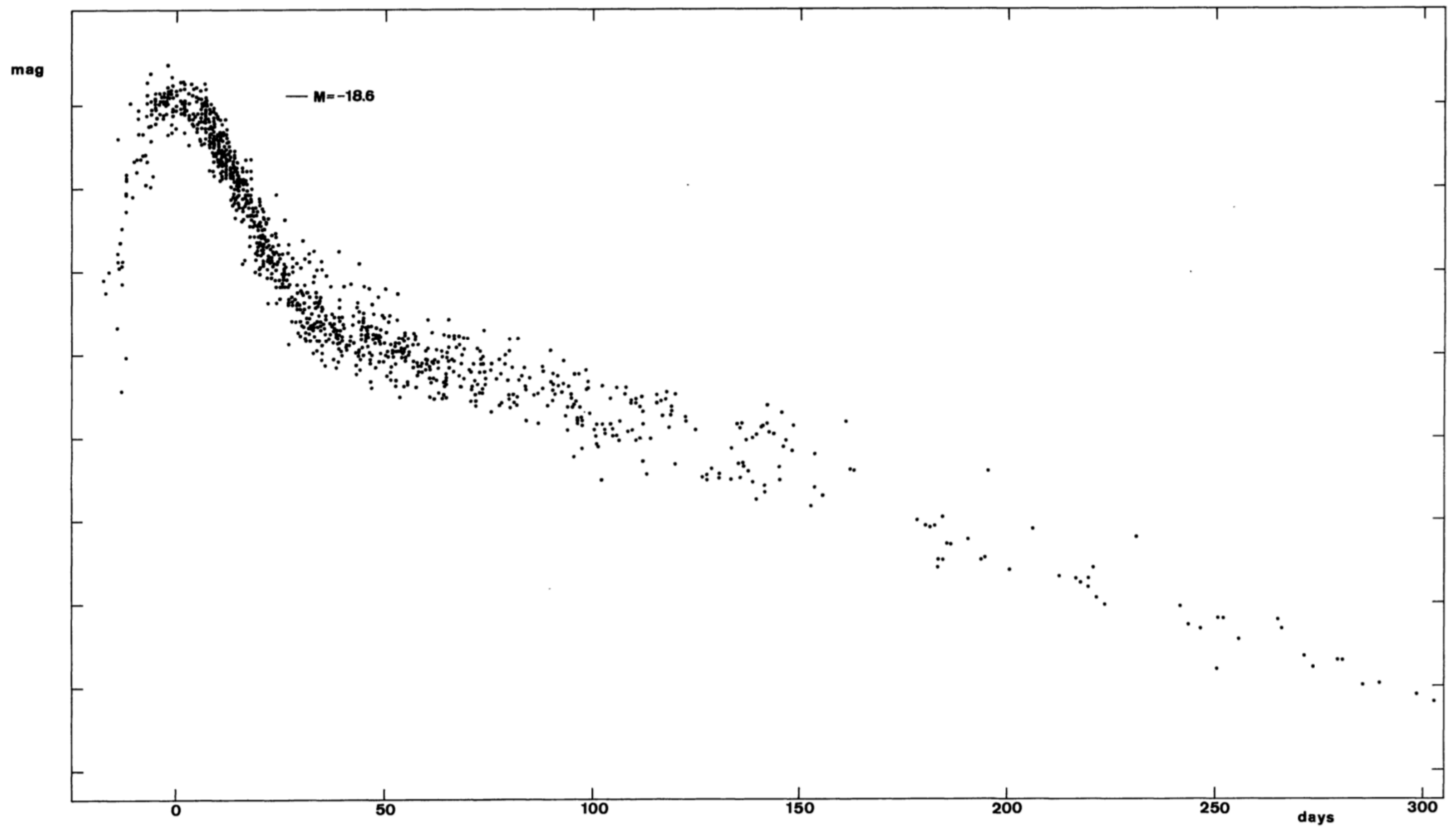

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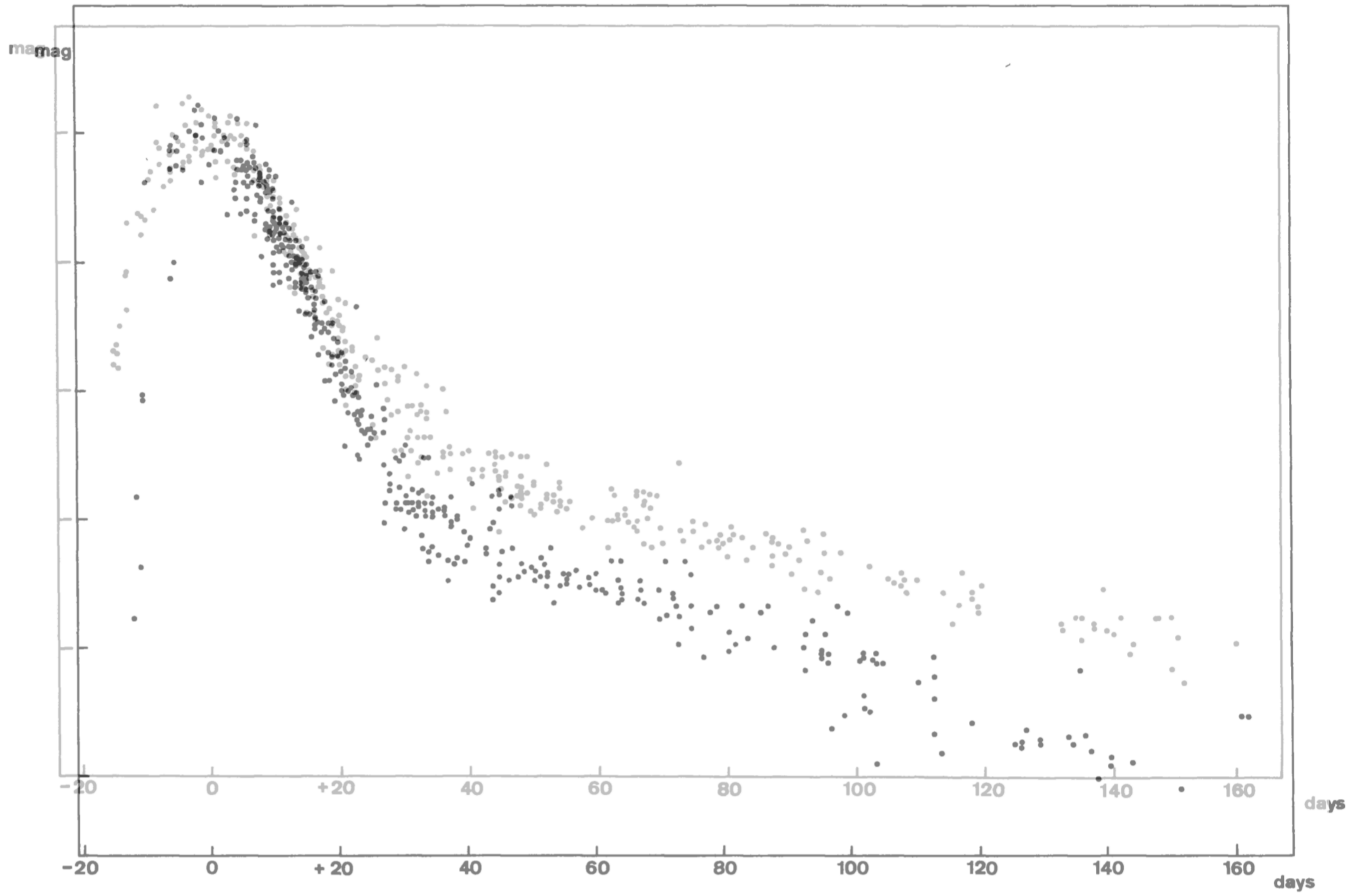


History of SN Ia cosmology

1977SvA....21..675P

1977SvA....21..675P

Light curves, color curves, and expansion velocity of type I supernovae as functions of the rate of brightness decline

Yu. P. Pskovskii

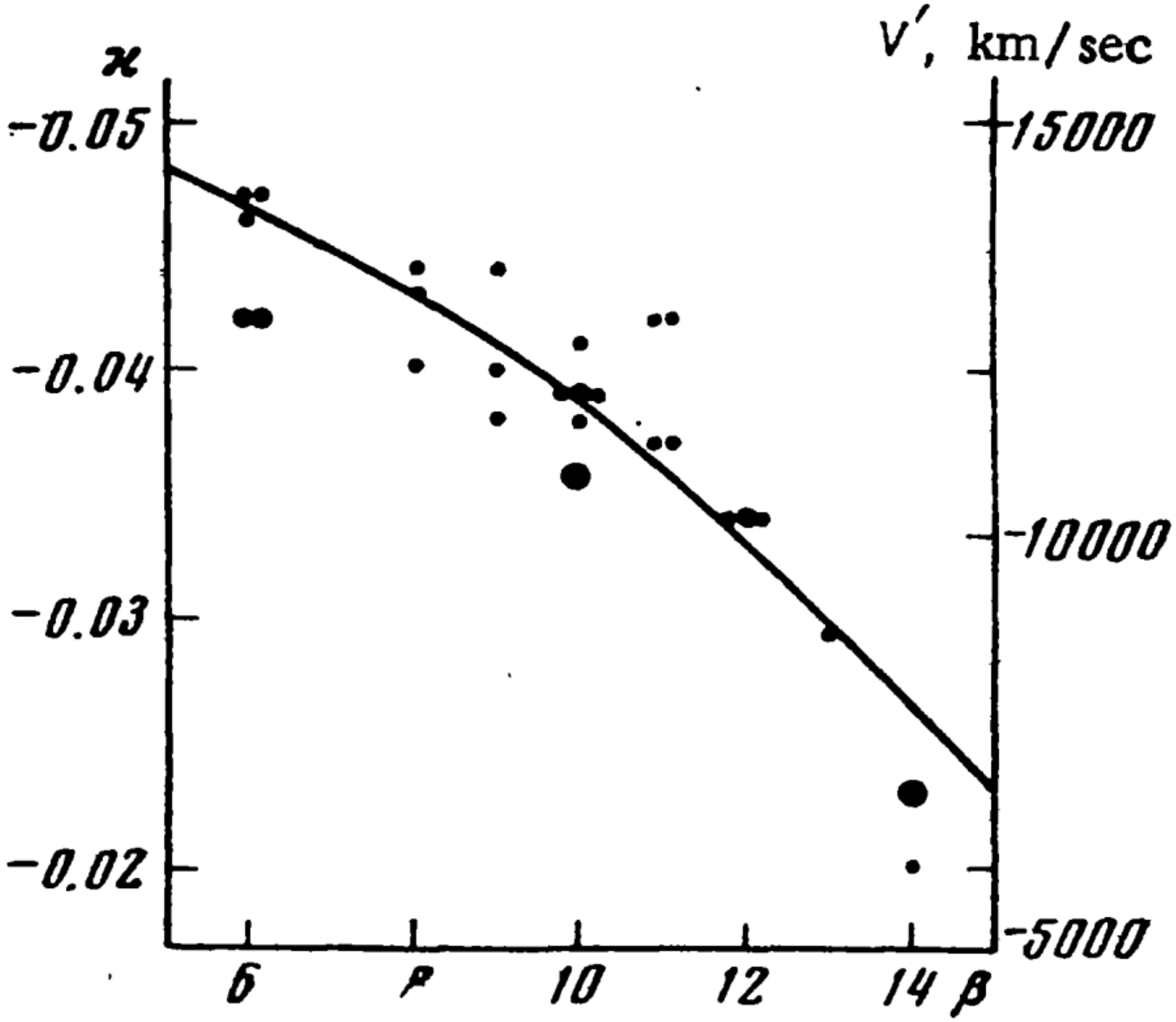
Shternberg Astronomical Institute, Moscow

(Submitted October 28, 1976)

Astron. Zh. **54**, 1188–1201 (November–December 1977)

A photometric classification of supernovae is proposed, using the rate β of decline in photographic brightness after maximum light as a parameter. The principal elements of the light curves, color curves, envelope expansion velocity, and absolute magnitude at maximum light depend on the photometric class of the supernova. The mean absolute magnitude of type I supernovae, corrected for absorption, is determined. The occurrence of the anomalous type I supernovae reported by Bertola is discussed.

PACS numbers: 97.60.Bw, 97.10.Ri, 97.10.Fy



The mean rate BETA (mag/100day) of decline in brightness from maximum light to the point at which the decline in brightness begin to slow down

Velocity, (defined as x defined as $(\lambda_o - \lambda_e)/\lambda_e$ which correlates with brightness

History of SN Ia cosmology

1979ApJ...232..404C

1979ApJ...232..404C

THE ASTROPHYSICAL JOURNAL, 232:404–408, 1979 September 1
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SUPERNOVAE AS A STANDARD CANDLE FOR COSMOLOGY

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New Mexico Institute of Mining and Technology, and Los Alamos Scientific Laboratory
Received 1978 September 5; accepted 1979 March 9

ABSTRACT

Supernovae can perhaps be found at $Z \approx 1$ using the Space Telescope and the Focal Plane Camera (cryogenic charge coupled devices) at a rate of approximately four per week using 3 hours per week of viewing time. If Type II supernovae are used as a self-calibrating candle at $Z \ll 1$, then Type I's can be calibrated from Type II's as a secondary standard candle (2 mag brighter) and used instead of Type II's for a less difficult determination of q_0. This assumes all Type I's are the same independent of Z whereas each Type II is self-calibrated. Adequate statistics of supernovae in nearby galaxies $Z \lesssim 1$ can further verify the uniqueness of Type I's. Three-color wide-band photometry performed over the period of the maximum luminosity of a Type I gives the time dilation $\propto (1 + Z)^{-1}$, color shift $\propto (1 + Z)^{-1}$, and apparent luminosity $\propto Z^{-2}[1 + 0.5(1 + q_0)Z + O(Z)]^{-2}(1 + Z)^{-2}$. A Type I supernova at maximum and $Z = 1$, $H_0 = 50$, should give rise to a statistically meaningful maximum single pixel signal of ~ 250 photoelectrons compared to an average galaxy center background of ~ 25 photoelectrons for an 80 s integration time. An average of ~ 100 large galaxies (10^{10} $L_\odot$) per field allows $\sim 10^4$ galaxies to be monitored using 3 hours of viewing time. Z can be determined by time dilation and color shift sufficiently accurately that the determination of q_0 will have twice the error of the calibration of Type I as a standard candle.

Subject headings: cosmology — stars: supernovae

Colgate (1979) suggested that observations of type I SNe at z~1 with the forthcoming Space Telescope could measure the deceleration parameter, q0.

History of SN Ia cosmology

1985ApJ...296..379E

1985ApJ...296..379E

THE ASTROPHYSICAL JOURNAL, **296**:379–389, 1985 September 15
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TYPE I SUPERNOVAE IN THE INFRARED AND THEIR USE AS DISTANCE INDICATORS

J. H. ELIAS,[1] K. MATTHEWS,[1] G. NEUGEBAUER,[1] AND S. E. PERSSON[2]
Received 1985 January 28; accepted 1985 March 22

ABSTRACT

New infrared data for 11 Type I supernovae are presented. These results, when combined with other published data for Type I supernovae, show that the light curves fall into two well-defined groups. The first, more common type—Type Ia—shows strong, variable, unexplained absorption at 1.2 μm and probably at 3.5 μm, while the second type—Type Ib—shows no such absorption and a slower decline after maximum. The light curves of the Type Ia supernovae appear to have a dispersion in color and absolute magnitude of ± 0.2 mag or less, making them potentially valuable for distance determination within the Local Supercluster.

Subject headings: cosmology — infrared: sources — stars: supernovae

These data are used to show that Type I supernovae separate into two groups in the infrared, based on their colors, and to examine the utility of the first group—Type la—as distance indicators.

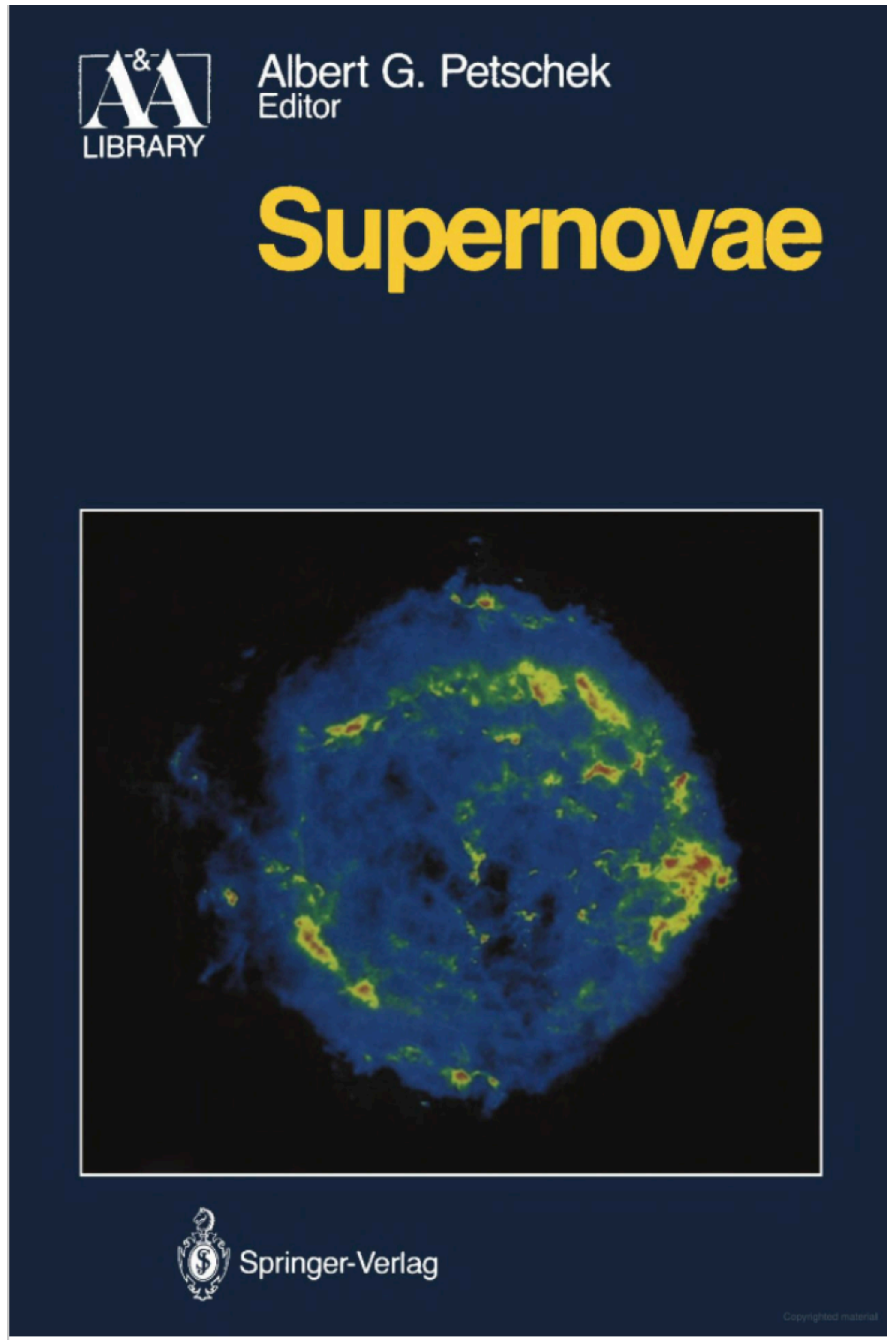
The results of our program to date provide two new results. First, there are two subtypes of Type I supernova, which can be readily distinguished on the basis of their infrared color curves. The more common, Type la supernovae show a strong, variable absorption at 1.2 /un; the Type lb supernovae do not.

NIR observations!

Elias 1985: coined the terms SN Ia for the dominant group and SN Ib for this new subclass

History of SN Ia cosmology

1990supe.conf....1H



1. **Classification of Supernovae**

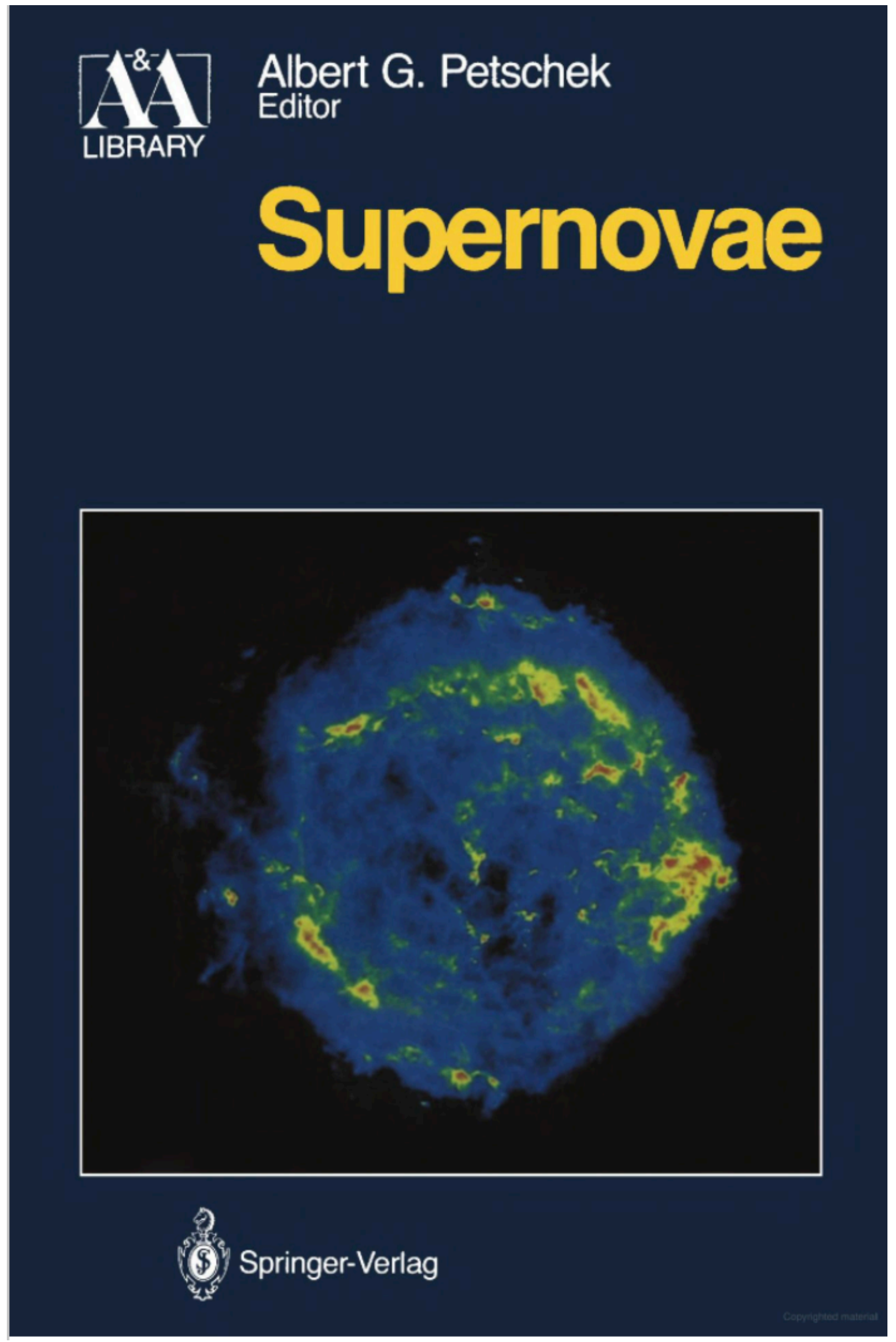
ROBERT P. HARKNESS and J. CRAIG WHEELER

The fundamental classification scheme for supernovae is based on their spectra

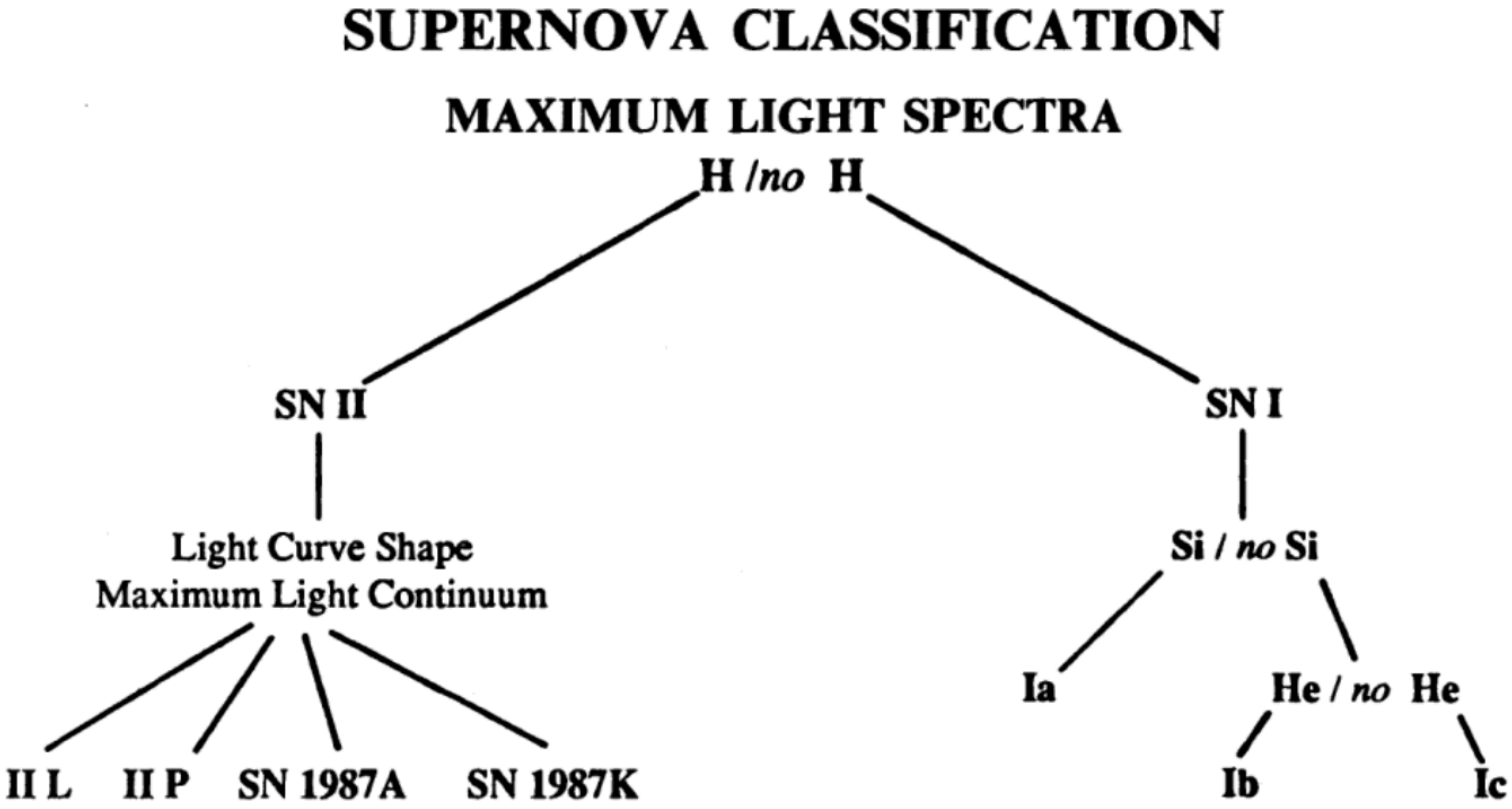
Presence of H or not: Type I or Type II	Minkowski 1941
Among type II, based on the shape of the light-curve: IIP or IIL	Barbon, Ciatti, Rosino 1973
For 25y we knew subclasses of SNI exist, but in the last 5 subclassifications emerged	Elias 85, Branch 86, Harkness 87…
Type Ia events show the characteristic Si II absorption at 6150A	
The events that fail to show such feature, can be further subdivided by the presence (SNIb) or absence (SNIc) of He I	Wheeler, Harkness 1986

History of SN Ia cosmology

1990supe.conf....1H



The fundamental classification scheme for supernovae is based on their spectra



1. **Classification of Supernovae**

ROBERT P. HARKNESS and J. CRAIG WHEELER

History of SN Ia cosmology

1993ApJ...413L.105P

1993ApJ...413L.105P

The Astrophysical Journal, 413:L105–L108, 1993 August 20
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THE ABSOLUTE MAGNITUDES OF TYPE Ia SUPERNOVAE

M. M. Phillips
Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatories,[1] Casilla 603, La Serena, Chile
Received 1993 March 22; accepted 1993 June 2

ABSTRACT

Absolute magnitudes in the *B*, *V*, and *I* bands are derived for nine well-observed Type Ia supernovae using host galaxy distances estimated via the surface brightness fluctuations or Tully-Fisher methods. These data indicate that there is a significant intrinsic dispersion in the absolute magnitudes at maximum light of Type Ia supernovae, amounting to ± 0.8 mag in *B*, ± 0.6 mag in *V*, and ± 0.5 mag in *I*. Moreover, the absolute magnitudes appear to be tightly correlated with the initial rate of decline of the *B* light curve, with the slope of the correlation being steepest in *B* and becoming progressively flatter in the *V* and *I* bands. This implies that the intrinsic $B-V$ colors of Type Ia supernovae at maximum light are not identical, with the fastest declining light curves corresponding to the intrinsically reddest events. Certain spectroscopic properties may also be correlated with the initial decline rate. These results are most simply interpreted as evidence for a range of progenitor masses, although variations in the explosion mechanism are also possible. Considerable care must be exercised in employing Type Ia supernovae as cosmological standard candles, particularly at large redshifts where Malmquist bias could be an important effect.

Subject headings: distance scale — supernovae: general

Previous measurements:
- from photometric plates
- contaminated by underlying host galaxy light
- contaminated by objects we know now are Ib/Ic

9 well observed SNe Ia with SBF and TF distances

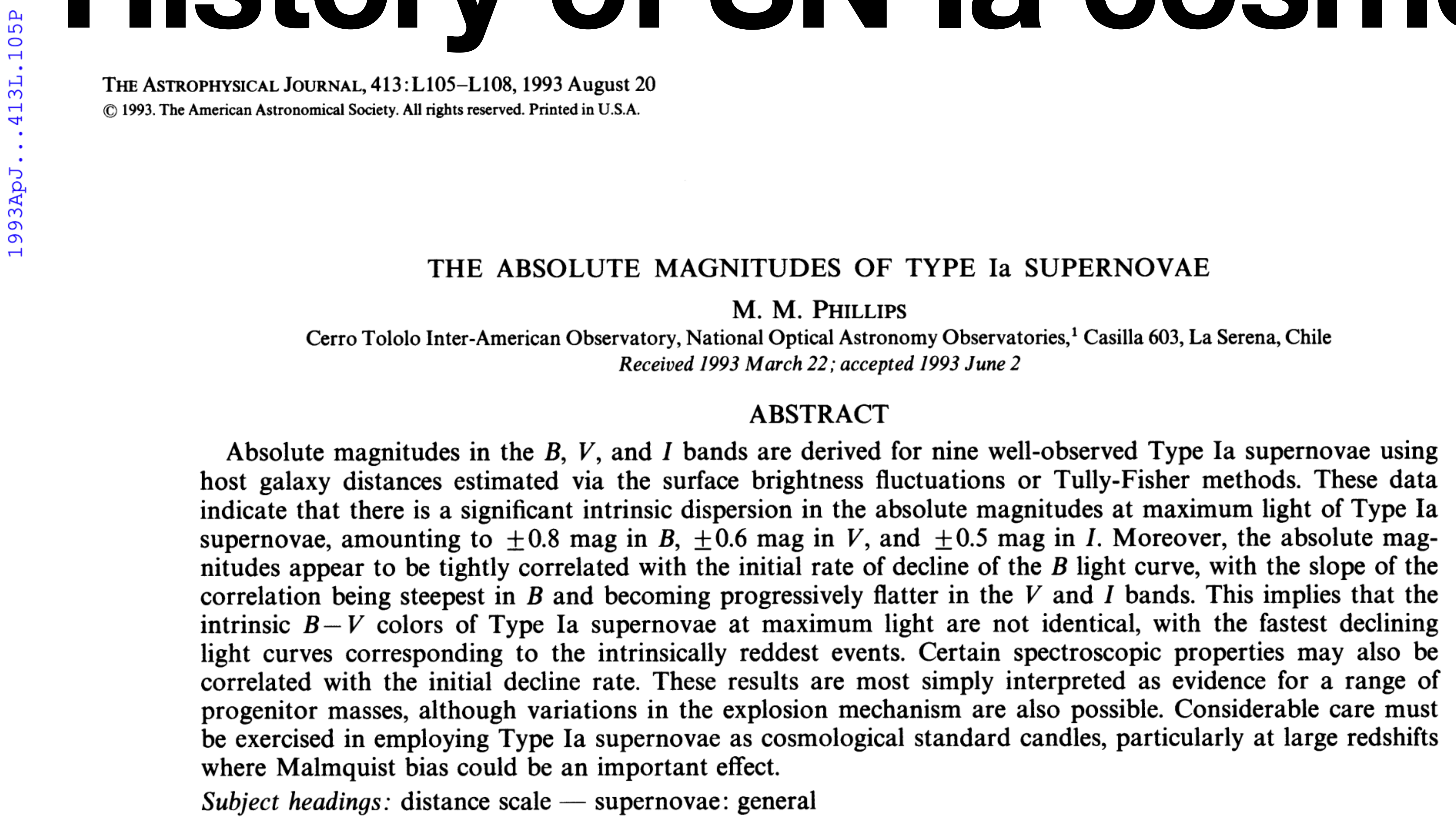
Defined Dm15:

“Rather than trying to determine the slope, a simpler and more robust procedure is to measure the total amount in magnitudes that the light curve decays from its peak brightness during some specified period following maximum light. After some experimenting, a time interval of 15 days was found to provide the greatest discrimination.”

“This finding has significant implications for the use of this class of objects as extragalactic distance indicators since the initial decline rate could, in principle, be used to correct the apparent peak luminosity (in analogy to the period-luminosity relationship for Cepheid variables)”

History of SN Ia cosmology

1993ApJ...413L.105P



1993ApJ...413L.105P

THE ASTROPHYSICAL JOURNAL, 413:L105–L108, 1993 August 20
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THE ABSOLUTE MAGNITUDES OF TYPE Ia SUPERNOVAE

M. M. PHILLIPS
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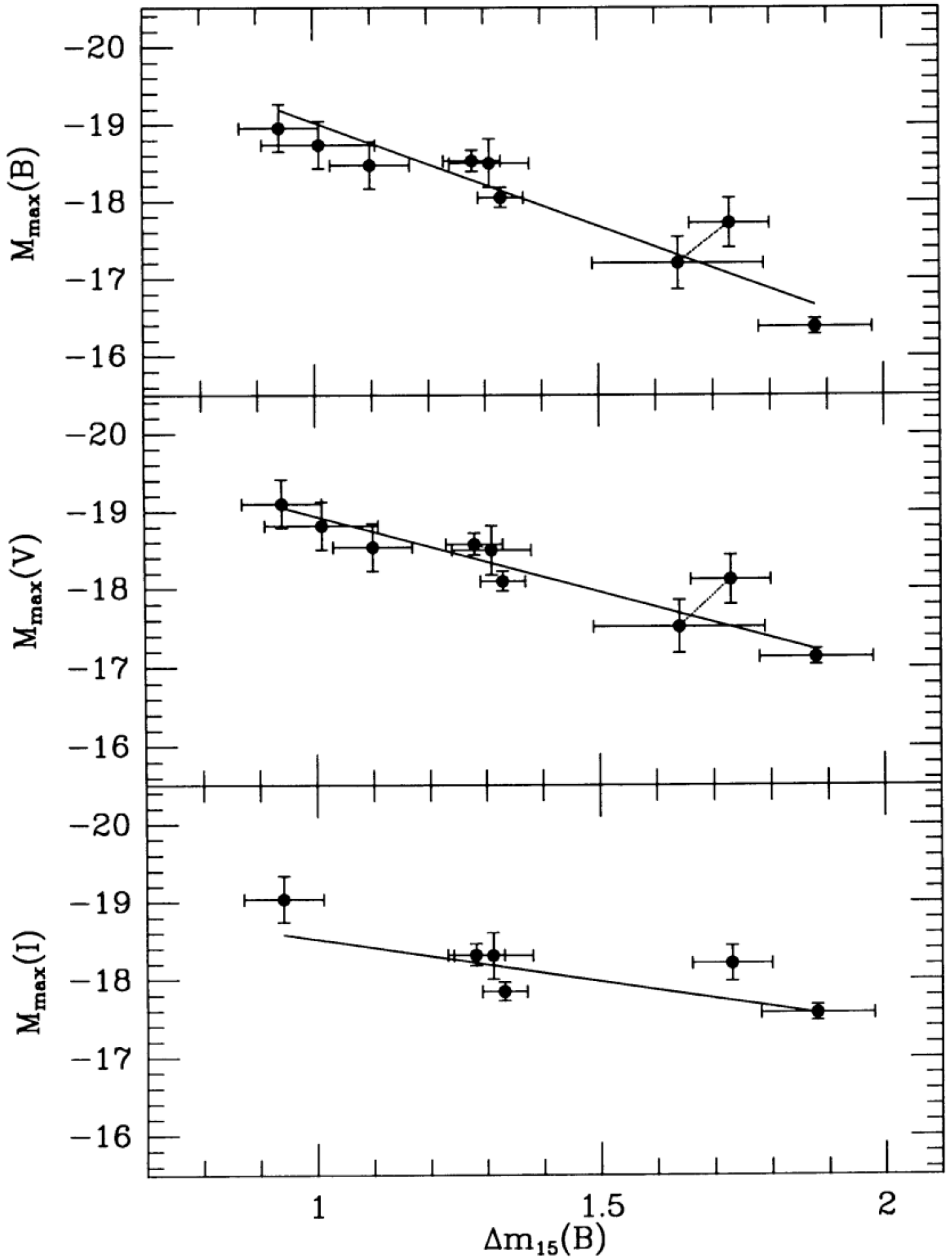
Received 1993 March 22; accepted 1993 June 2

ABSTRACT

Absolute magnitudes in the *B*, *V*, and *I* bands are derived for nine well-observed Type Ia supernovae using host galaxy distances estimated via the surface brightness fluctuations or Tully-Fisher methods. These data indicate that there is a significant intrinsic dispersion in the absolute magnitudes at maximum light of Type Ia supernovae, amounting to ± 0.8 mag in *B*, ± 0.6 mag in *V*, and ± 0.5 mag in *I*. Moreover, the absolute magnitudes appear to be tightly correlated with the initial rate of decline of the *B* light curve, with the slope of the correlation being steepest in *B* and becoming progressively flatter in the *V* and *I* bands. This implies that the intrinsic $B-V$ colors of Type Ia supernovae at maximum light are not identical, with the fastest declining light curves corresponding to the intrinsically reddest events. Certain spectroscopic properties may also be correlated with the initial decline rate. These results are most simply interpreted as evidence for a range of progenitor masses, although variations in the explosion mechanism are also possible. Considerable care must be exercised in employing Type Ia supernovae as cosmological standard candles, particularly at large redshifts where Malmquist bias could be an important effect.

Subject headings: distance scale — supernovae: general



Defined Dm15:

“Rather than trying to determine the slope, a simpler and more robust procedure is to measure the total amount in magnitudes that the light curve decays from its peak brightness during some specified period following maximum light. After some experimenting, a time interval of 15 days was found to provide the greatest discrimination.”

History of SN Ia cosmology

1993AJ....106.2392H

1993AJ....106.2392H

THE ASTRONOMICAL JOURNAL VOLUME 106, NUMBER 6 DECEMBER 1993

THE 1990 CALÁN/TOLOLO SUPERNOVA SEARCH

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ABSTRACT

We have started a search for supernovae as a collaboration between the University of Chile and the Cerro Tololo Inter-American Observatory, with the aim of producing a moderately distant ($0.01 < z < 0.10$) sample of Type Ia and Type II supernovae suitable for cosmological studies. The project began in mid-1990 and continues to the present. This paper reports on the Calán/Tololo discoveries in the course of 1990, and on the spectroscopic and photometric observations gathered for these objects. All of these observations were obtained with CCDs, with the extensive collaboration of visiting astronomers. Great care was exercised in the reduction of the light curves in order to properly correct for the background light of the host galaxy of each supernova. Of the four supernovae found in 1990, one proved to be a SN II-n; the remaining three were members of the Type Ia class at redshifts that ranged between $z = 0.04$–0.05. One of the Type Ia events, SN 1990af, was found in the elusive premaximum phase at a redshift of $z = 0.0503$, and was observed through maximum light. Peak magnitudes for the other two SNe Ia, which were not observed at maximum light, were derived using a χ^2 minimization technique to fit the data with various template curves that represent a broad range of SNe Ia light curves. In future papers we will make use of these estimates in order to discuss the Hubble diagram of SNe Ia.

History of SN Ia cosmology

1996AJ....112.2391H

THE ASTRONOMICAL JOURNAL VOLUME 112, NUMBER 6 DECEMBER 1996

THE ABSOLUTE LUMINOSITIES OF THE CALAN/TOLOLO TYPE Ia SUPERNOVAE

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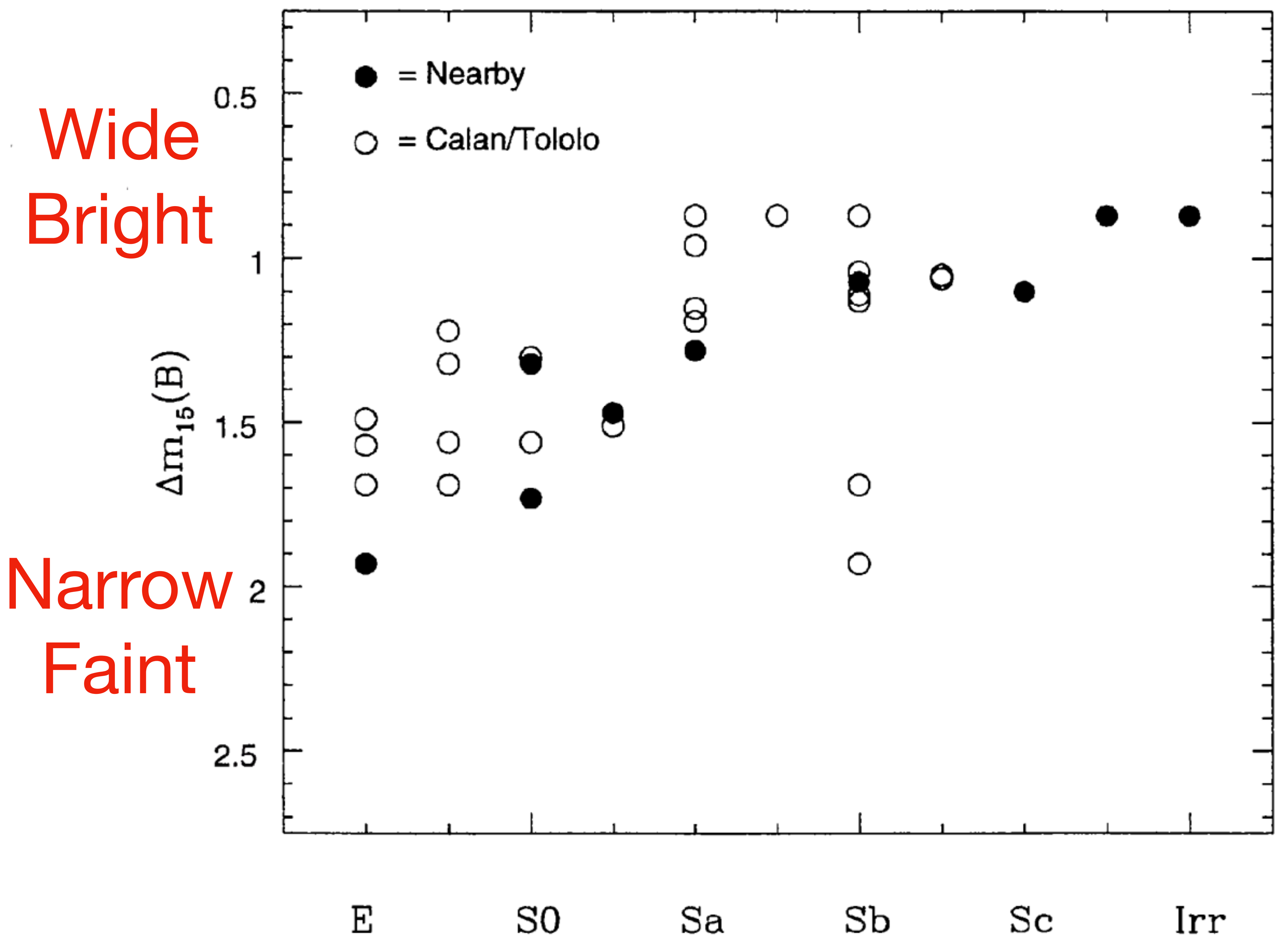
Received 1996 January 10; revised 1996 September 5

ABSTRACT

We examine the absolute luminosities of 29 SNe Ia in the Calán/Tololo survey. We confirm a relation between the peak luminosity of the SNe and the decline rate as measured by the light curve, as suggested by Phillips [ApJ, 413, L105 (1993)]. We derive linear slopes to this magnitude-decline rate relation in $BV(I)_{KC}$ colors, using a sample with $B_{MAX}-V_{MAX}<0.2^m$. The scatter around this linear relation (and thus the ability to measure SNe Ia distances) ranges from 0.13^m (in the I band) to 0.17^m (in the B band). We also find evidence for significant correlations between the absolute magnitudes or the decline rate of the light curve, and the morphological type of the host galaxy. © *1996 American Astronomical Society.*



History of SN Ia cosmology

1997ApJ...483..565P

MEASUREMENTS[1] OF THE COSMOLOGICAL PARAMETERS Ω AND Λ FROM THE FIRST SEVEN SUPERNOVAE AT $z \geq 0.35$

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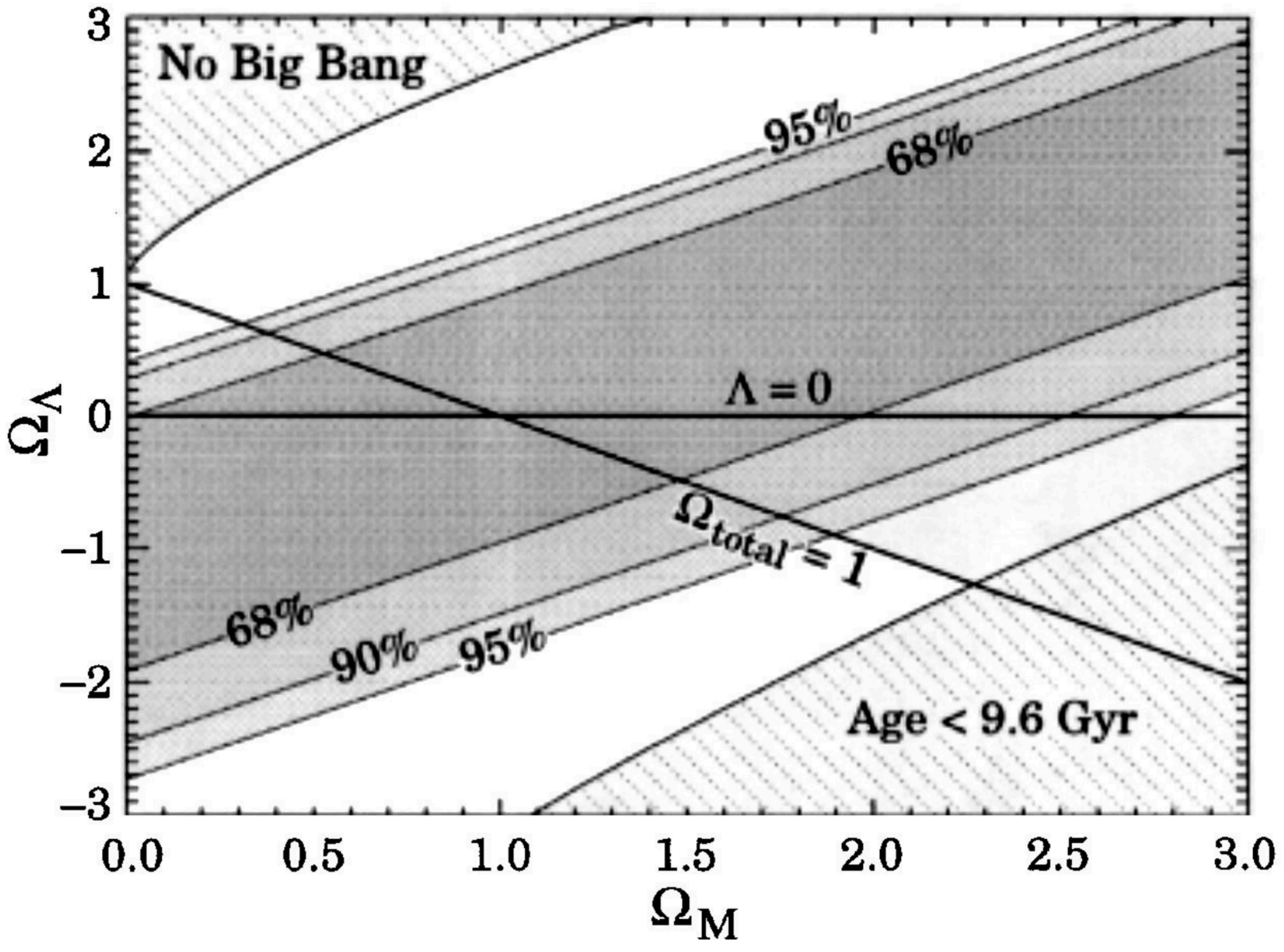
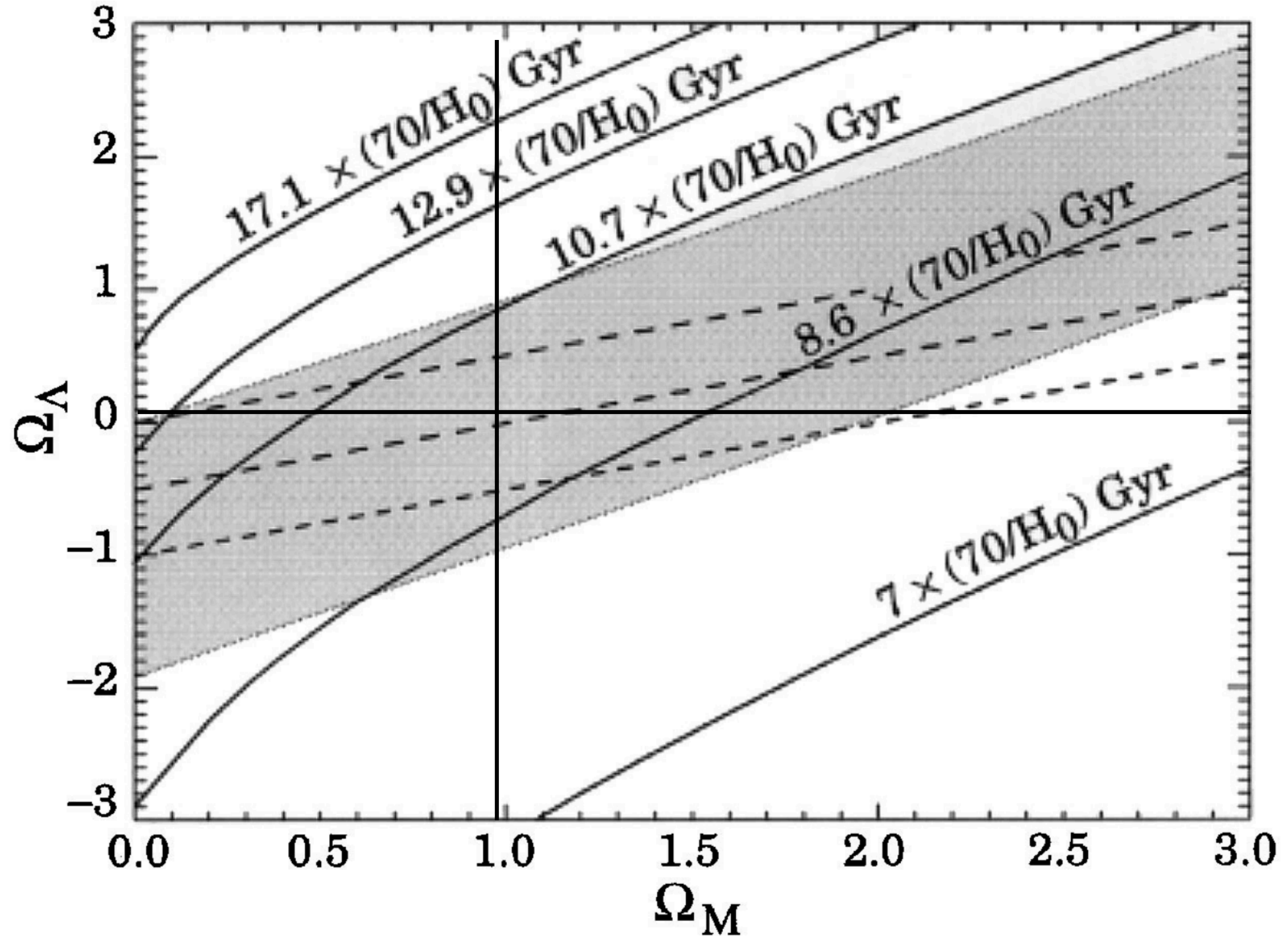
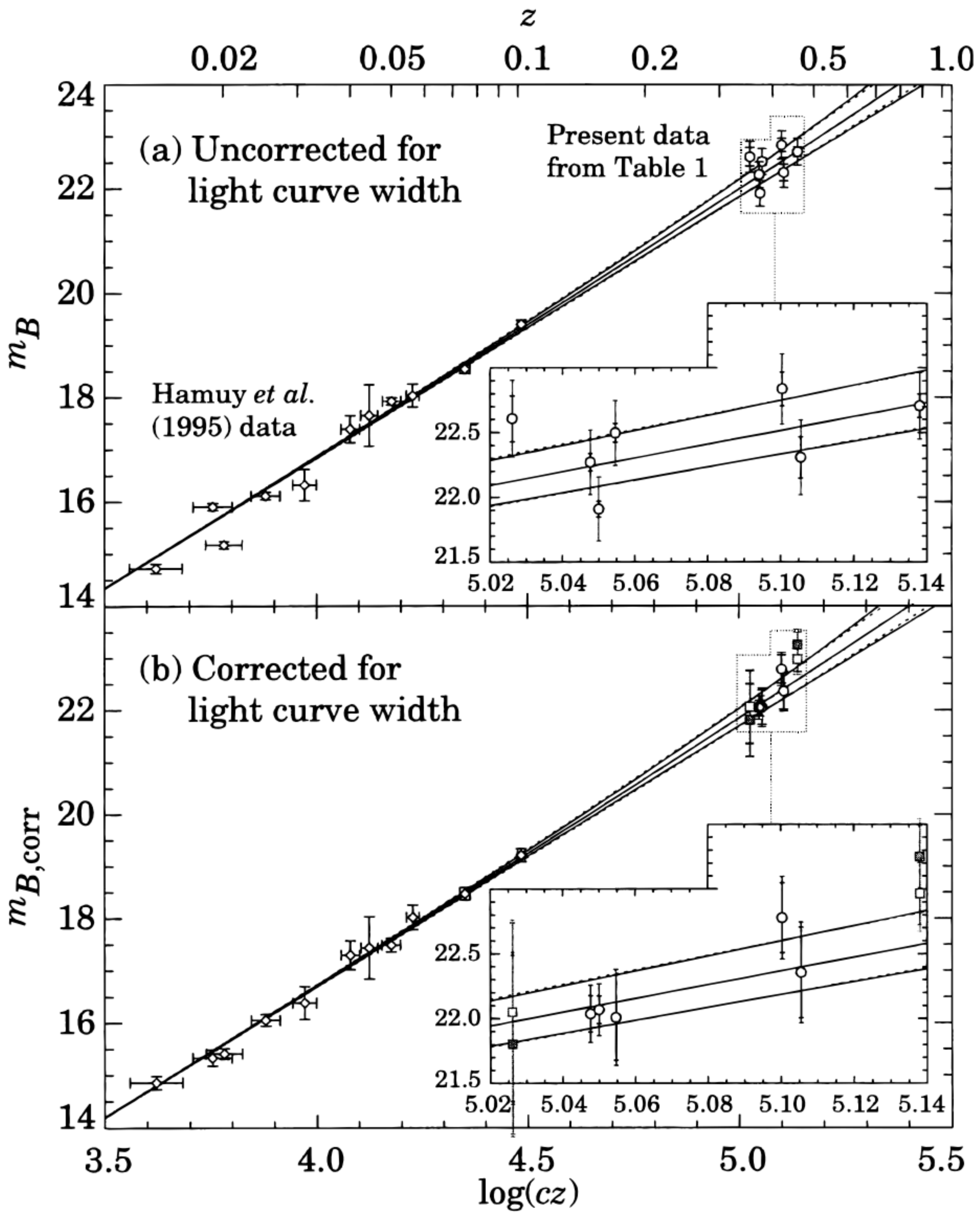
(THE SUPERNOVA COSMOLOGY PROJECT)
Received 1996 August 26; accepted 1997 February 6

First 7 high-z supernovae!







OM=0.88 for a L=0 cosmology
OM=0.94 (L=0.06) for a flat cosmology

Age of the Universe ~10 Gyr!!!
Either lower age or lower H0

History of SN Ia cosmology

1998A&A...331..815T

Astron. Astrophys. 331, 815–820 (1998)

ASTRONOMY AND ASTROPHYSICS

A two-parameter luminosity correction for Type Ia supernovae*

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Received 9 October 1997 / Accepted 10 November 1997

$$M_B = -19.48 + b\,(\Delta m_{15} - 1.05) + R\,(B - V)$$

Abstract. If, in addition to the usual luminosity correction described by the light curve slope parameter b, we introduce a color correction parameter R, then an extraordinarily good fit is realized for all the 29 distant Type Ia supernovae of the recent Calán/Tololo supernova survey. The reduced χ^2 found is much lower than can be expected. All of the intrinsic dispersion is thereby removed from the data sample, leaving perfectly standardized candles insofar as one can measure with present techniques. The best-fit solution has a mysteriously low value for R (referred to the B-band) of about 2 and a value of $b \approx 0.5$ which is smaller than previously reported without the color correction. These parameters lead, using pre-Hipparcos distances for Cepheid calibrations, to essentially the same value for the Hubble constant. Our preliminary value, subject to further investigation of Cepheid-calibrated supernovae using this same color correction, is $H_0 = 60 \pm 6$ kms^{-1}Mpc^{-1}.

History of SN Ia cosmology

1998AJ....116.1009R

16 High-z SNe with 0.16<z<0.62
34 Calan-Tololo and CfA z<0.15

THE ASTRONOMICAL JOURNAL, 116:1009–1038, 1998 September
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OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

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Received 1998 March 13; revised 1998 May 6

ABSTRACT

We present spectral and photometric observations of 10 Type Ia supernovae (SNe Ia) in the redshift range $0.16 \le z \le 0.62$. The luminosity distances of these objects are determined by methods that employ relations between SN Ia luminosity and light curve shape. Combined with previous data from our High-*z* Supernova Search Team and recent results by Riess et al., this expanded set of 16 high-redshift supernovae and a set of 34 nearby supernovae are used to place constraints on the following cosmological parameters: the Hubble constant (H_0), the mass density (Ω_M), the cosmological constant (i.e., the vacuum energy density, Ω_Λ), the deceleration parameter (q_0), and the dynamical age of the universe (t_0). The distances of the high-redshift SNe Ia are, on average, 10%–15% farther than expected in a low mass density ($\Omega_M = 0.2$) universe without a cosmological constant. Different light curve fitting methods, SN Ia subsamples, and prior constraints unanimously favor eternally expanding models with positive cosmological constant (i.e., $\Omega_\Lambda > 0$) and a current acceleration of the expansion (i.e., $q_0 < 0$). With no prior constraint on mass density other than $\Omega_M \ge 0$, the spectroscopically confirmed SNe Ia are statistically consistent with $q_0 < 0$ at the 2.8 σ and 3.9 σ confidence levels, and with $\Omega_\Lambda > 0$ at the 3.0 σ and 4.0 σ confidence levels, for two different fitting methods, respectively. Fixing a "minimal" mass density, $\Omega_M = 0.2$, results in the weakest detection, $\Omega_\Lambda > 0$ at the 3.0 σ confidence level from one of the two methods. For a flat universe prior ($\Omega_M + \Omega_\Lambda = 1$), the spectroscopically confirmed SNe Ia require $\Omega_\Lambda > 0$ at 7 σ and 9 σ formal statistical significance for the two different fitting methods. A universe closed by ordinary matter (i.e., $\Omega_M = 1$) is formally ruled out at the 7 σ to 8 σ confidence level for the two different fitting methods. We estimate the dynamical age of the universe to be 14.2 ± 1.7 Gyr including systematic uncertainties in the current Cepheid distance scale. We estimate the likely effect of several sources of systematic error, including progenitor and metallicity evolution, extinction, sample selection bias, local perturbations in the expansion rate, gravitational lensing, and sample contamination. Presently, none of these effects appear to reconcile the data with $\Omega_\Lambda = 0$ and $q_0 \ge 0$.

Key words: cosmology: observations — supernovae: general

1999ApJ...517..565P

42 High-z SNe with 0.18<z<0.83
18 Calan-Tololo z<0.1

THE ASTROPHYSICAL JOURNAL, 517:565–586, 1999 June 1
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MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

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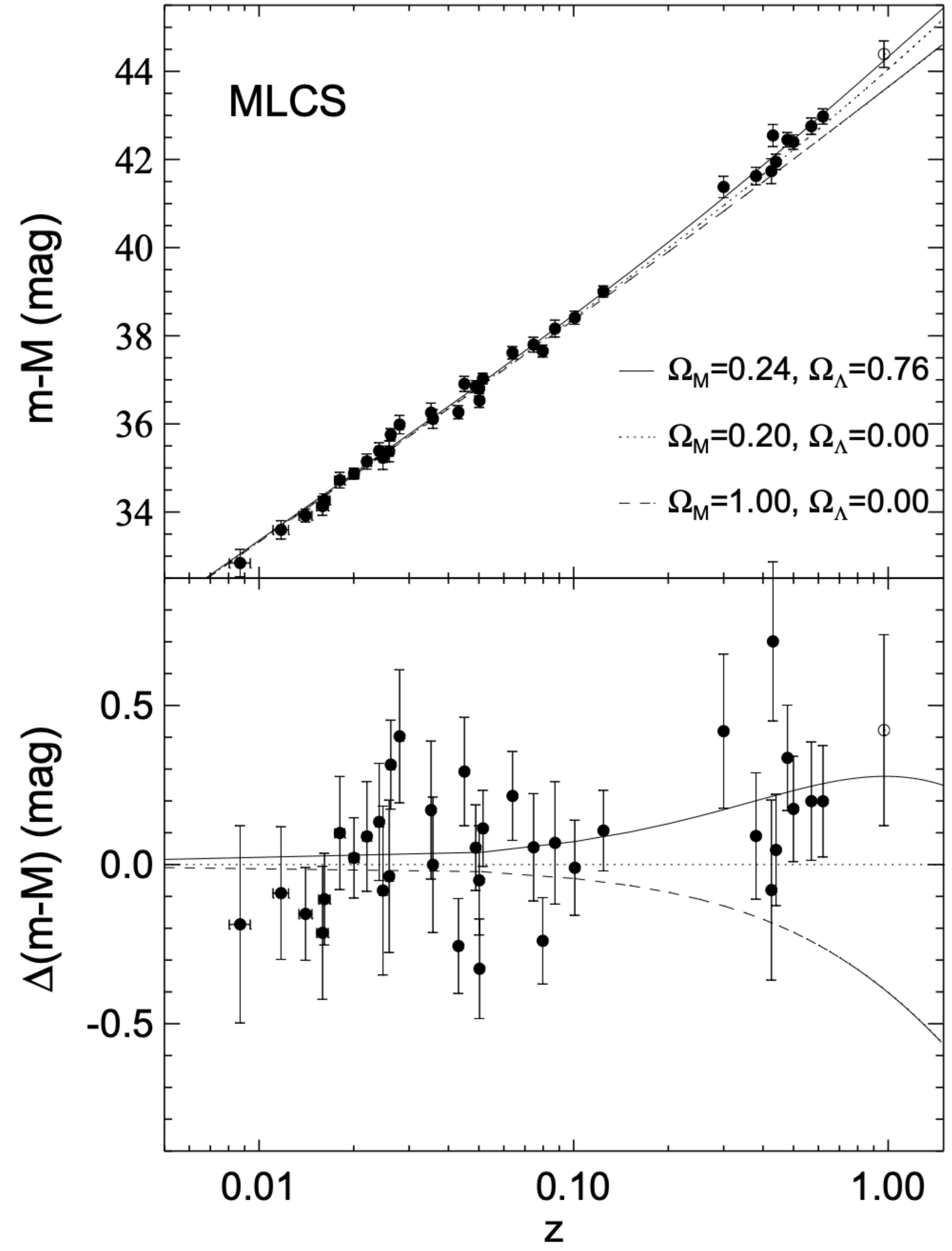
ABSTRACT

We report measurements of the mass density, Ω_M, and cosmological-constant energy density, Ω_Λ, of the universe based on the analysis of 42 type Ia supernovae discovered by the Supernova Cosmology Project. The magnitude-redshift data for these supernovae, at redshifts between 0.18 and 0.83, are fitted jointly with a set of supernovae from the Calán/Tololo Supernova Survey, at redshifts below 0.1, to yield values for the cosmological parameters. All supernova peak magnitudes are standardized using a SN Ia light-curve width-luminosity relation. The measurement yields a joint probability distribution of the cosmological parameters that is approximated by the relation $0.8\Omega_M - 0.6\Omega_\Lambda \approx -0.2 \pm 0.1$ in the region of interest ($\Omega_M \lesssim 1.5$). For a flat ($\Omega_M + \Omega_\Lambda = 1$) cosmology we find $\Omega_M^{\rm flat} = 0.28^{+0.09}_{-0.08}$ (1 σ statistical) $^{+0.05}_{-0.04}$ (identified systematics). The data are strongly inconsistent with a $\Lambda = 0$ flat cosmology, the simplest inflationary universe model. An open, $\Lambda = 0$ cosmology also does not fit the data well: the data indicate that the cosmological constant is nonzero and positive, with a confidence of $P(\Lambda > 0) = 99\%$, including the identified systematic uncertainties. The best-fit age of the universe relative to the Hubble time is $t_0^{\rm flat} = 14.9^{+1.4}_{-1.1}(0.63/h)$ Gyr for a flat cosmology. The size of our sample allows us to perform a variety of statistical tests to check for possible systematic errors and biases. We find no significant differences in either the host reddening distribution or Malmquist bias between the low-redshift Calán/Tololo sample and our high-redshift sample. Excluding those few supernovae that are outliers in color excess or fit residual does not significantly change the results. The conclusions are also robust whether or not a width-luminosity relation is used to standardize the supernova peak magnitudes. We discuss and constrain, where possible, hypothetical alternatives to a cosmological constant.

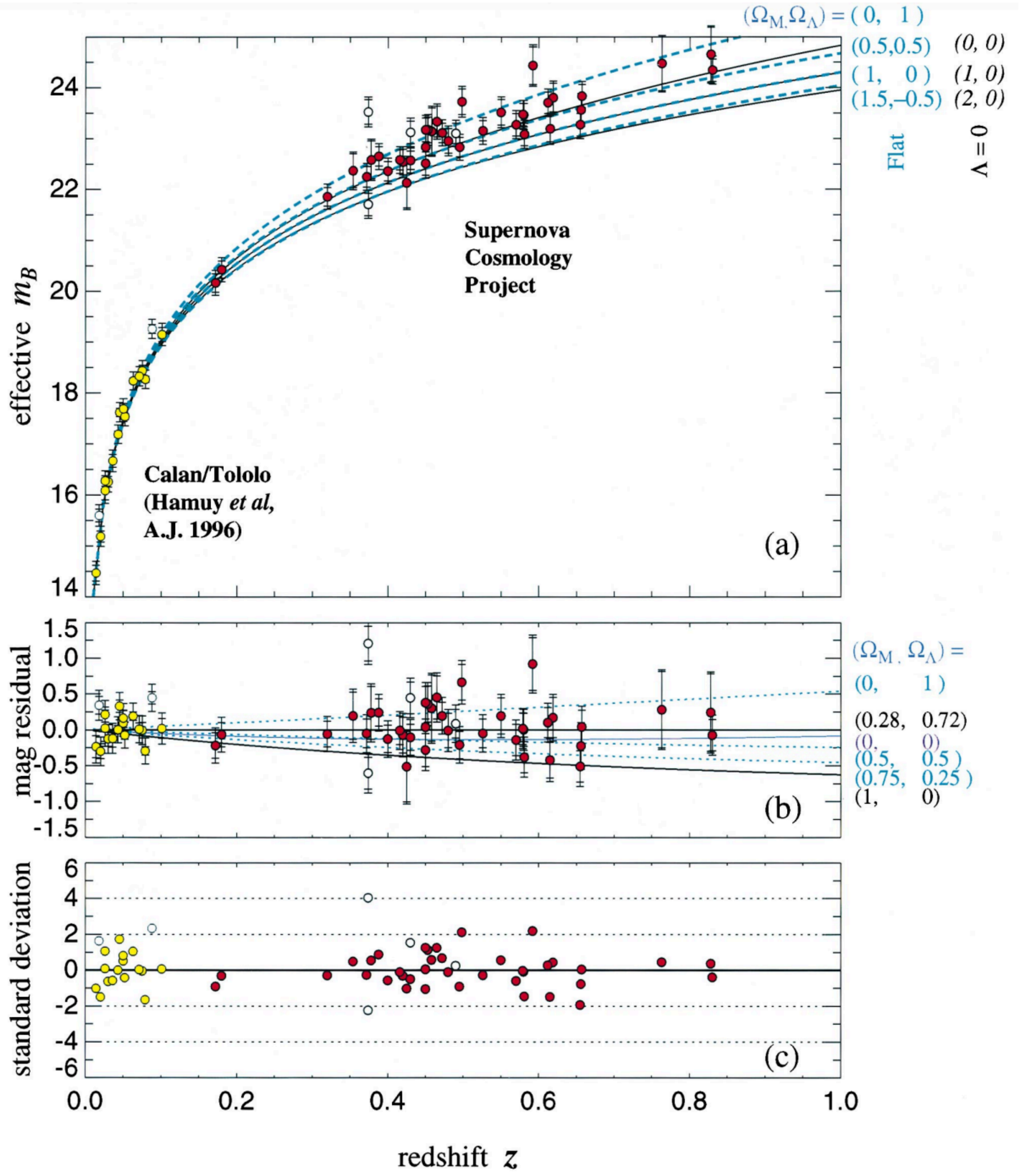
Subject headings: cosmology: observations — distance scale — supernovae: general

History of SN Ia cosmology

1998AJ....116.1009R

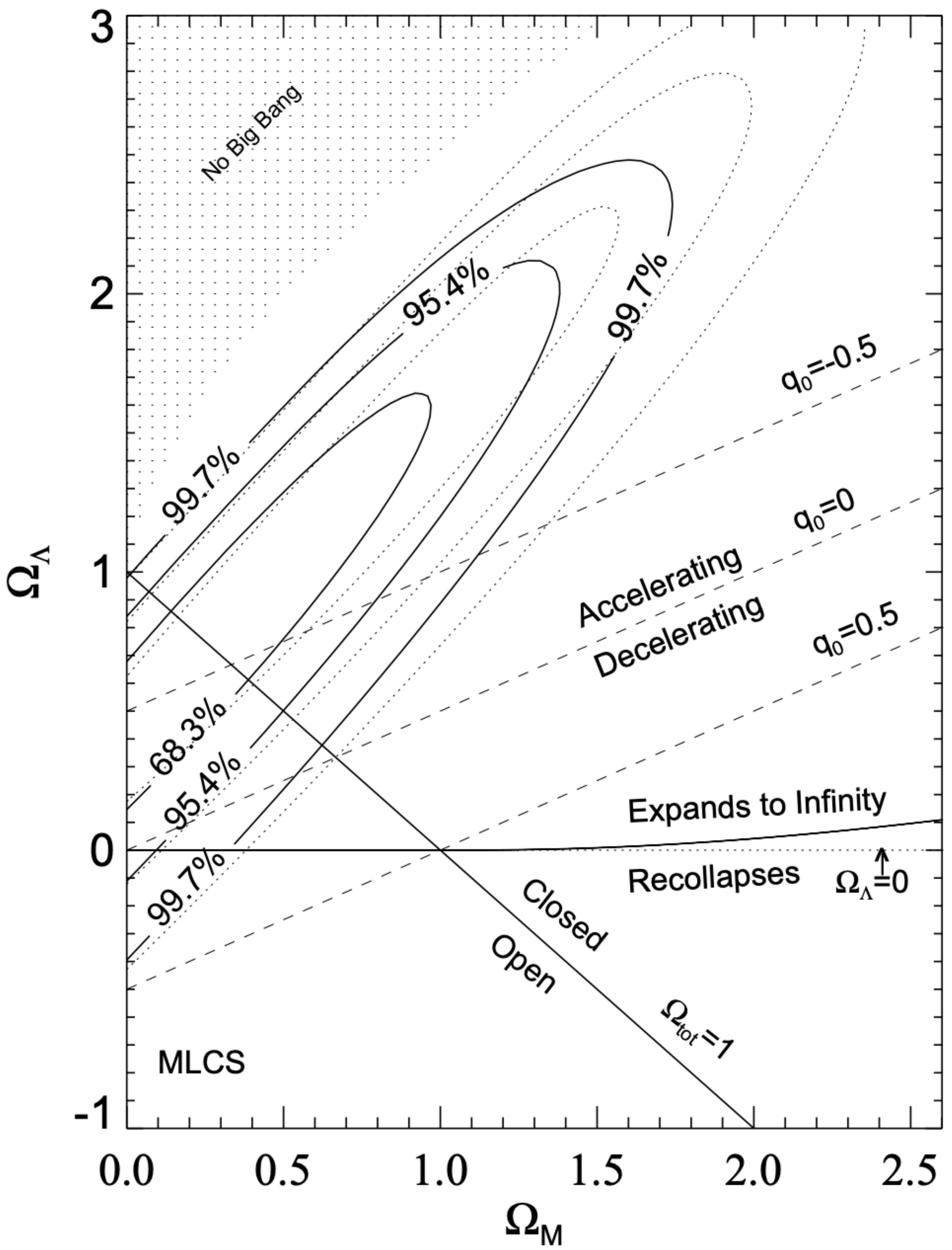


1999ApJ...517..565P

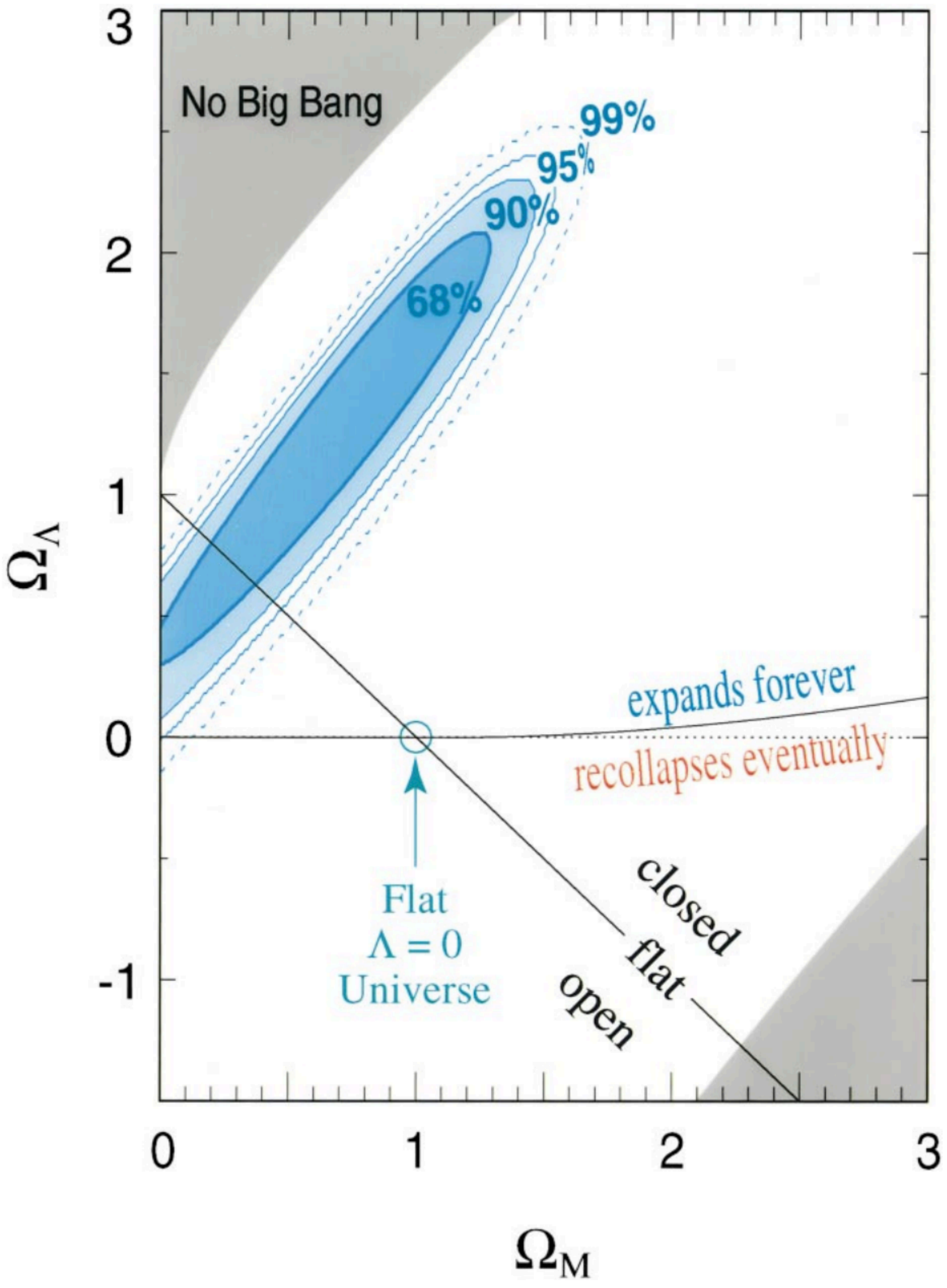


History of SN Ia cosmology

1998AJ....116.1009R



1999ApJ...517..565P



History of SN Ia cosmology

1999AJ....118.1766P

THE ASTRONOMICAL JOURNAL, 118:1766–1776, 1999 October
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THE REDDENING-FREE DECLINE RATE VERSUS LUMINOSITY RELATIONSHIP FOR TYPE Ia SUPERNOVAE

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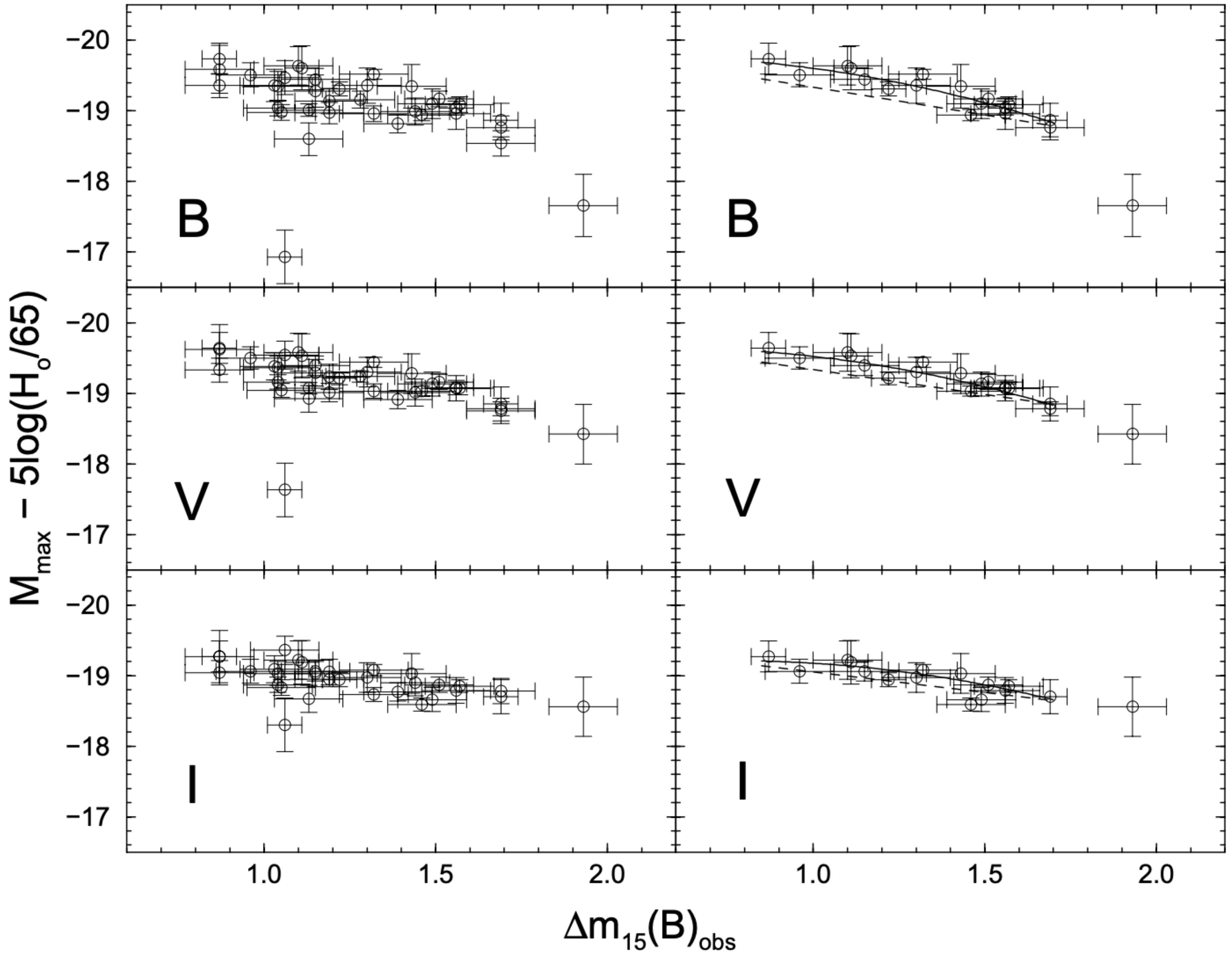
Received 1999 January 27; accepted 1999 July 1

ABSTRACT

We develop a method for estimating the host galaxy dust extinction for type Ia supernovae based on an observational coincidence first noted by Lira, who found that the $B-V$ evolution during the period from 30 to 90 days after V maximum is remarkably similar for all events, regardless of light-curve shape. This fact is used to calibrate the dependence of the $B_{\max}-V_{\max}$ and $V_{\max}-I_{\max}$ colors on the light-curve decline rate parameter $\Delta m_{15}(B)$, which can, in turn, be used to separately estimate the host galaxy extinction. Using these methods to eliminate the effects of reddening, we reexamine the functional form of the decline rate versus luminosity relationship and provide an updated estimate of the Hubble constant of $H_0 = 63.3 \pm 2.2(\text{internal}) \pm 3.5(\text{external})$ km s^{-1} Mpc^{-1}.
Key words: distance scale — supernovae: general

41 final sample of Calan/Tololo SNIa z>0.01

Removing 23 with host galaxy extinction

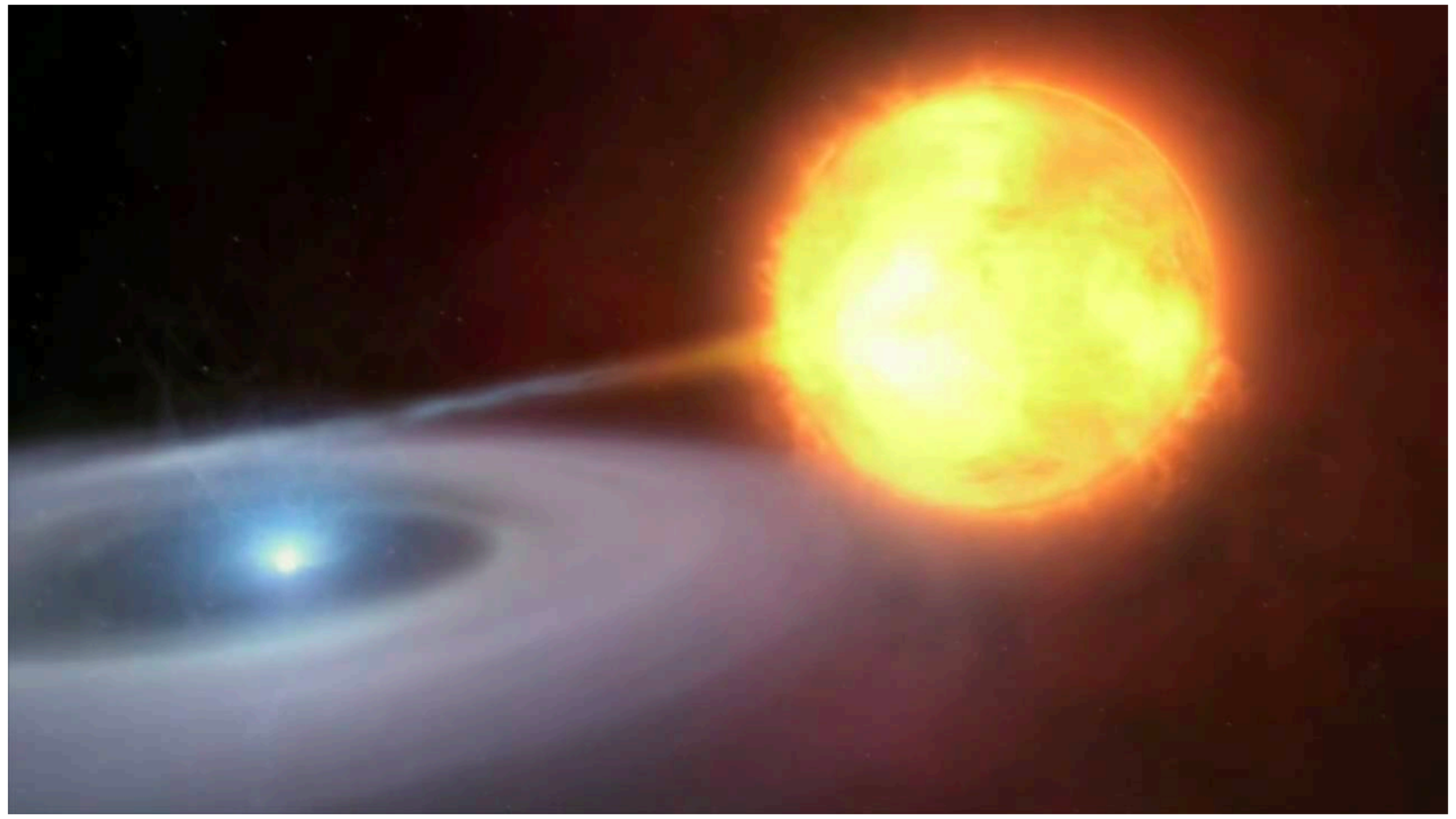


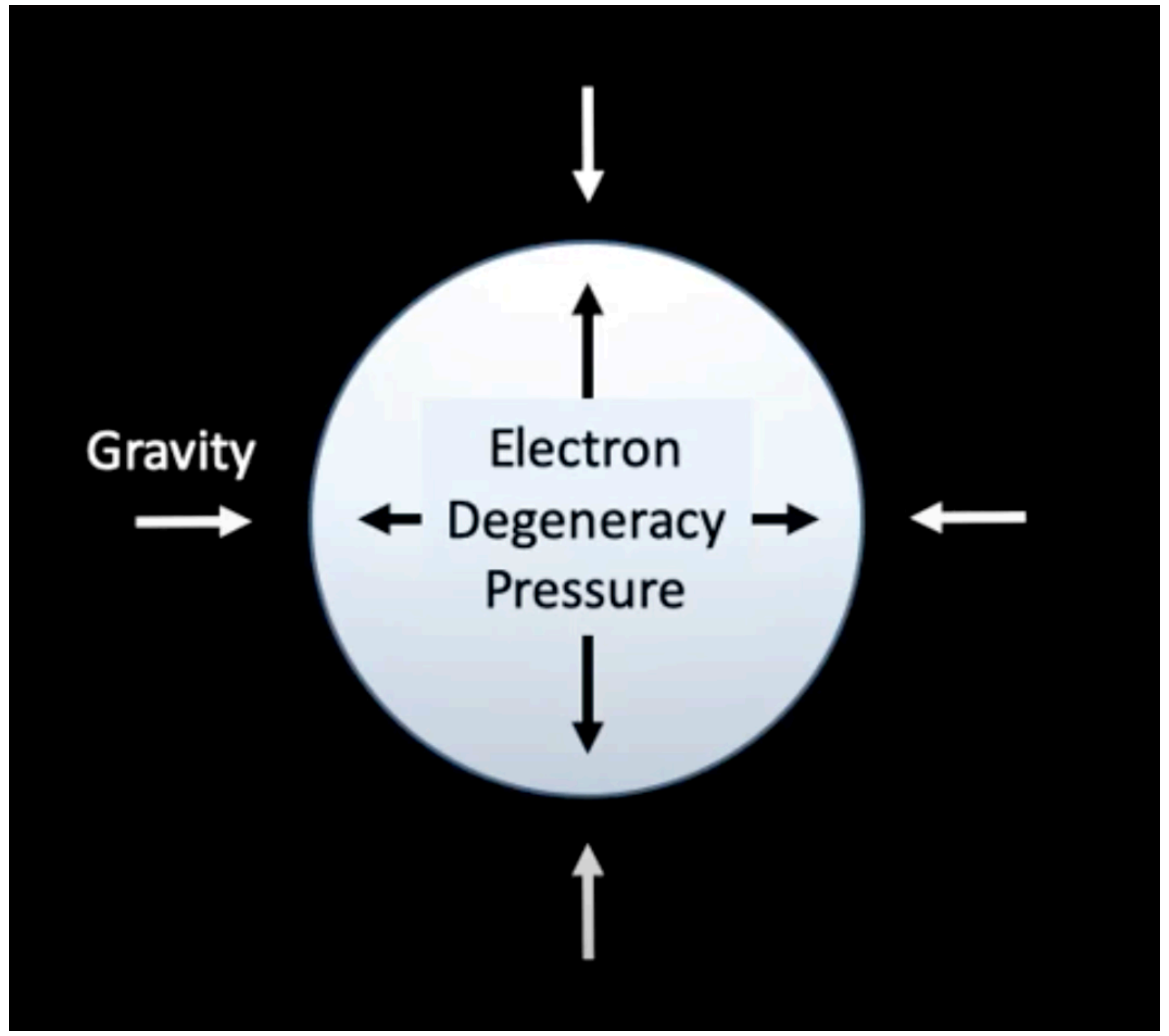
Type Ia supernovae Physics

- Thermonuclear explosions of CO white dwarfs (MS, mass < 8 $M_{\odot}$)

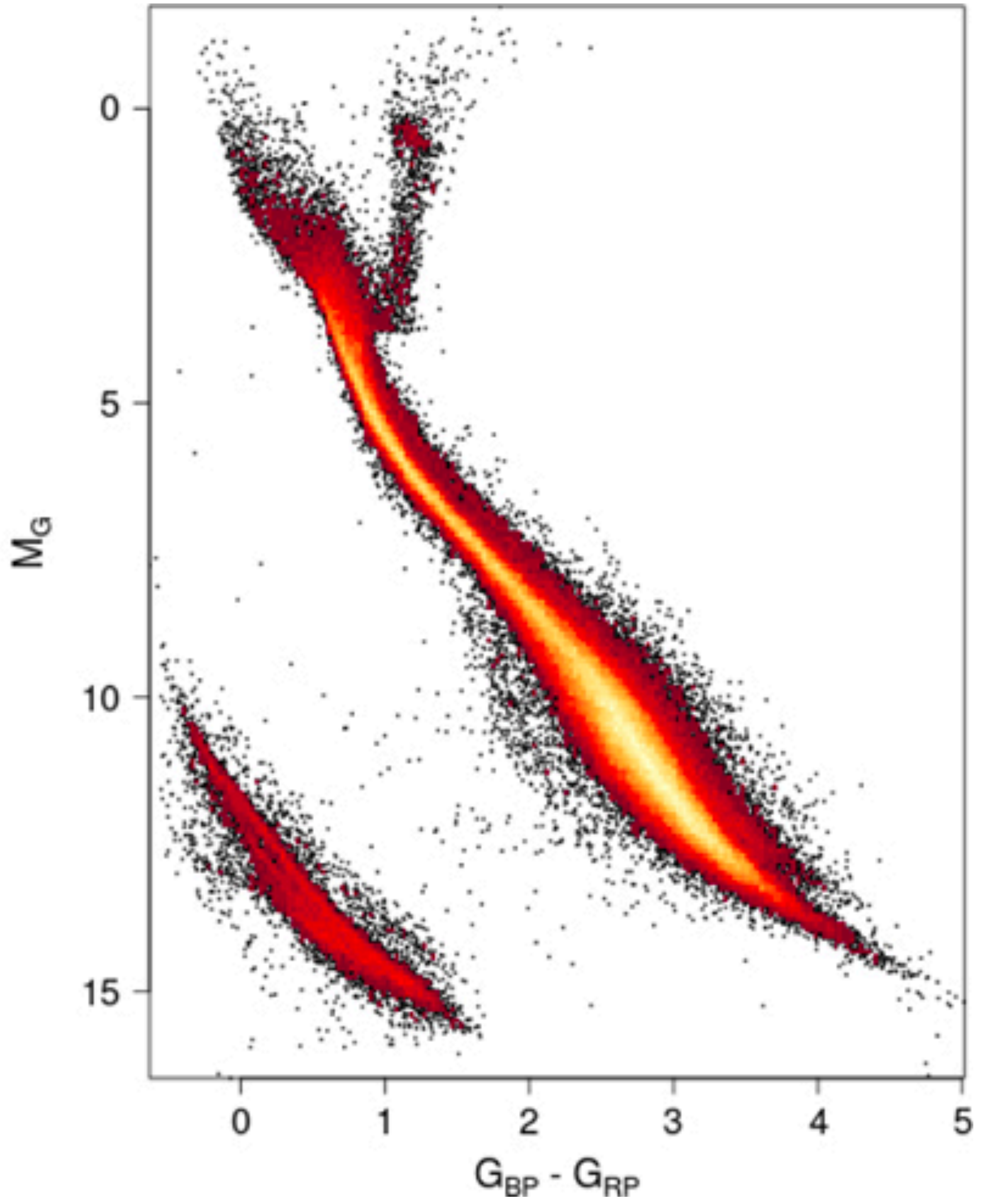
- Binary (or triple!) systems where the exploding star accreting material from a companion until reaches a critical mass (M_{Ch}) for C ignition

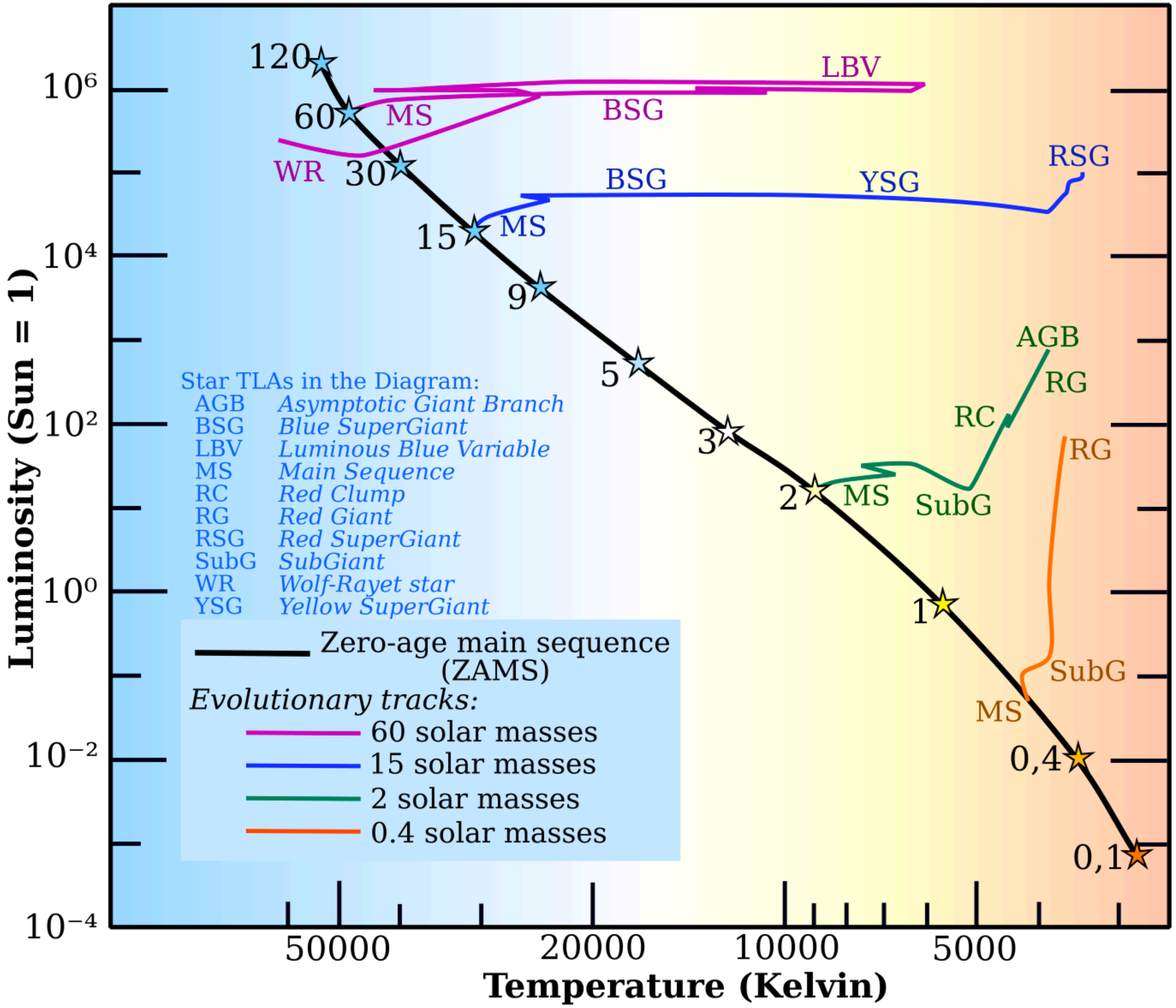
- Why so important?
  - cosmological probes
  - produce large amount of Fe-group
  - we do not know progenitors and explosion mechanisms well



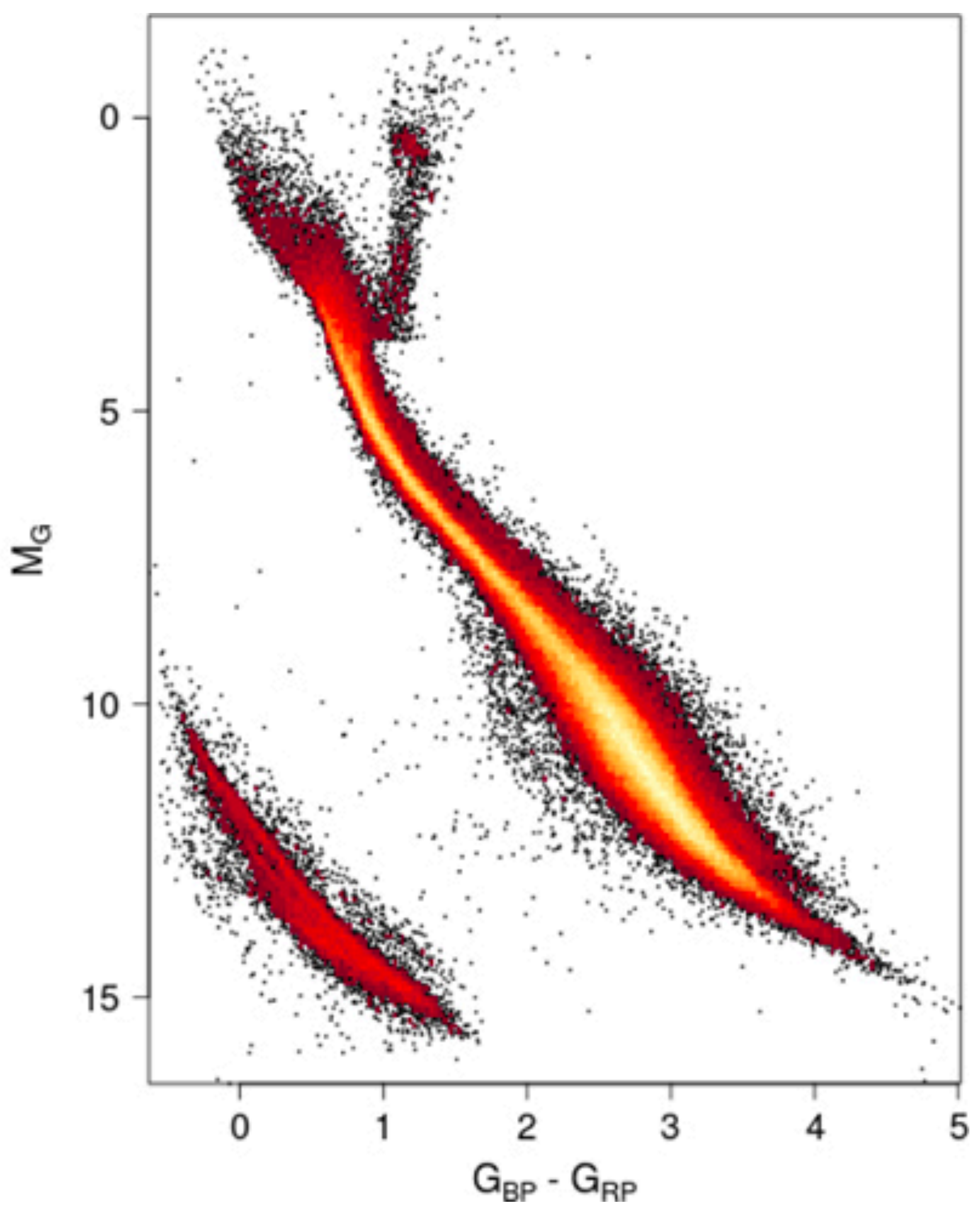


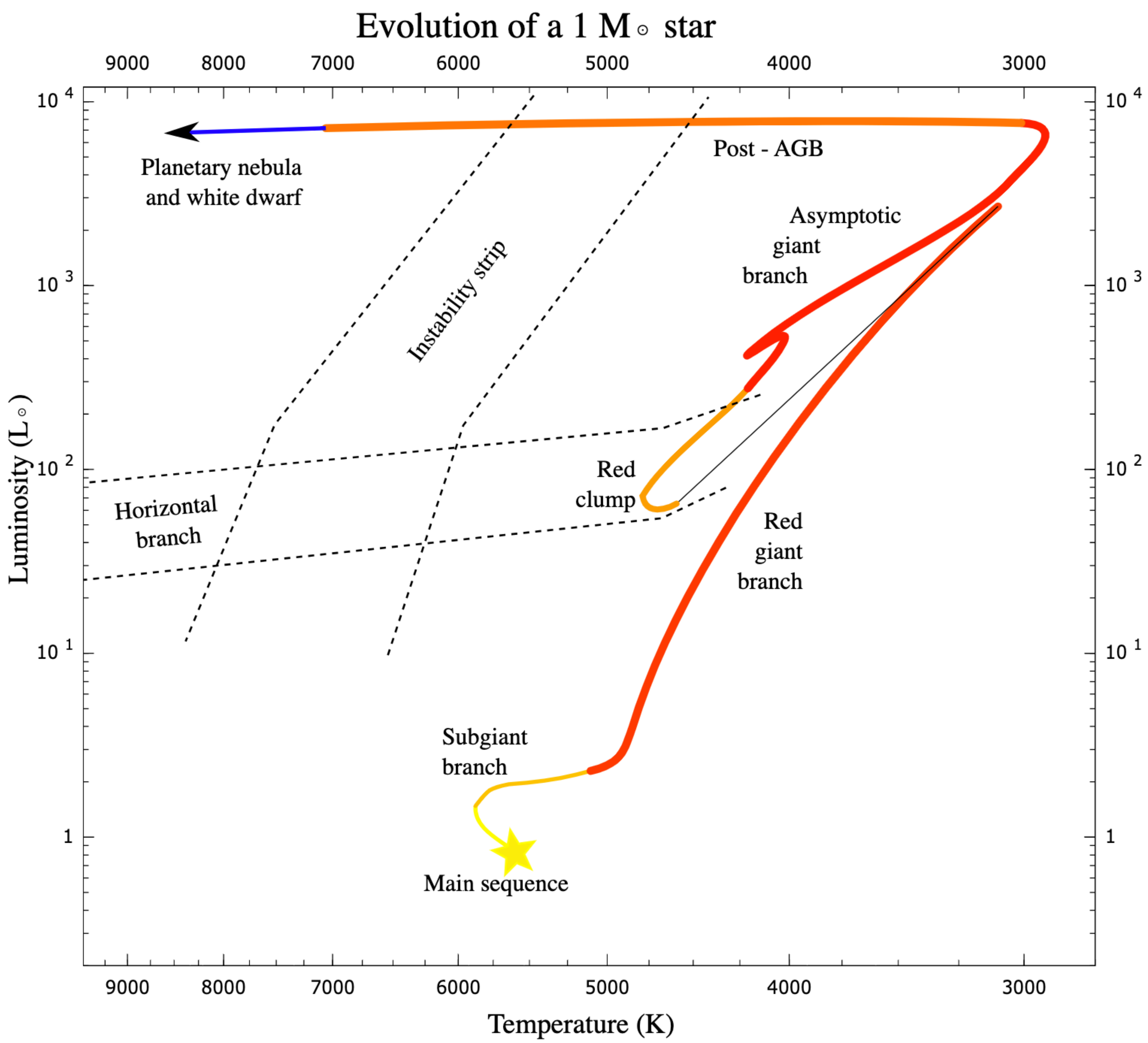
Stellar evolution





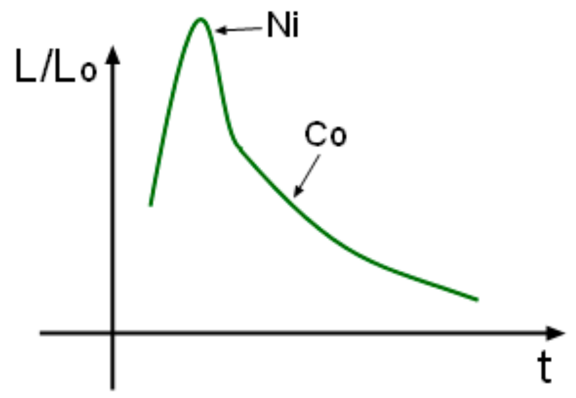
Stellar evolution

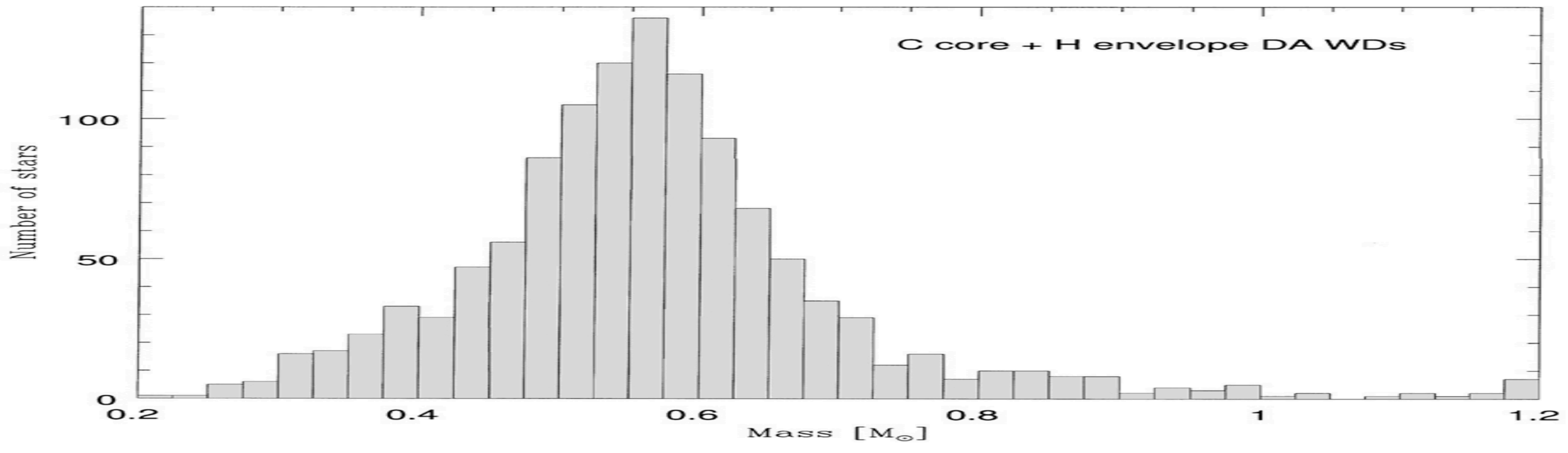




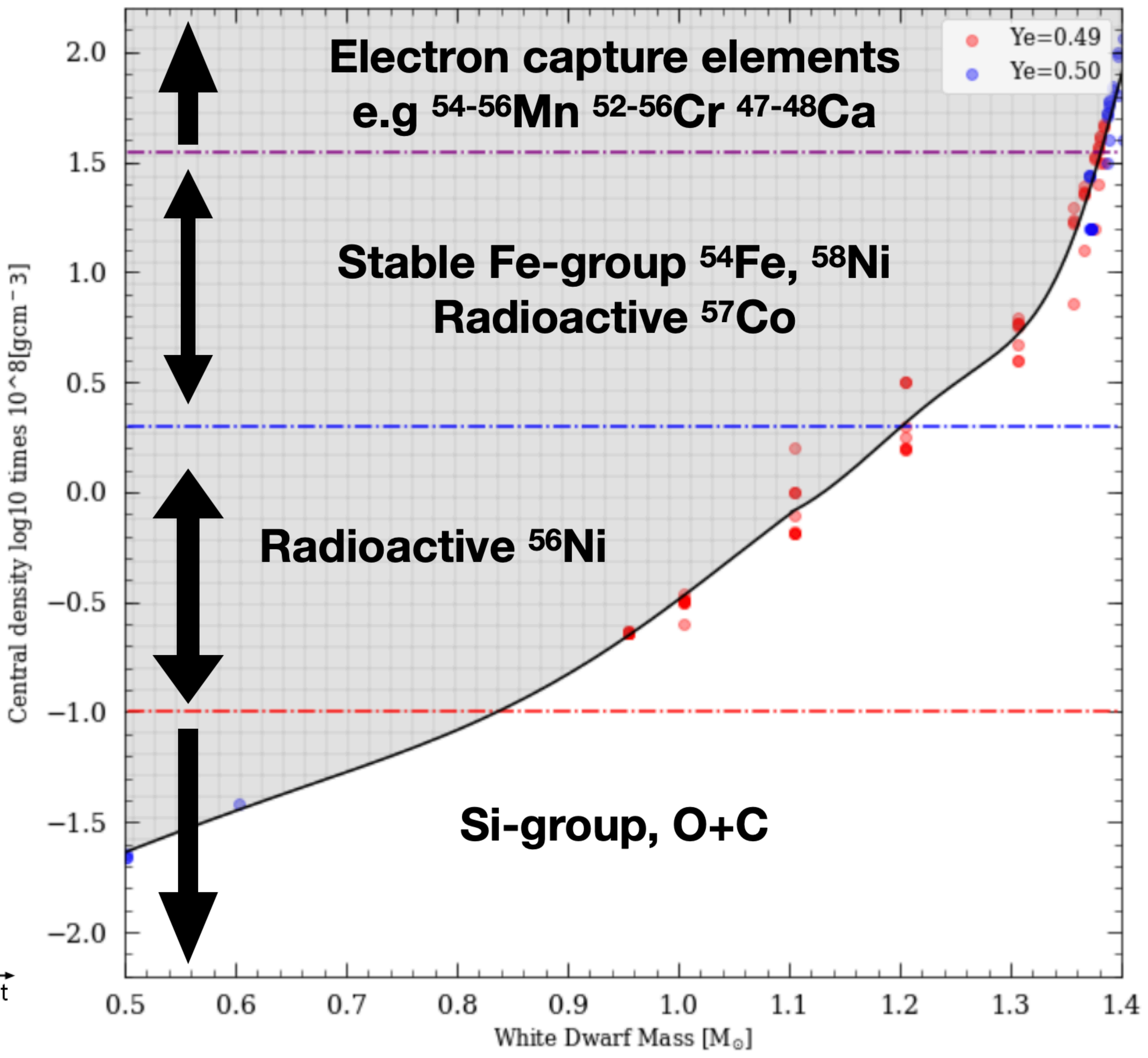
Death of a WD

- Thermonuclear explosion of a CO WD (Hoyle&Fowler60)
- Outcome is dominated by temperature and density of the burning
- ^{56}Ni drives the luminous display (Pankey62, Colgate&MeKee69)
- L_{peak} ~ ^{56}Ni mass (Arnett82) $$^{56}\mathrm{Ni} \xrightarrow{t_{1/2}= 6.08d} {}^{56}\mathrm{Co} \xrightarrow{t_{1/2}= 77.2d} {}^{56}\mathrm{Fe}$$
- Fusion drives the explosion, but radioactivity makes it shine!





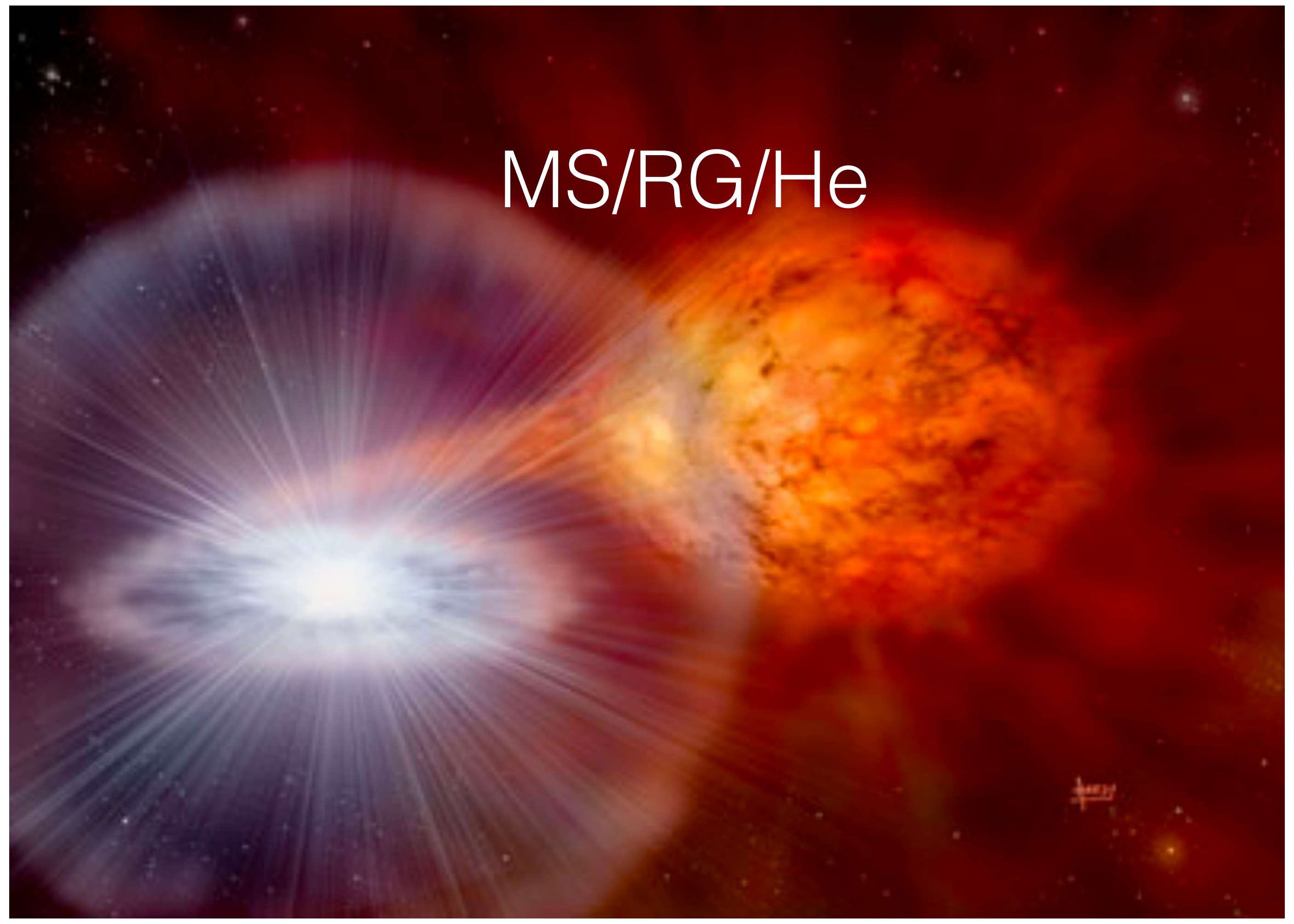
Madej+04



Ashall21

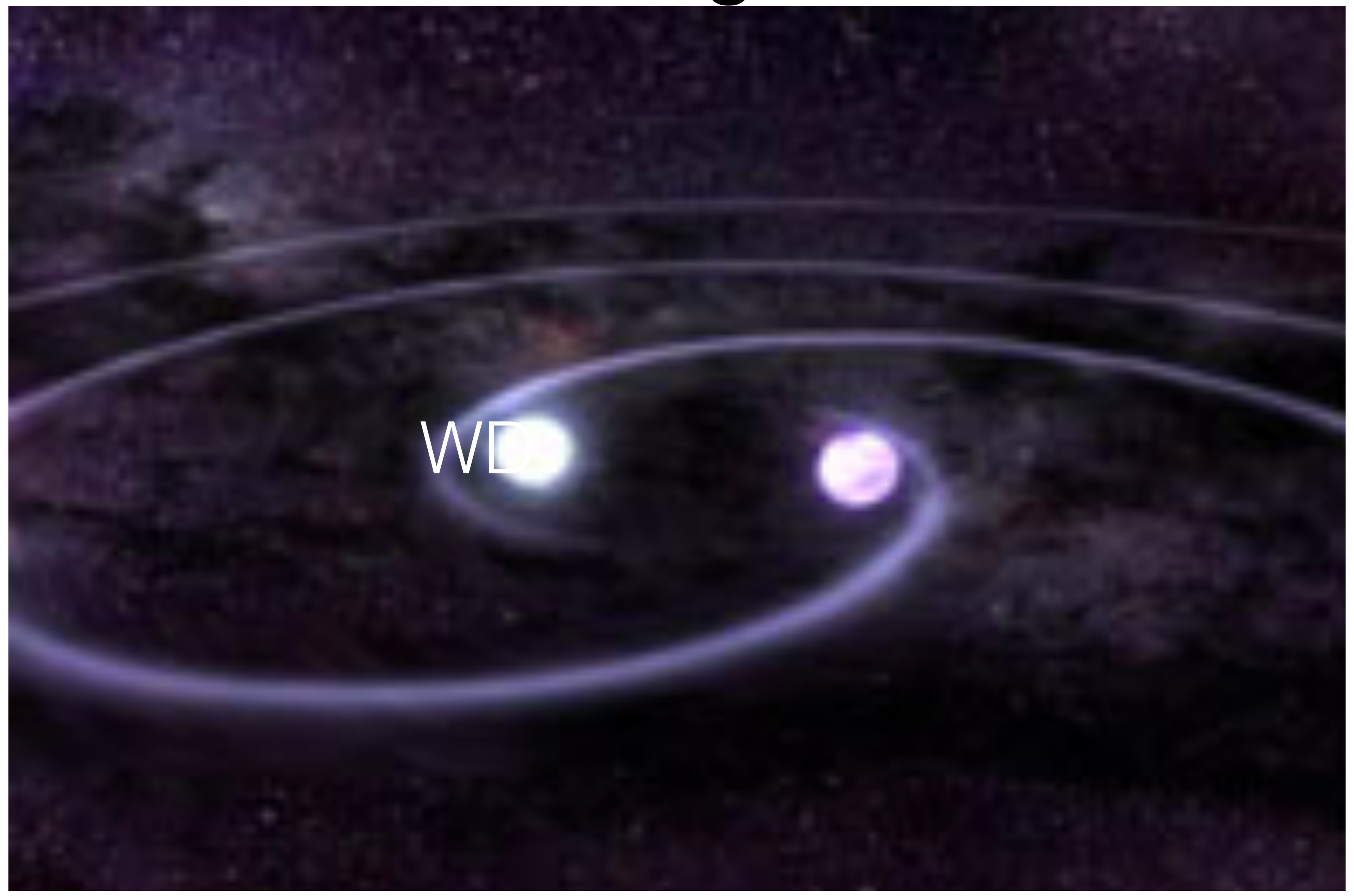
Progenitor Scenarios

Single degenerate

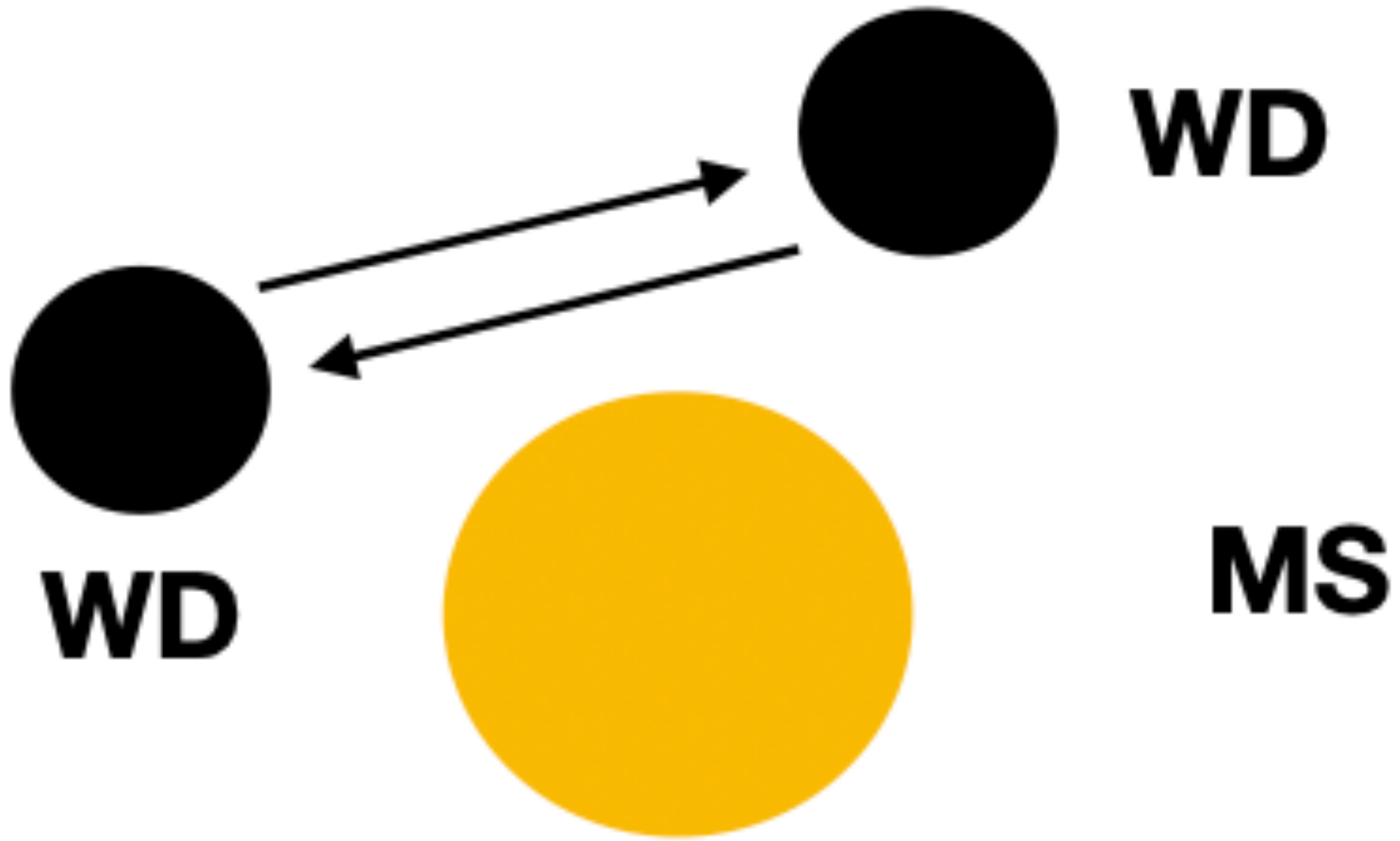


M_{ch}
sub-M_{ch}

Double degenerate

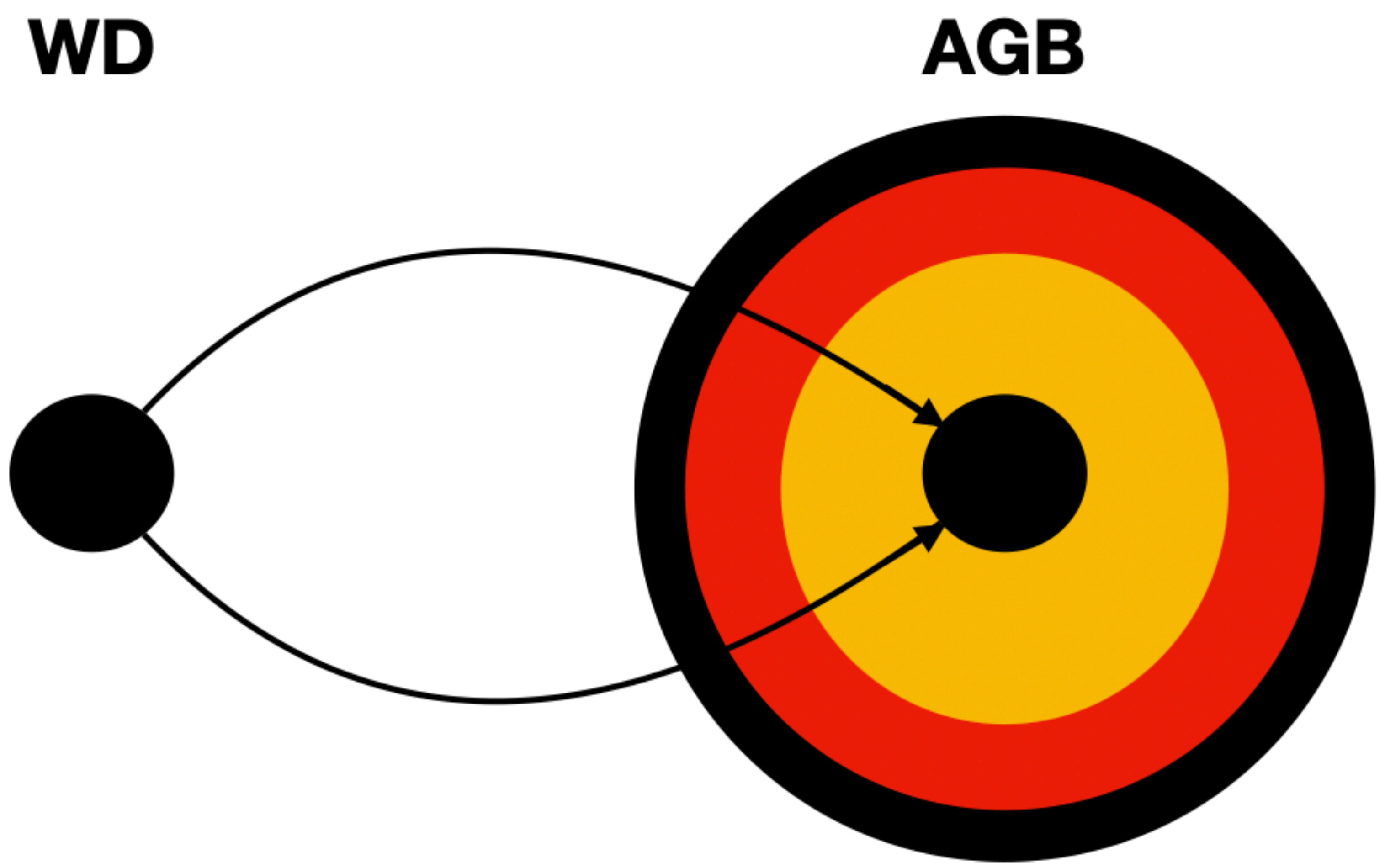


M_{ch}
sub-M_{ch}
super-M_{ch}



M_{ch}
sub-M_{ch}
super-M_{ch}

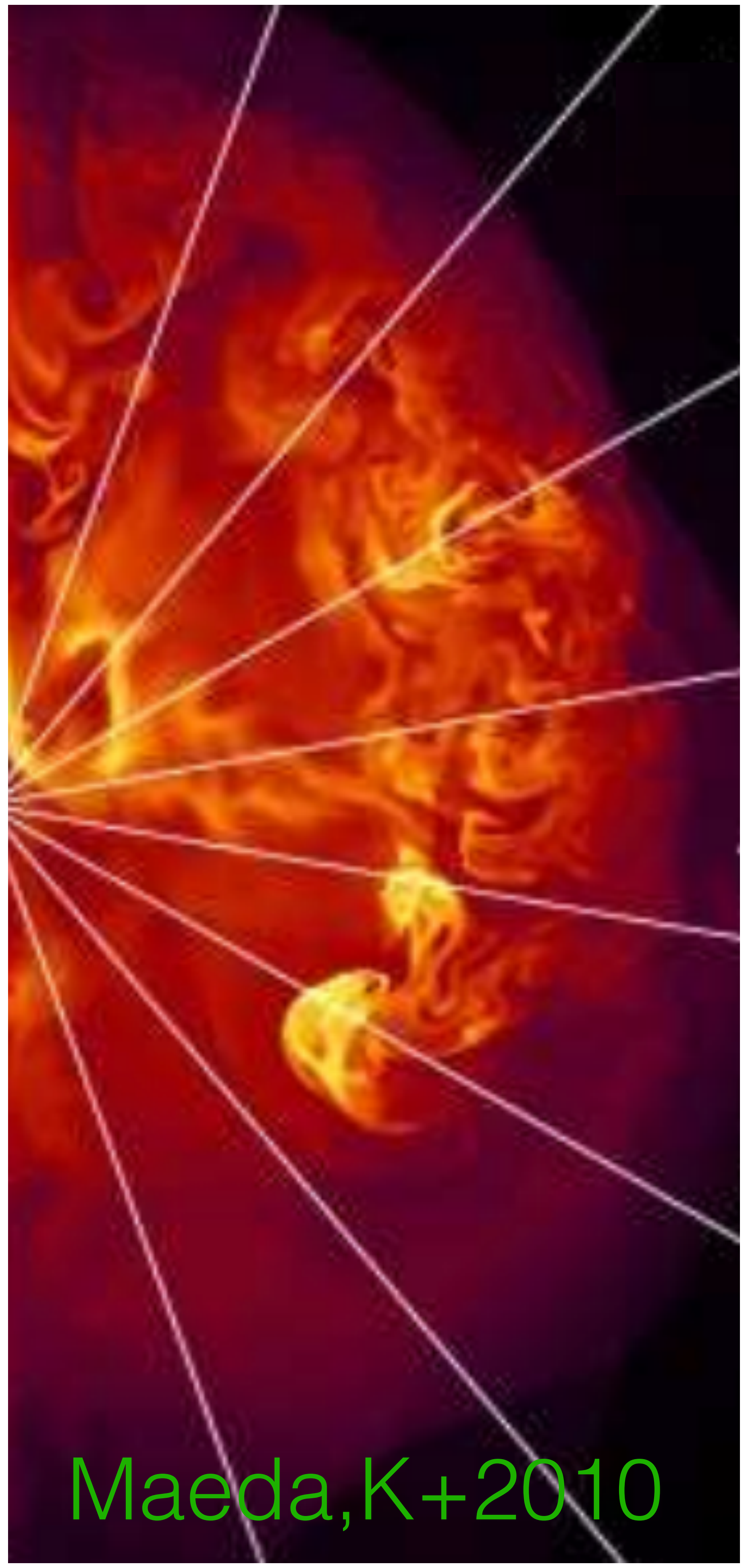
Triple system



M_{ch}
sub-M_{ch}
super-M_{ch}

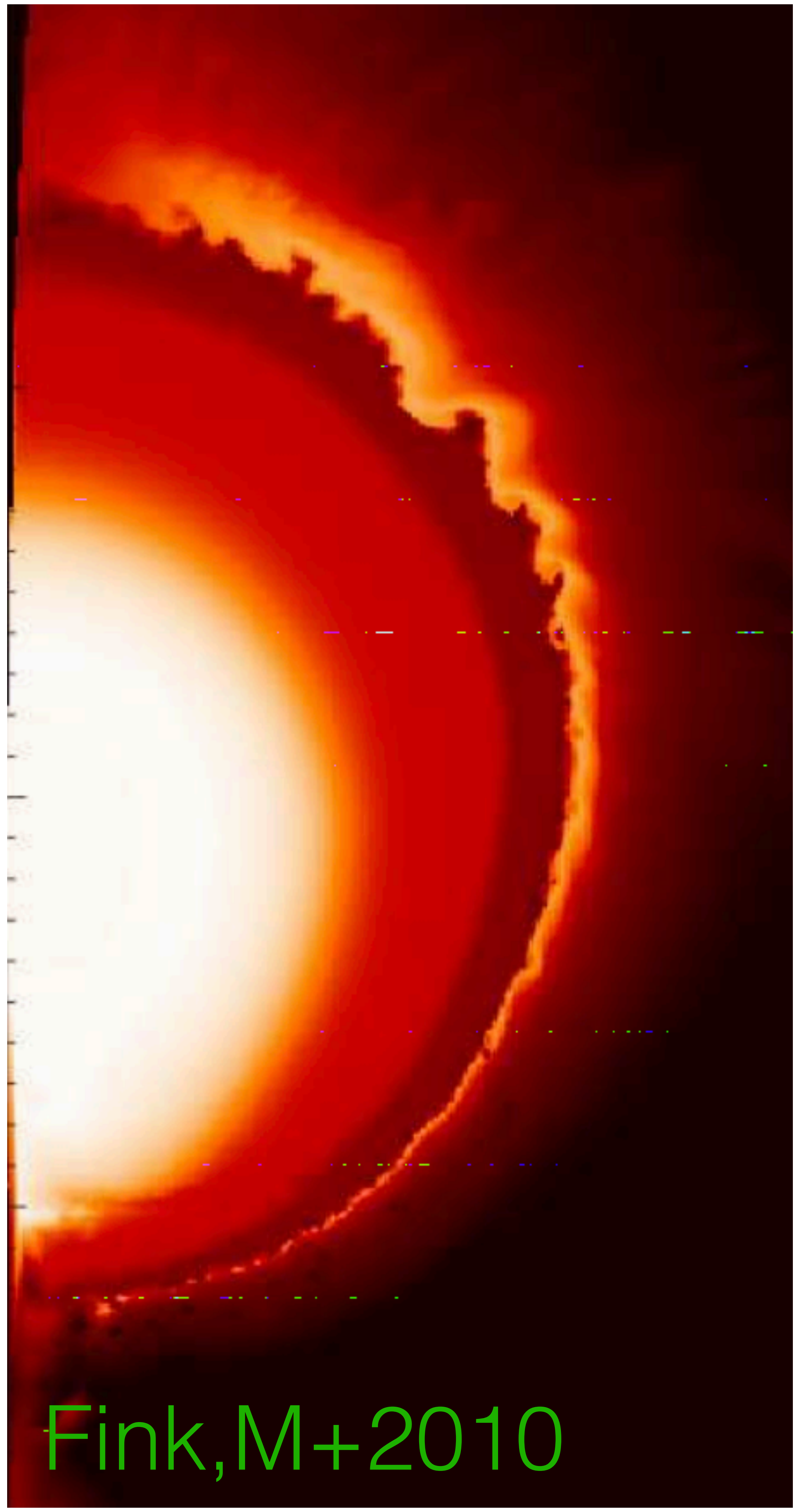
Core degenerate

Explosion Mechanism



Central Carbon Ignition
Requires near MCh WD

Outer Carbon Ignition
Requires two WD, which head on collide or violently merge



Surface He Ignition
Requires sub-MCh WD

Flame front

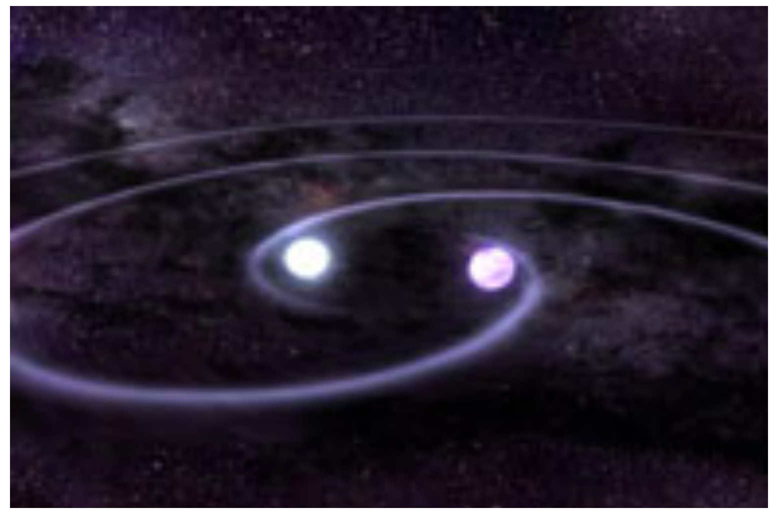
Subsonic burning speed
Rayleigh-Taylor unstable

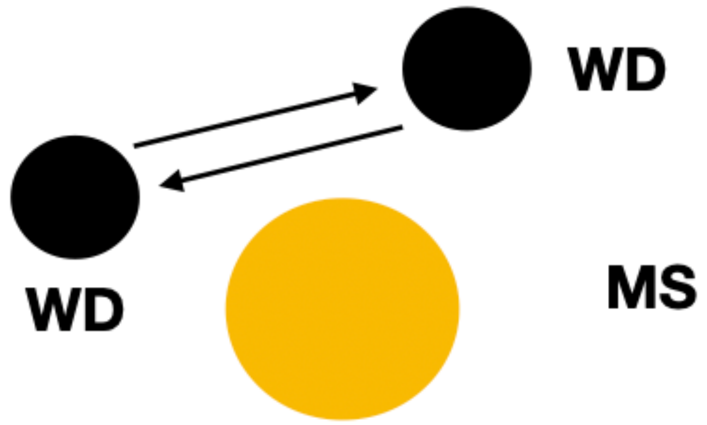
Deflagration

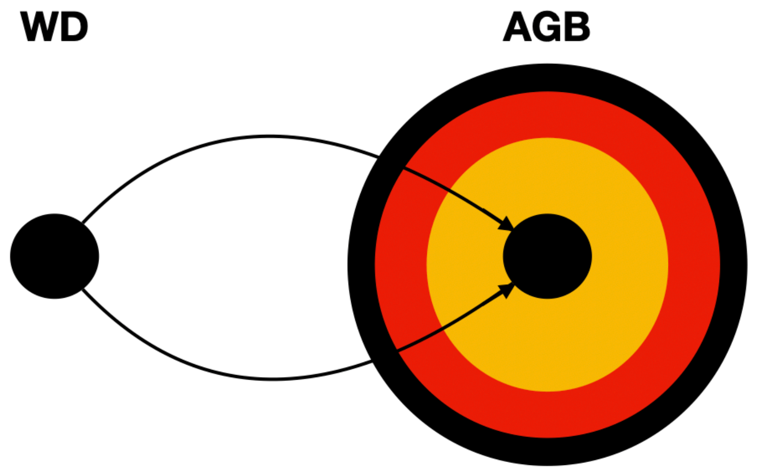
Supersonic burning speed
No mixing of the ejecta

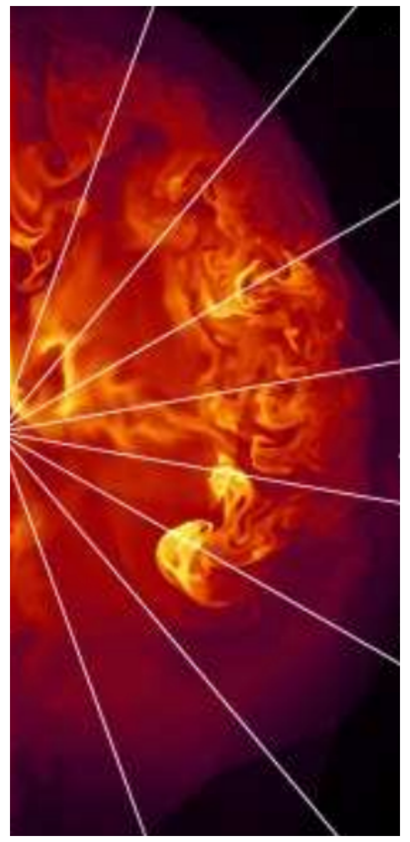
Detonation

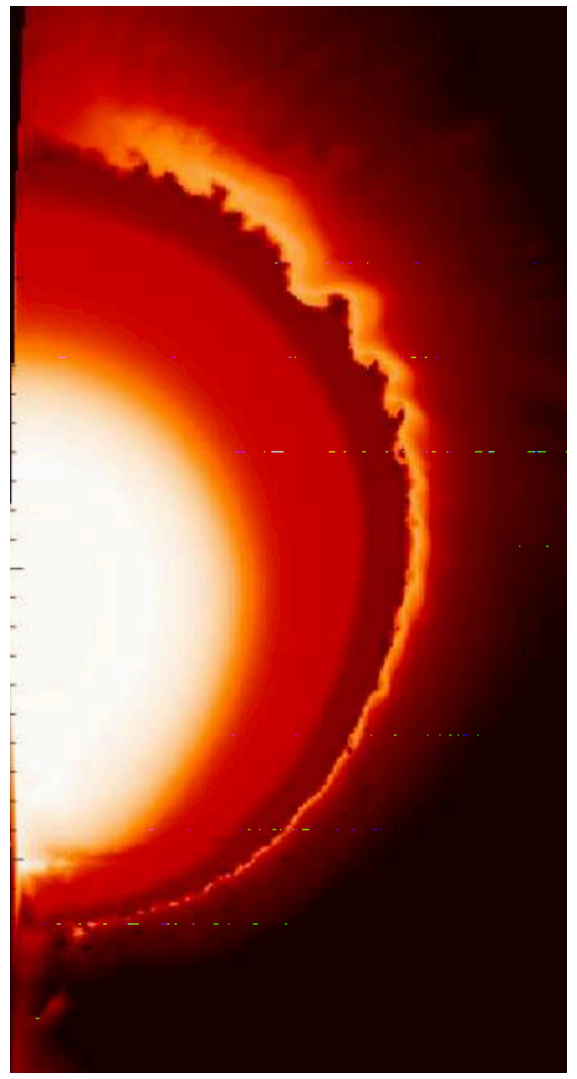
Progenitor scenario and explosion mechanism



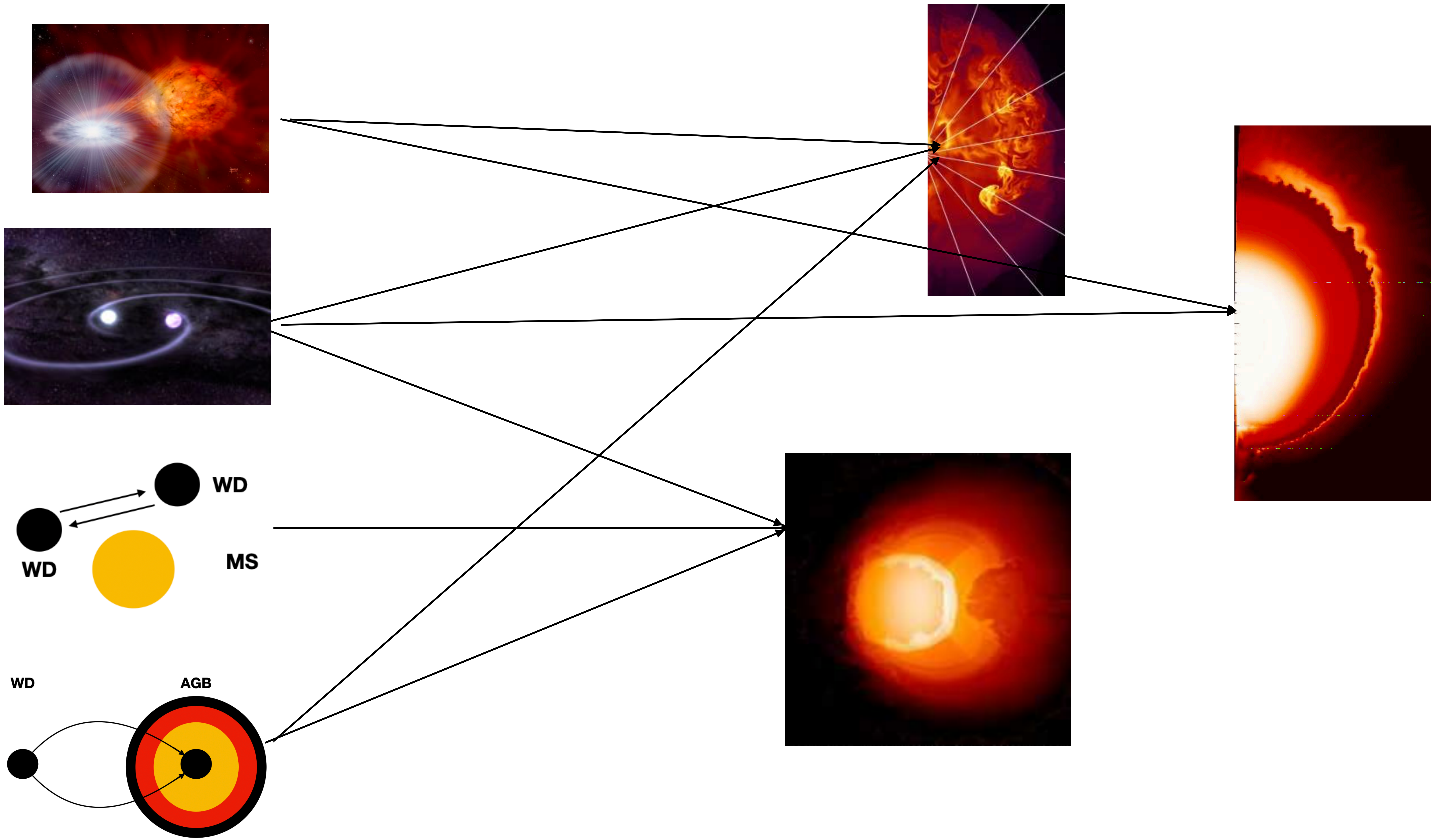








Progenitor scenario and explosion mechanism



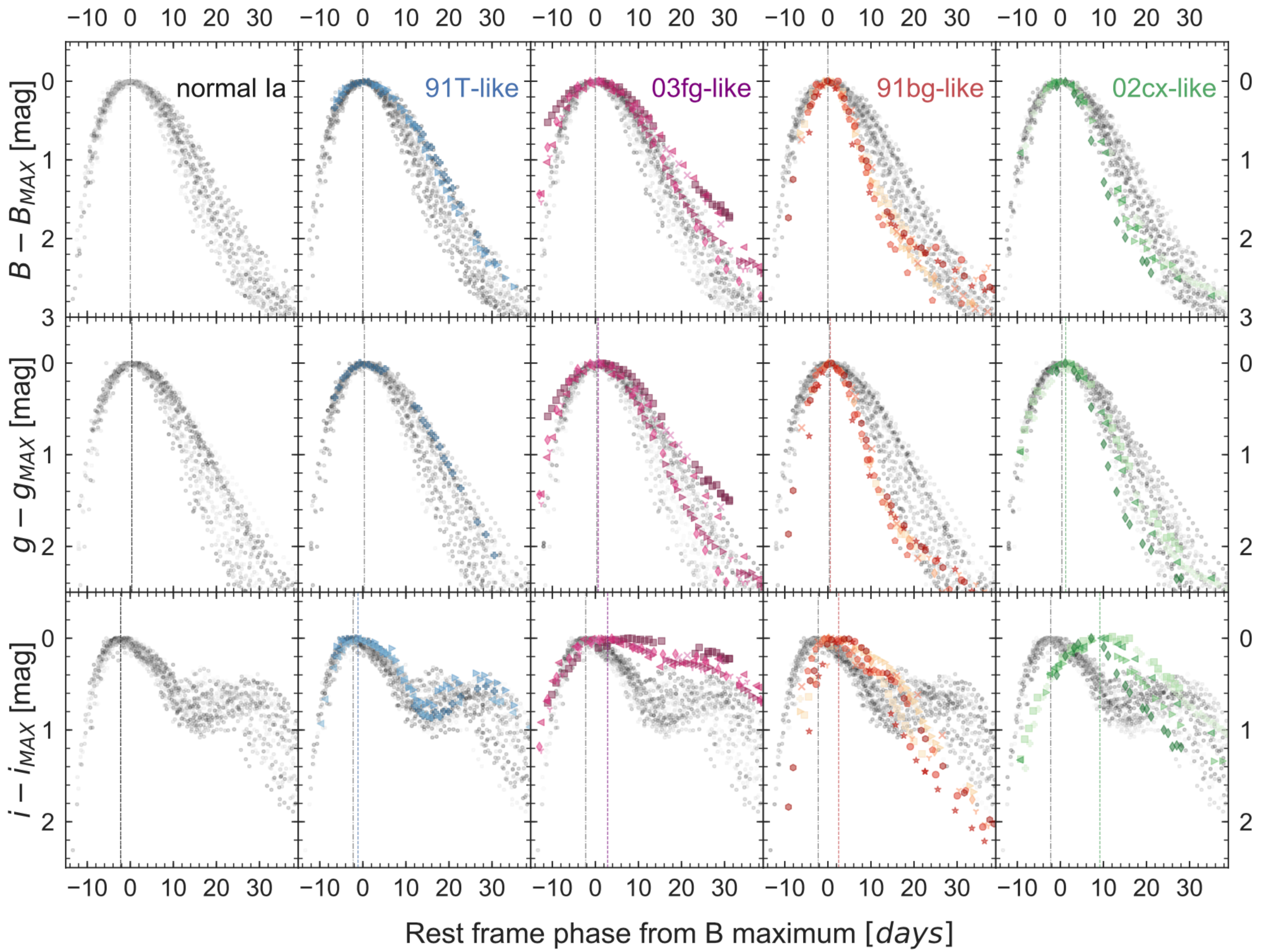
Progenitor scenario

$\neq$

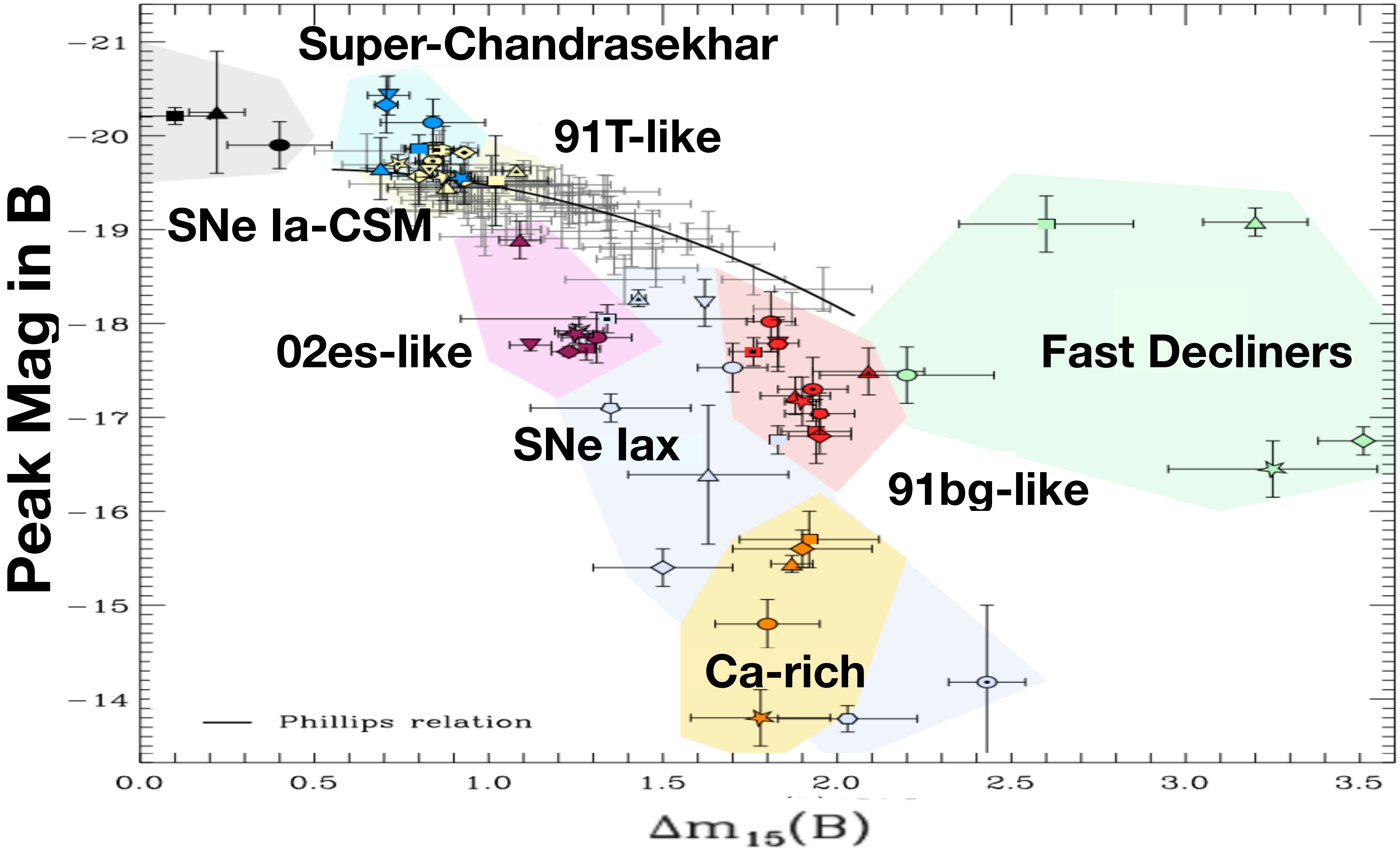
Explosion mechanism

The lack of understanding about SNe Ia progenitors and explosions could produce one of the largest systematics in cosmological experiments

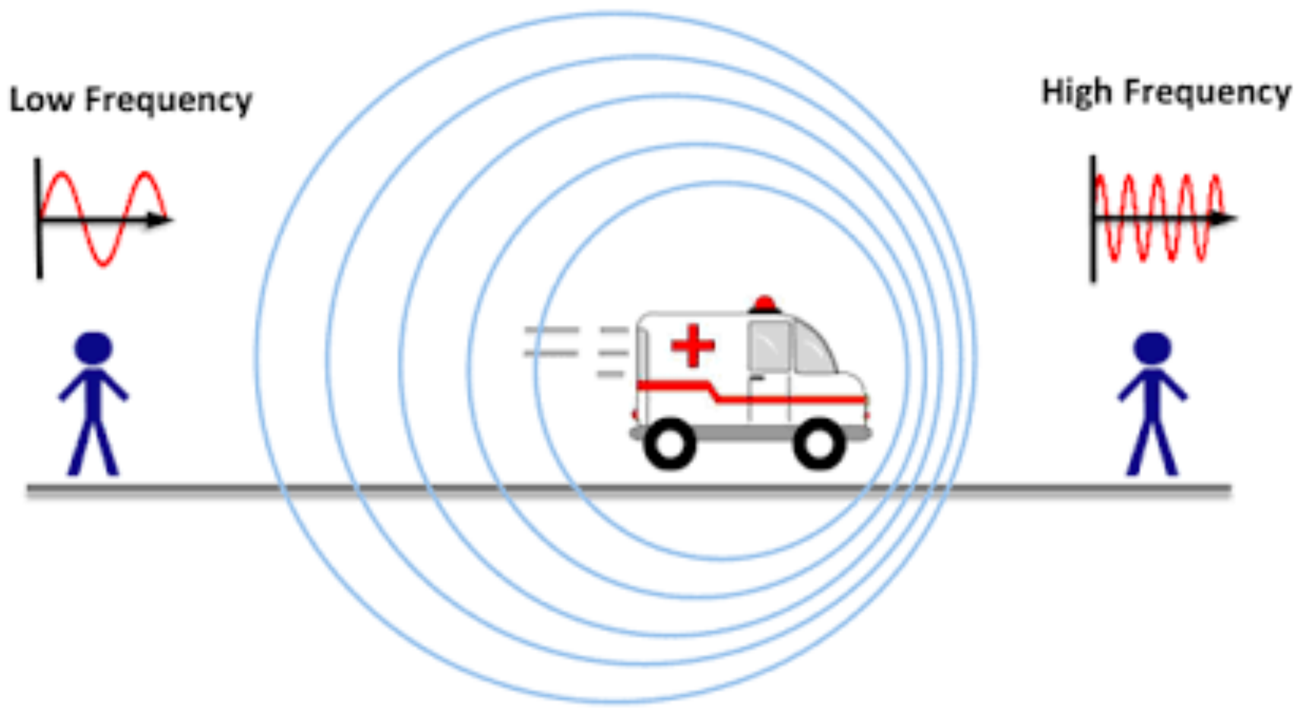
Type Ia supernovae subtypes

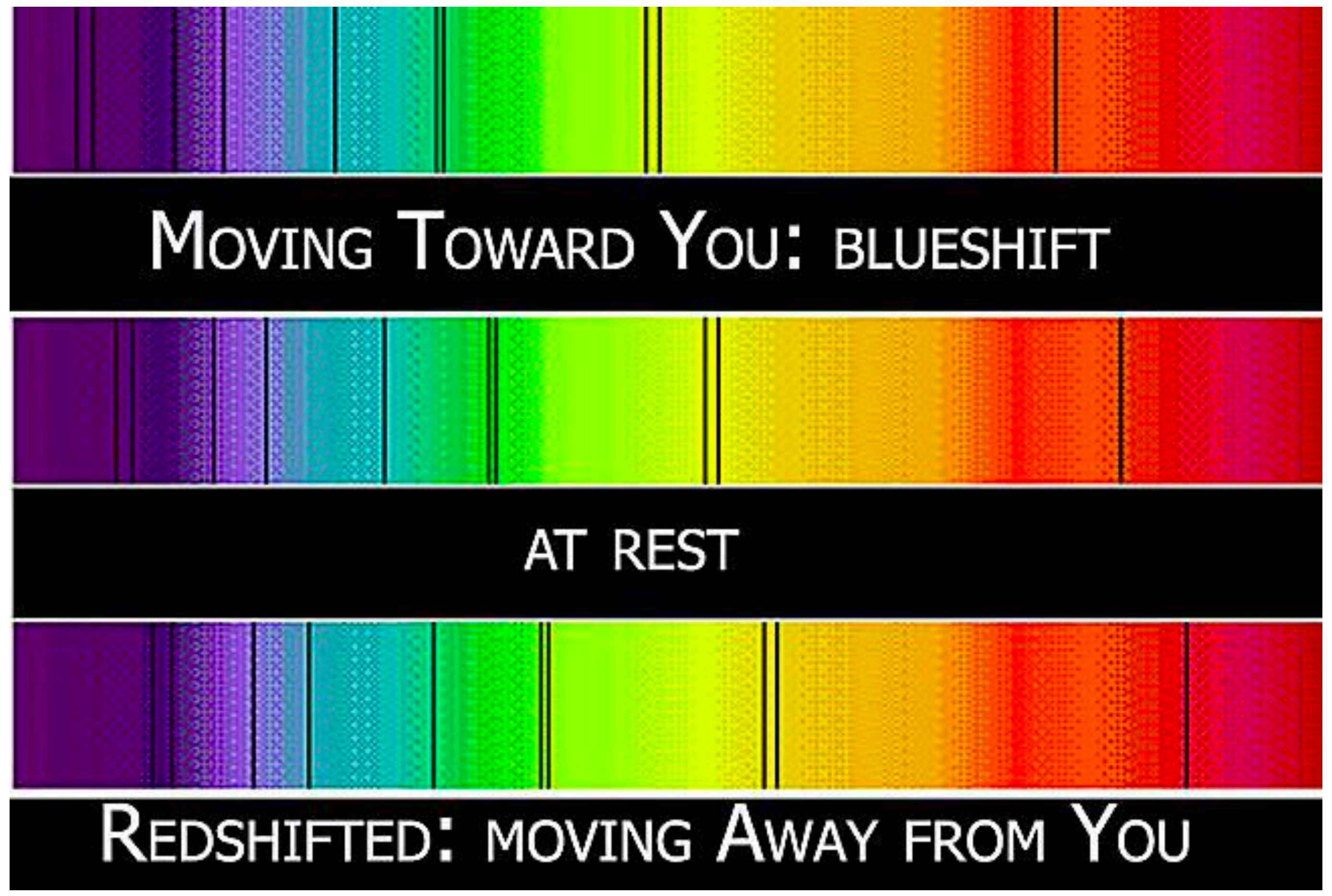


Type Ia supernovae zoo



Moving Universe - redshift

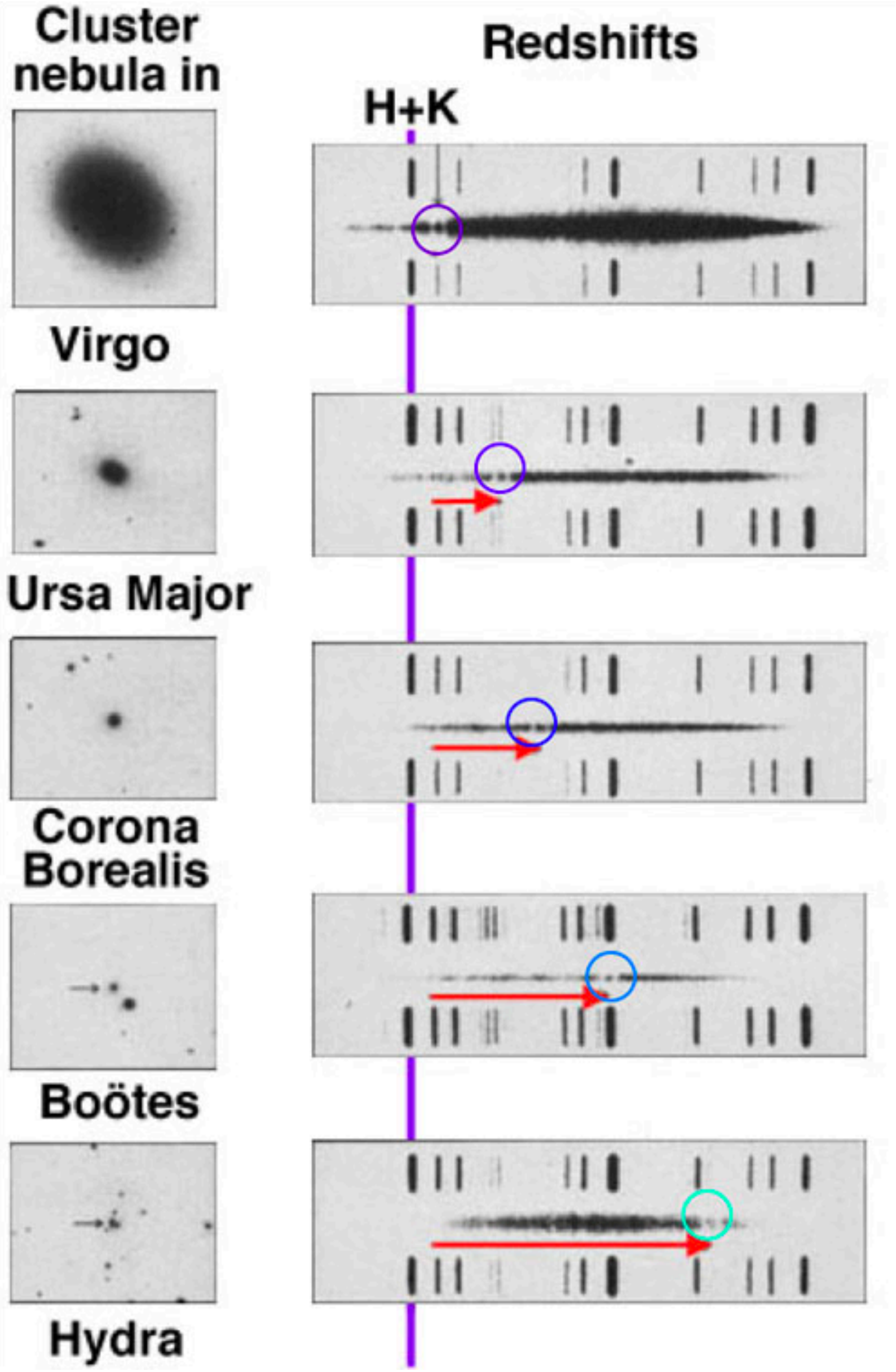




"Redshift" $$z = \frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}$$

Sounds gets low-pitched, light gets redder when emisor is moving away from observer

Moving Universe - redshift



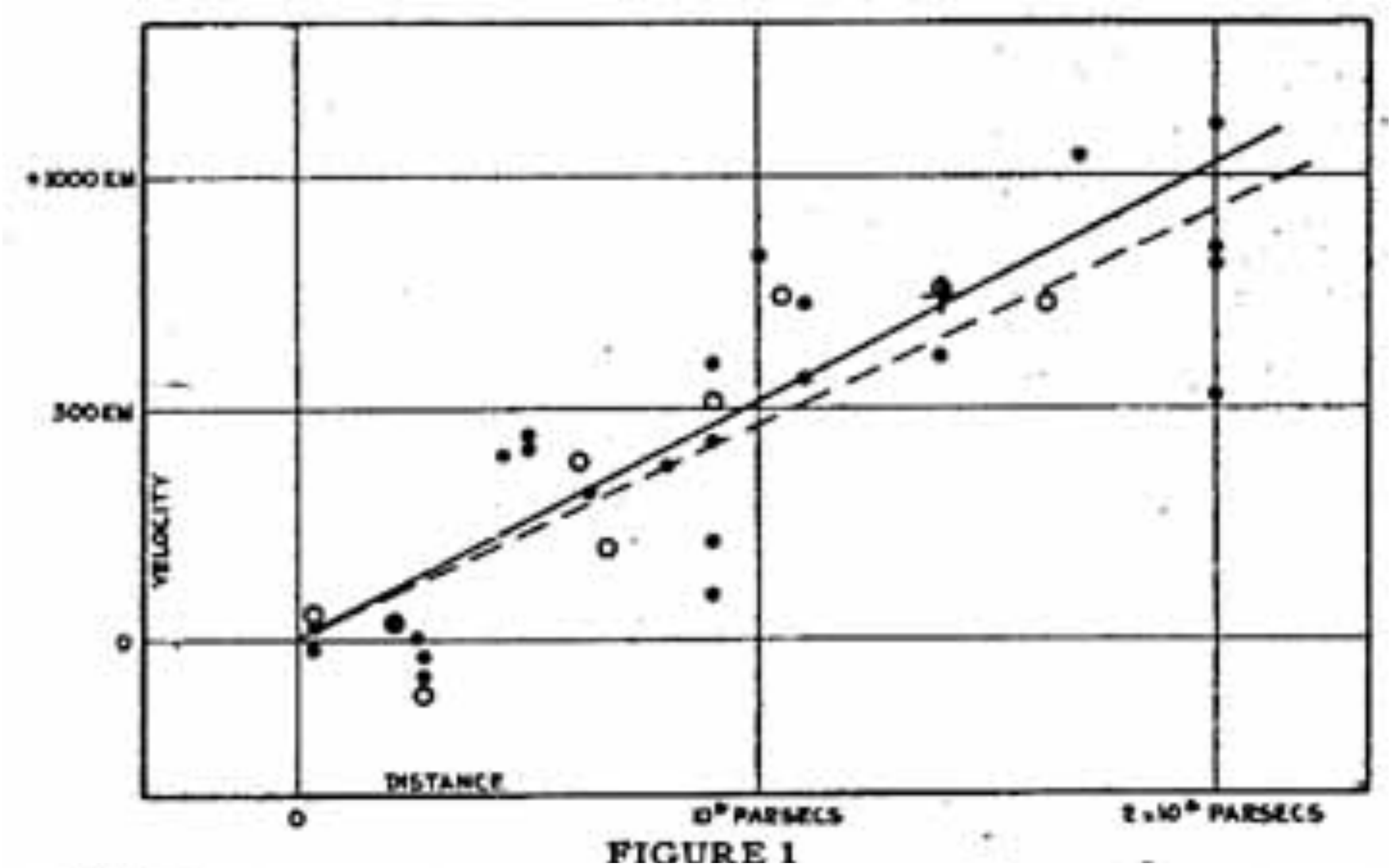
Sounds gets low-pitched, light gets redder when emisor is moving away from observer

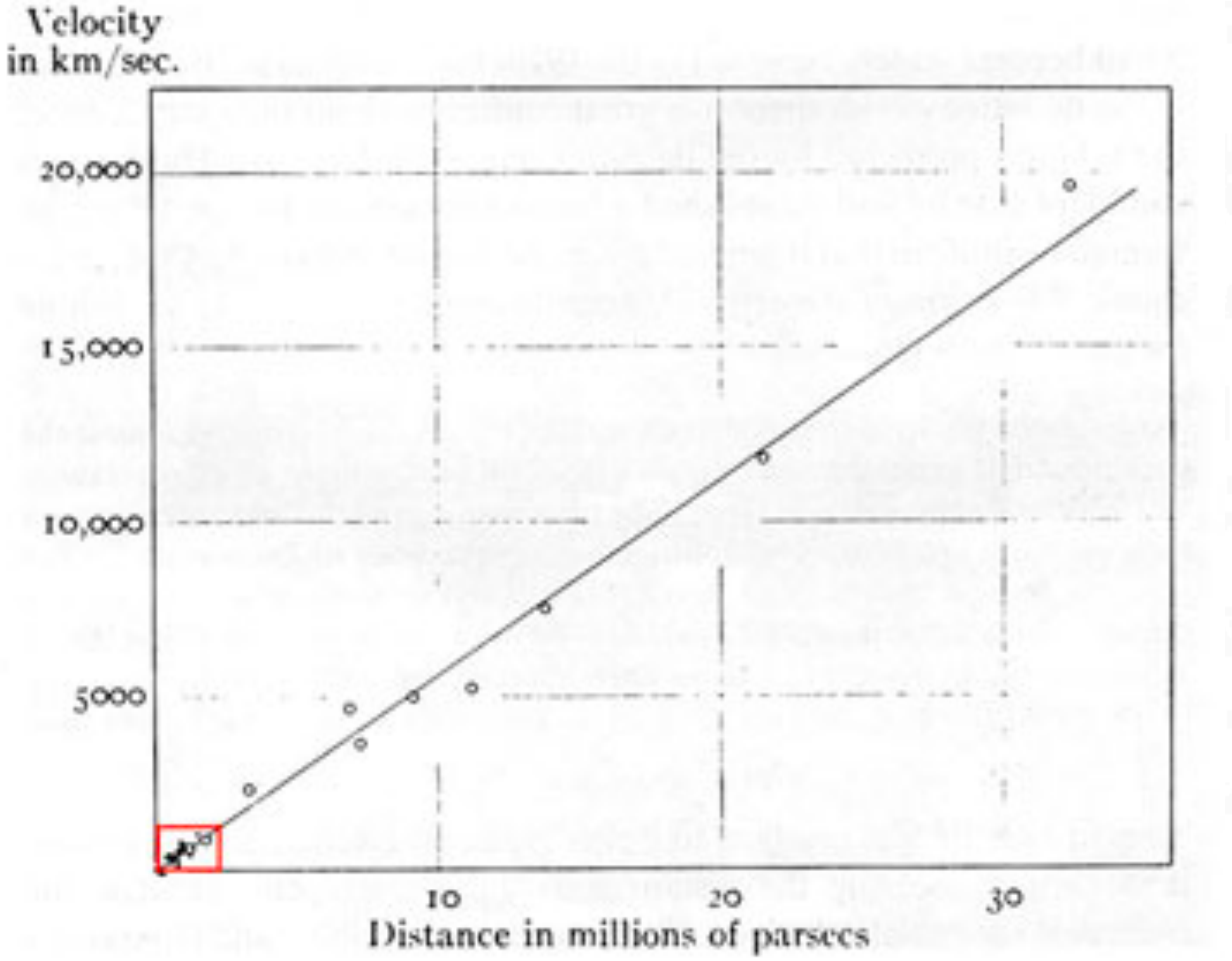
1913: Vesto Slipher found that M31 spectrum exhibits a significant shift of 300 km/sec towards the blue.

1914: Slipher presents 14 additional objects *(nebulae)* some with blue, but most with red shifted wavelengths

1927: Lemaître realises the higher the redshift, the smaller the angular size of these objects

Moving Universe - redshift





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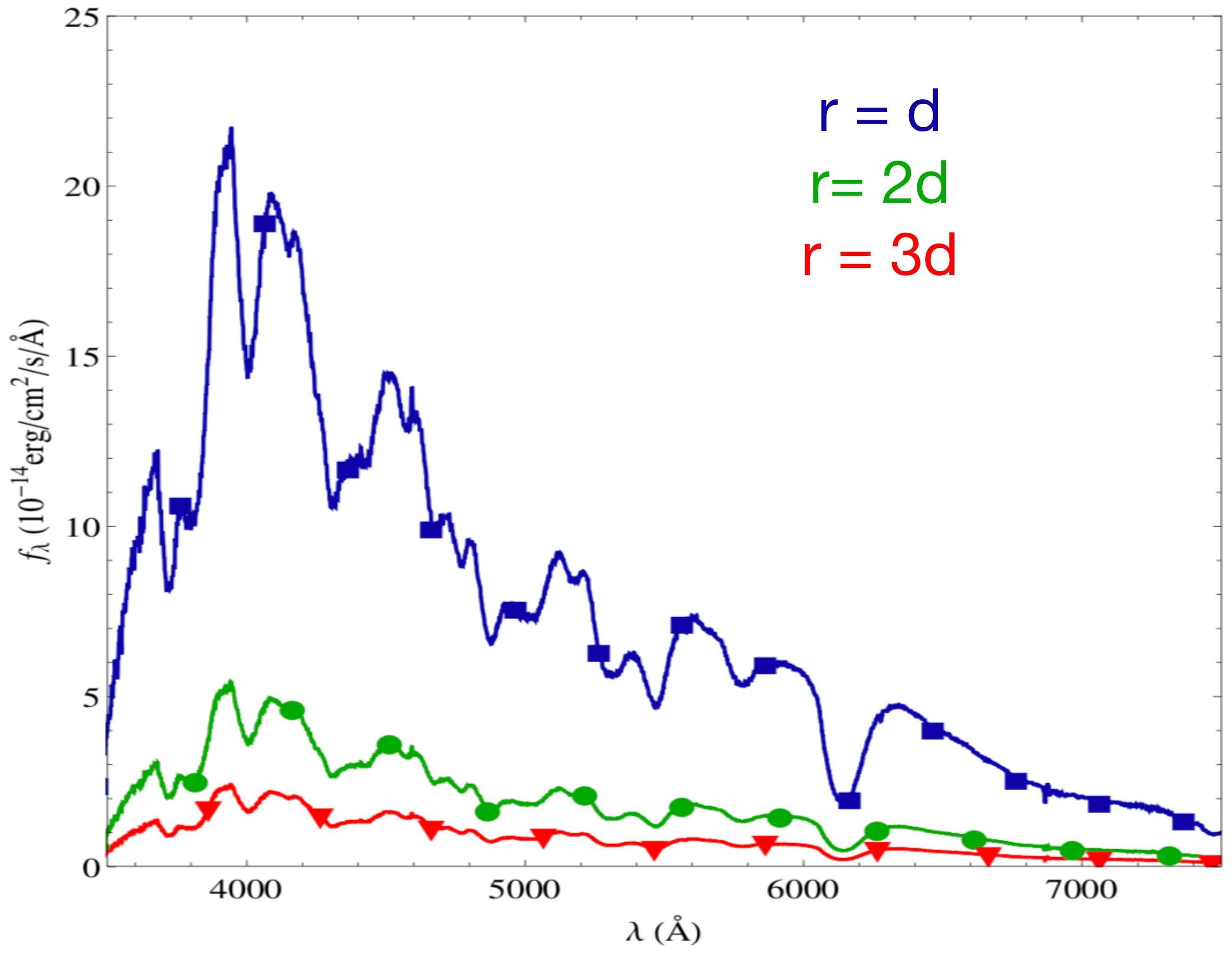
1927: Lemaître realises the higher the redshift, the smaller the angular size of these objects

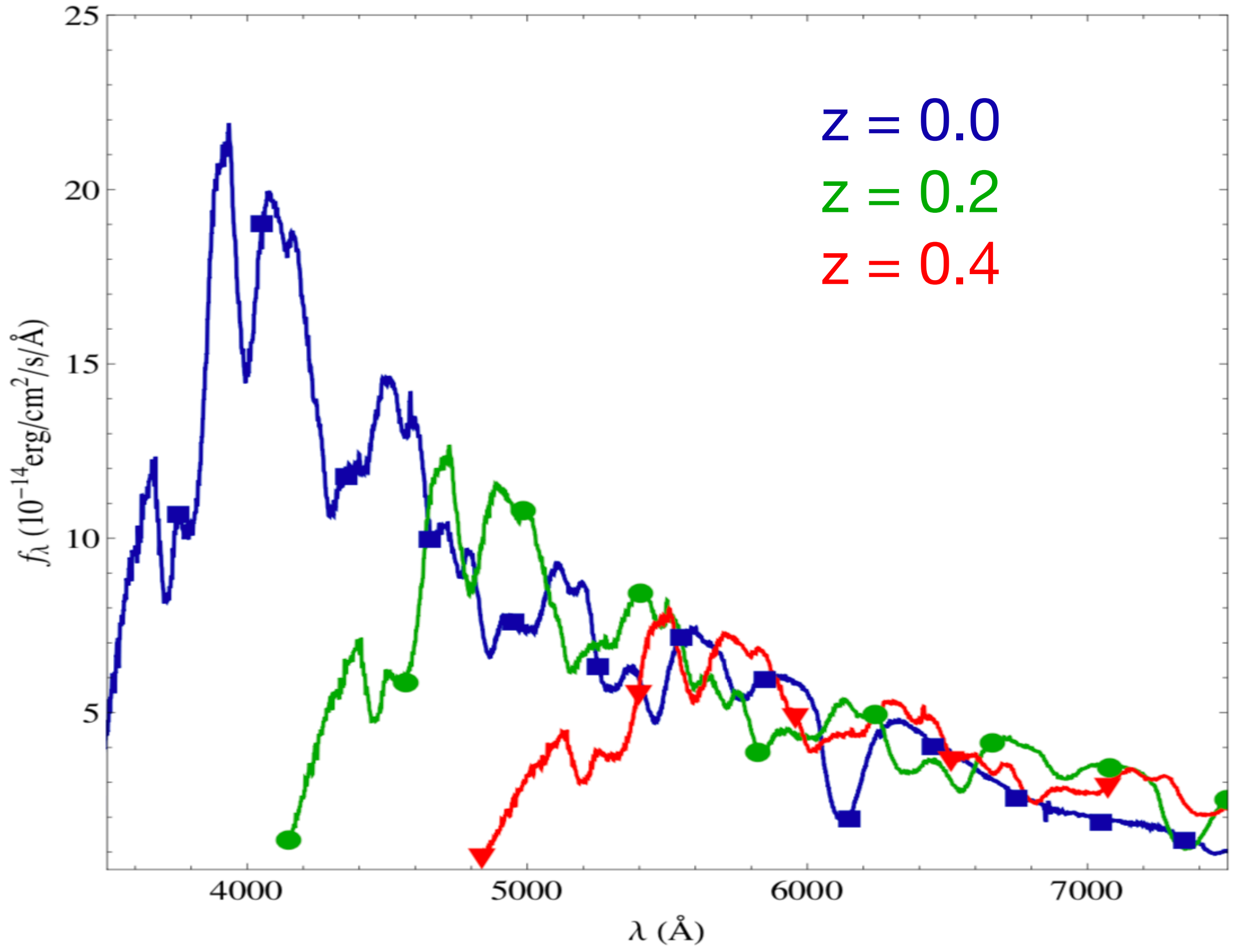
1929: Hubble presents the first diagram of velocity vs distance (using Leavitt P-L relation of Cepheids)

Founds a proportionality relation: Hubble constant (H_0)

Redshift & K-correction

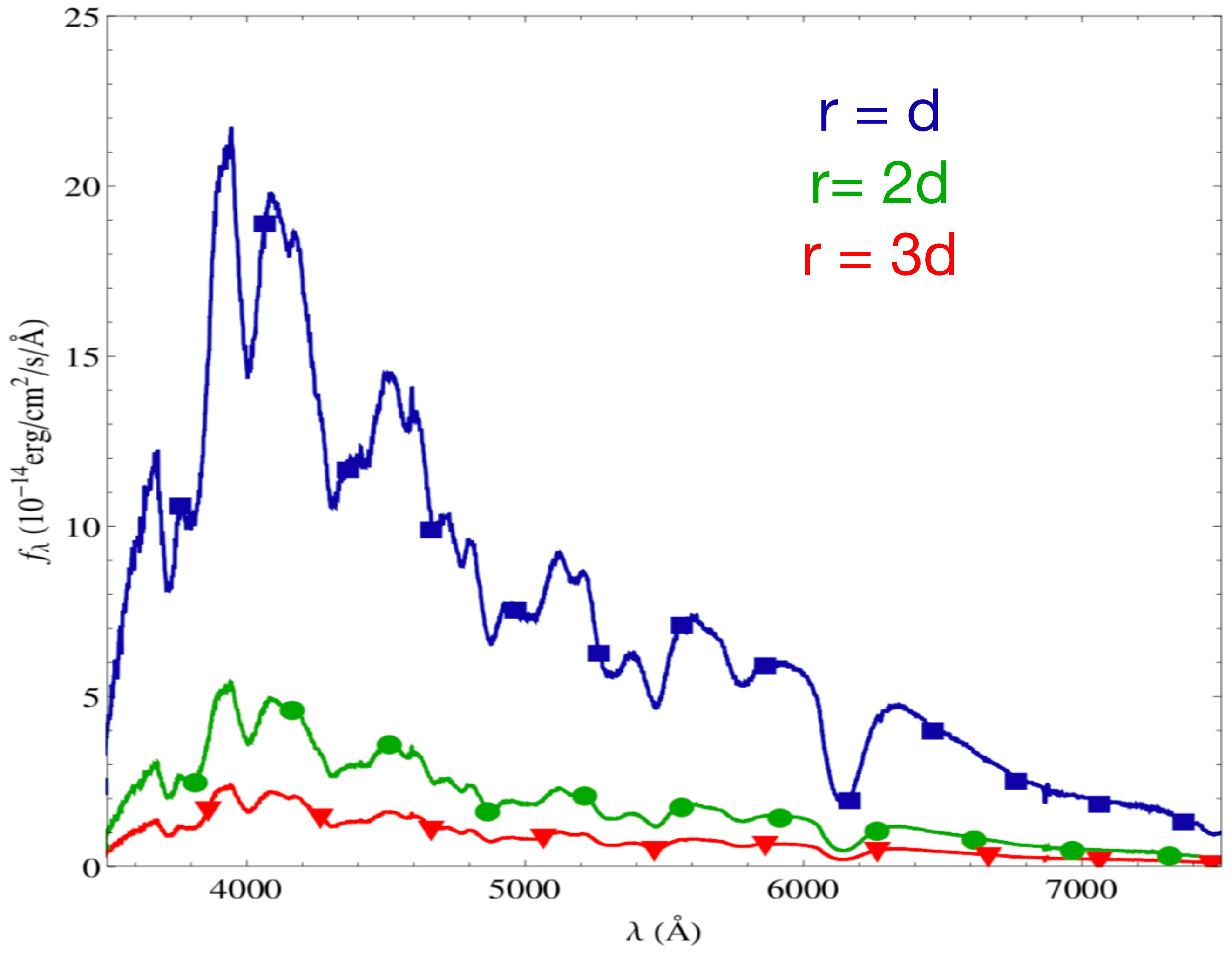
coelho+2014

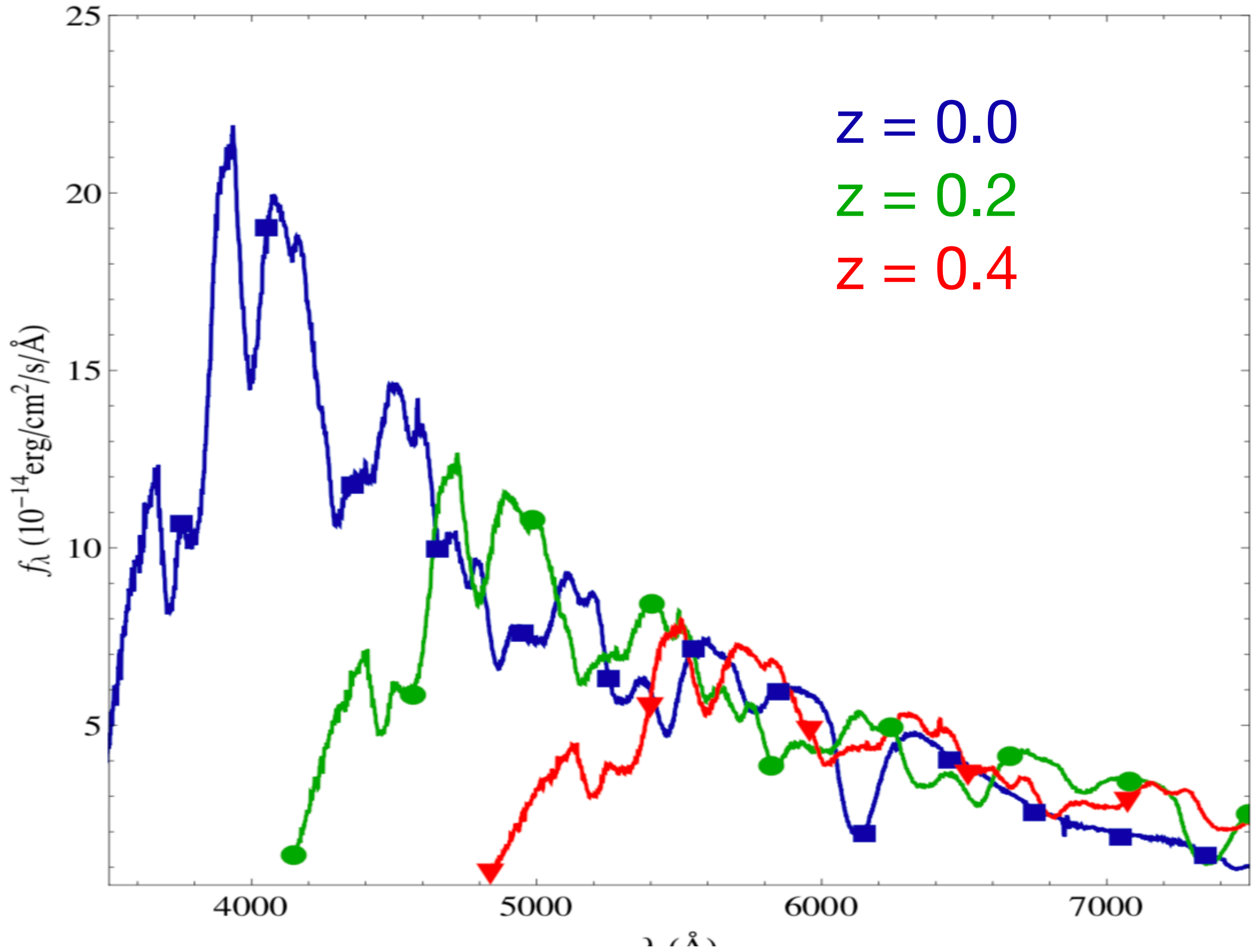




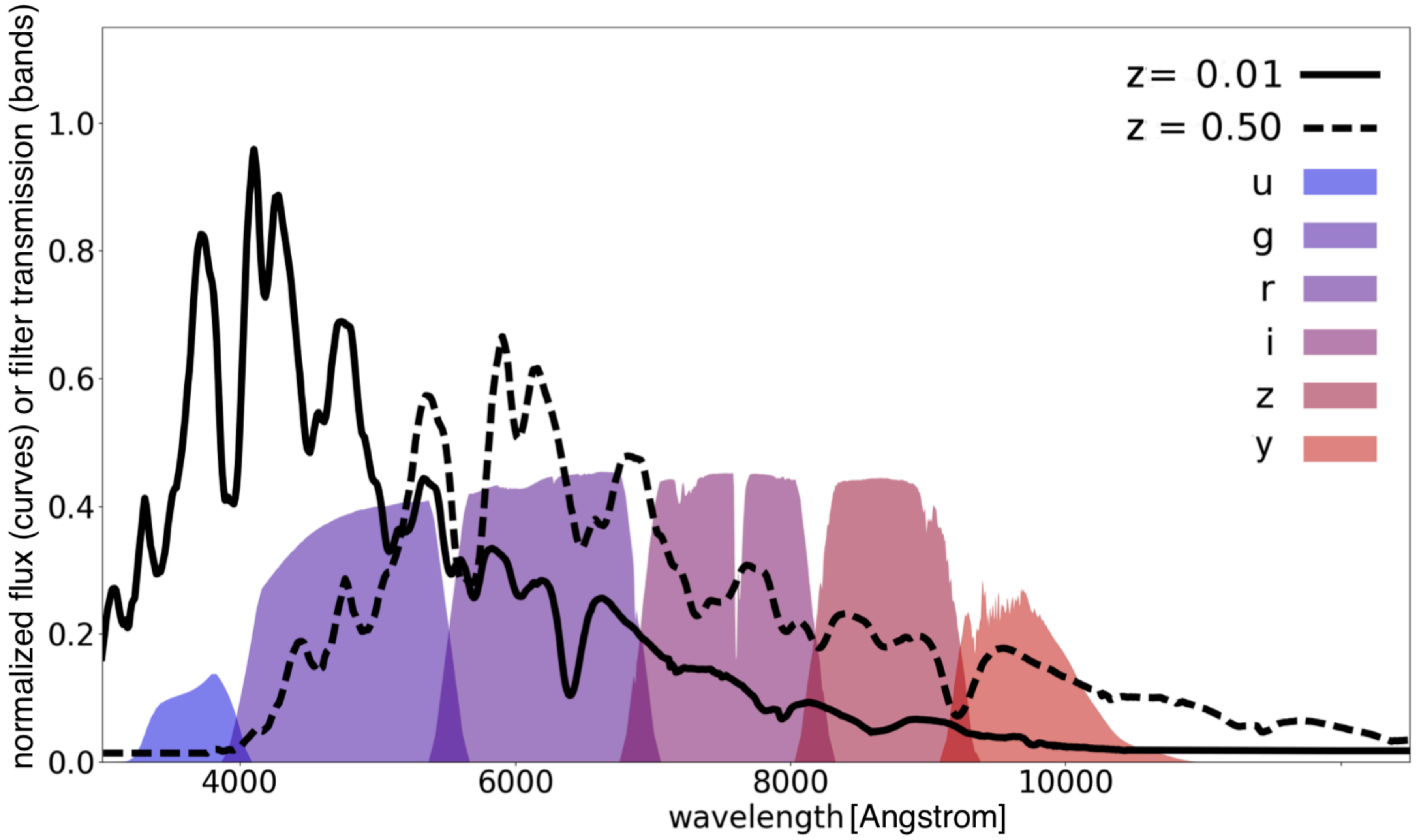
Redshift & K-correction

coelho+2014



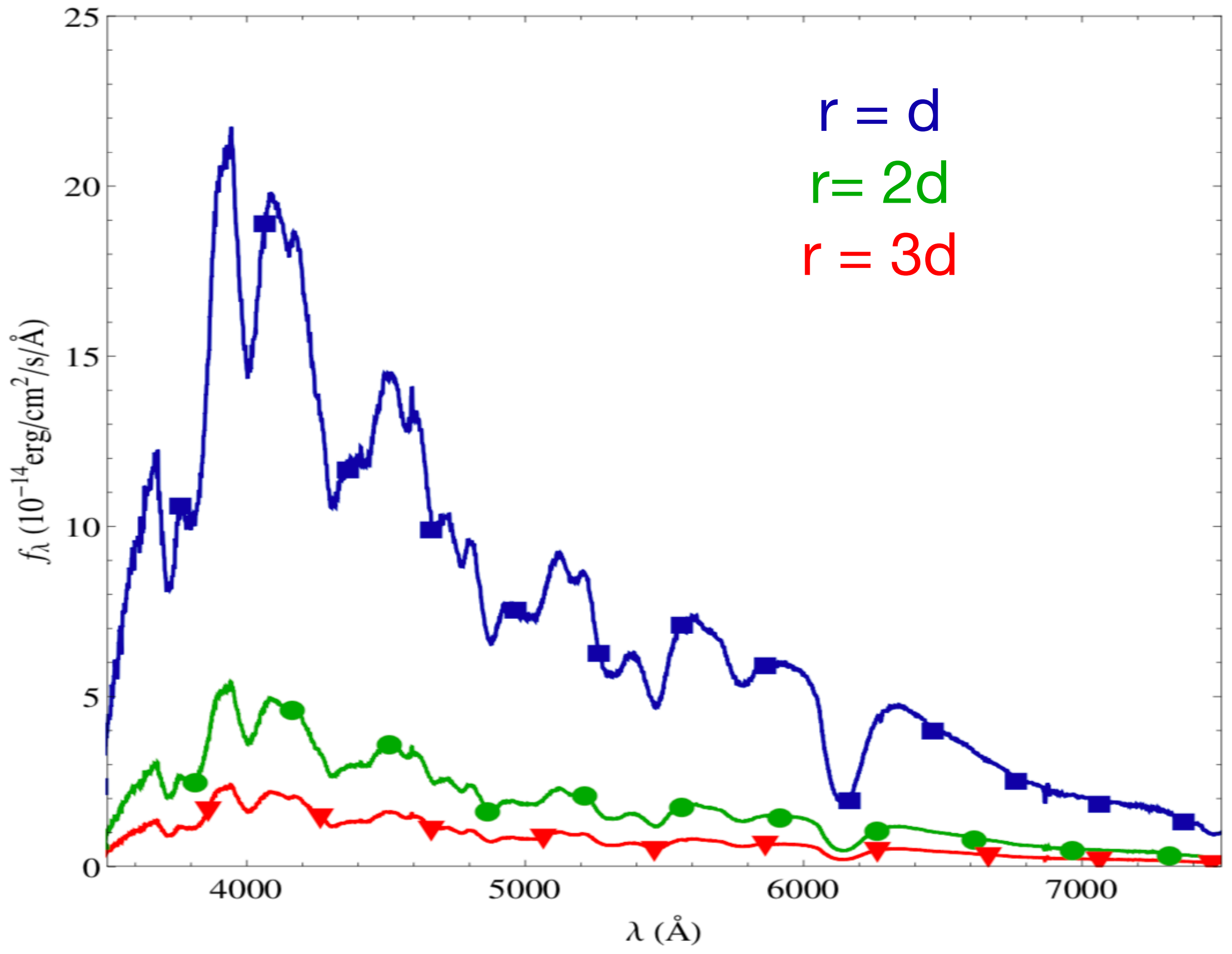


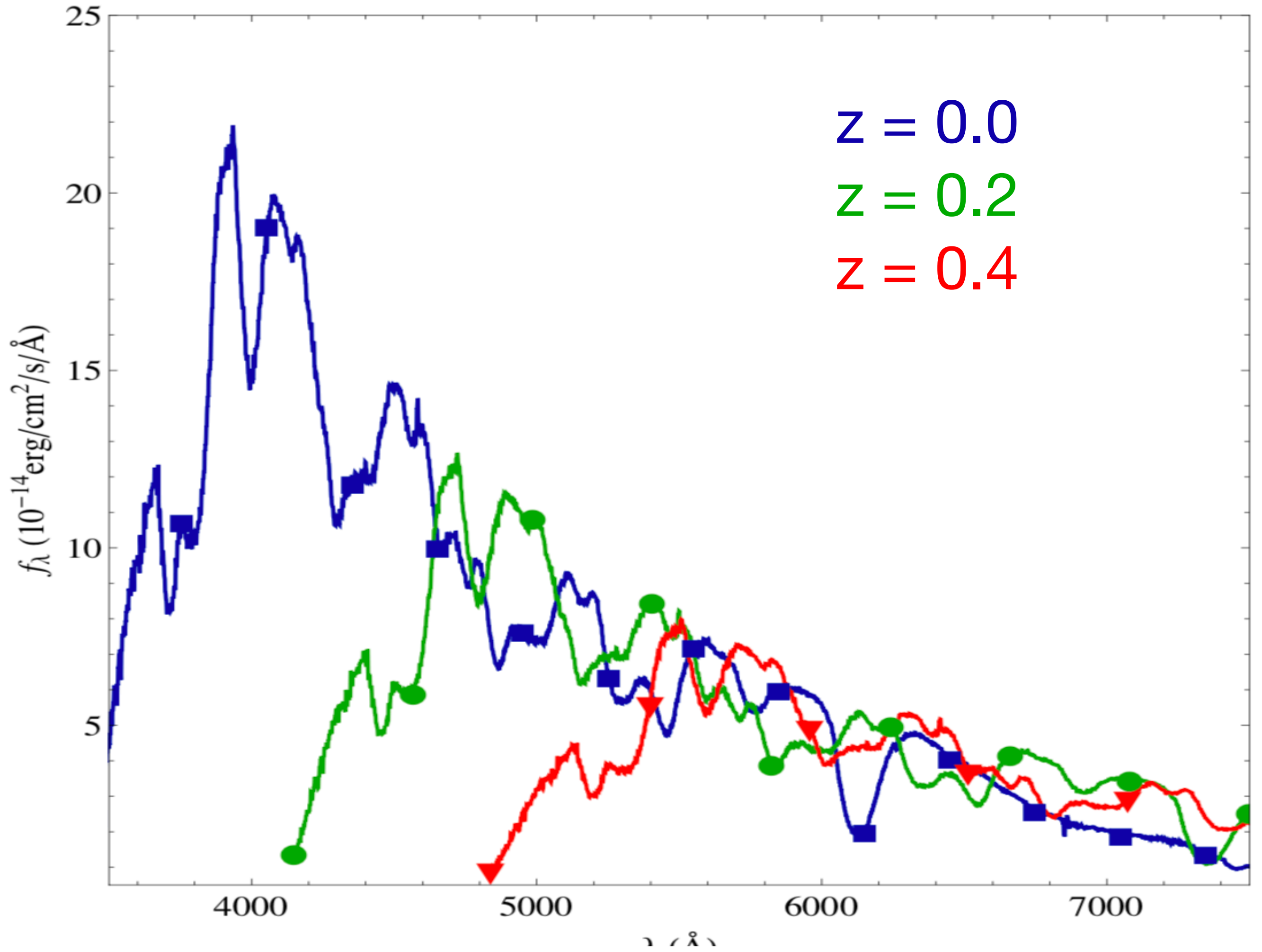
Plasticc18

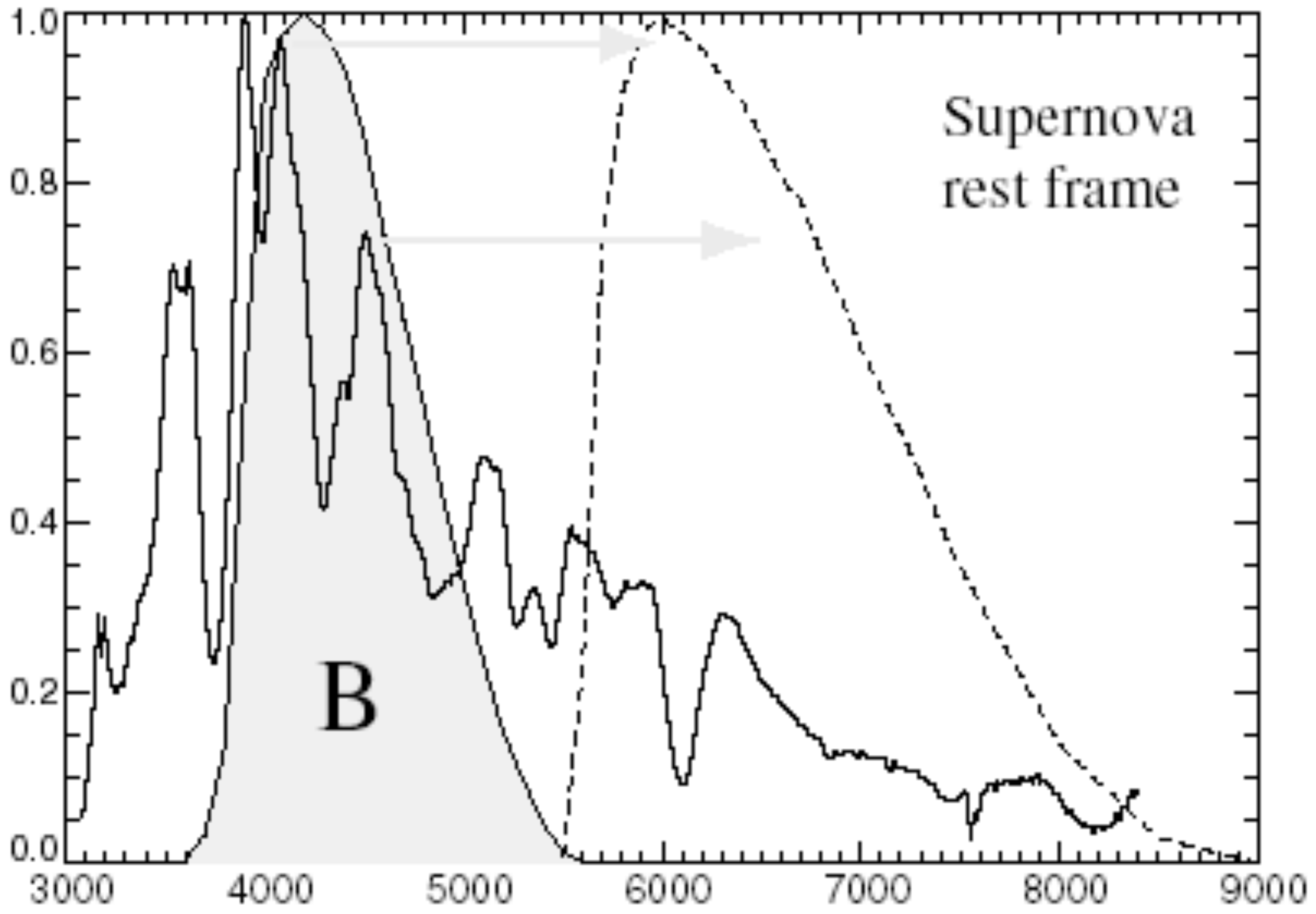


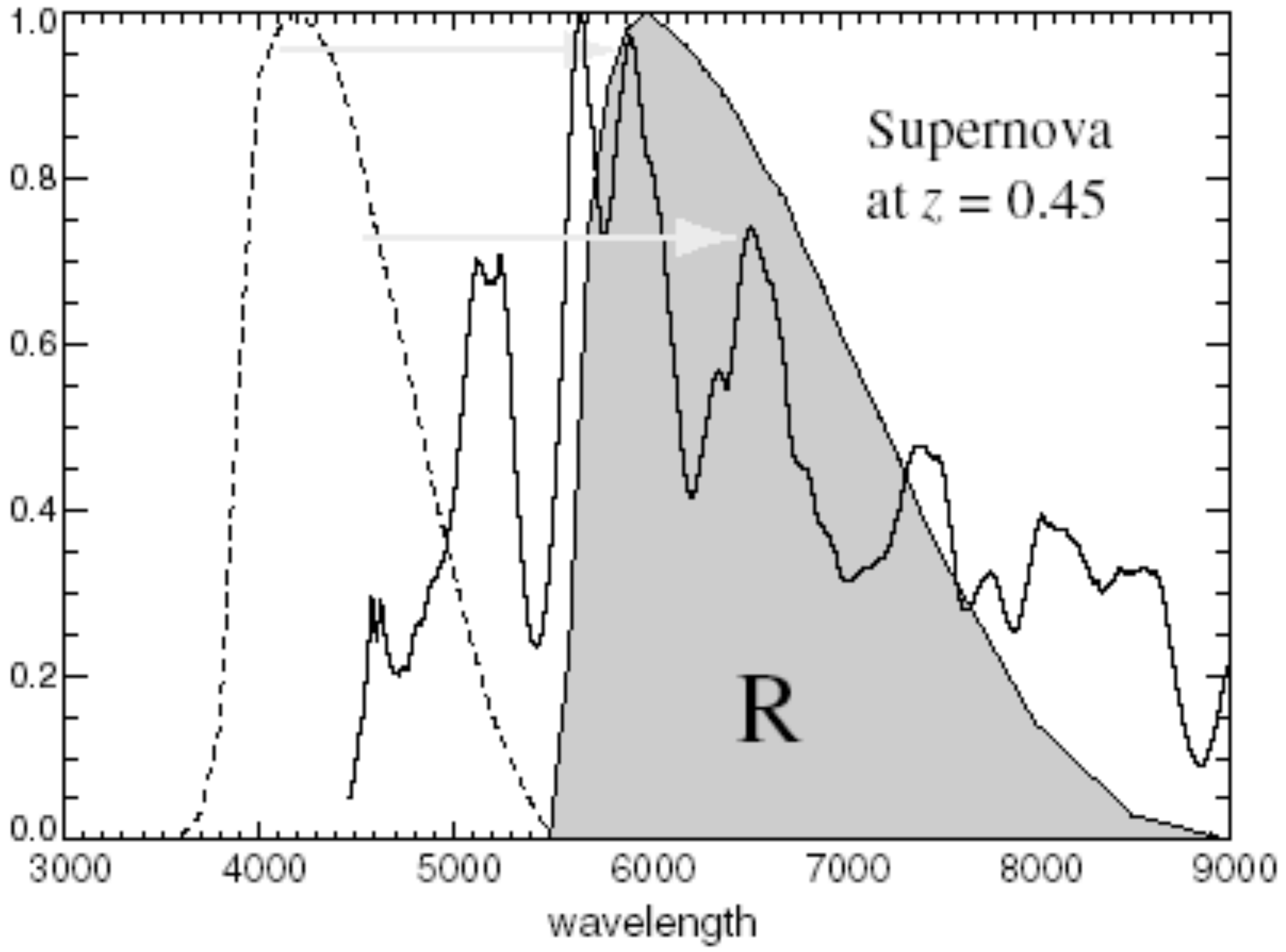
Redshift & K-correction

coelho+2014









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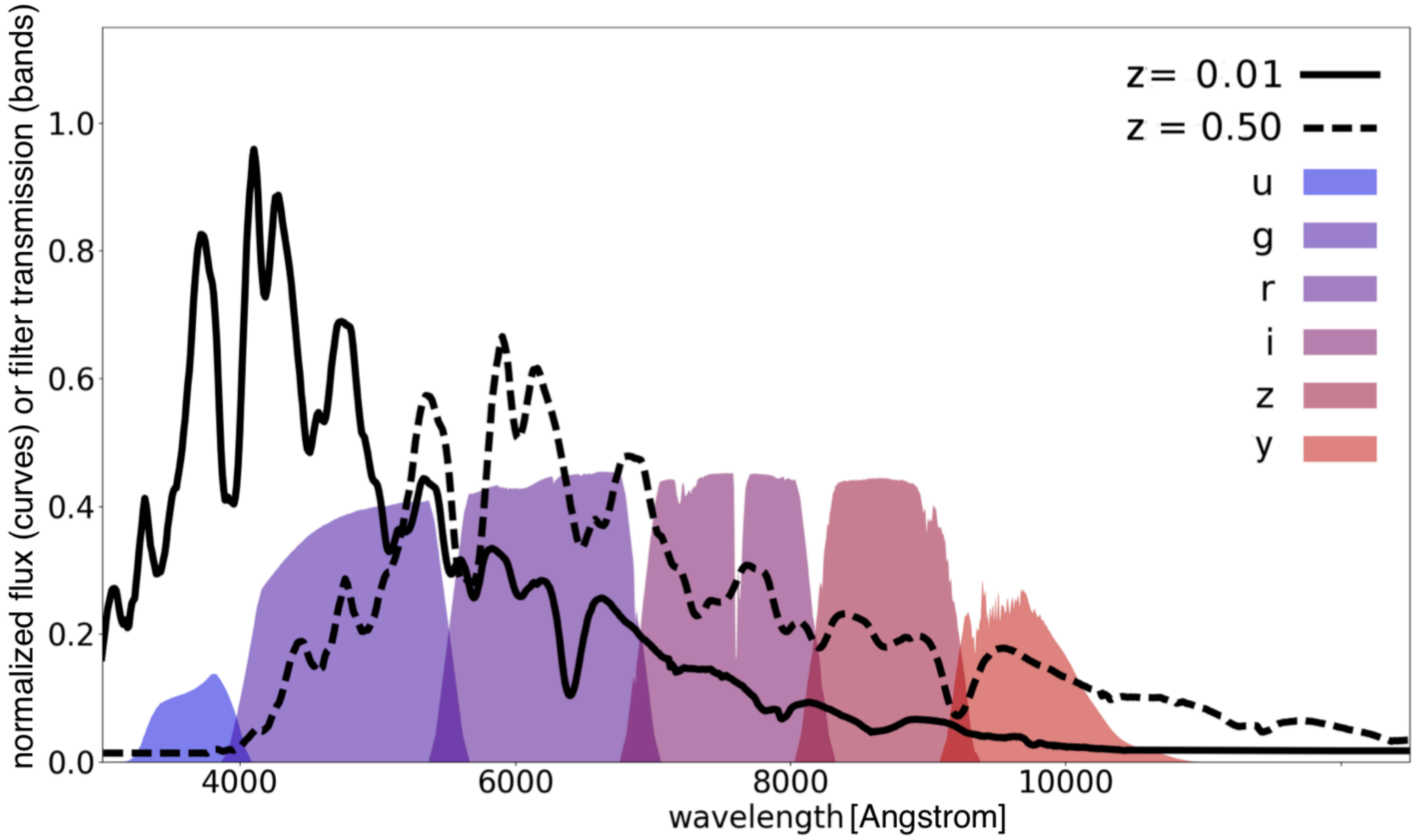
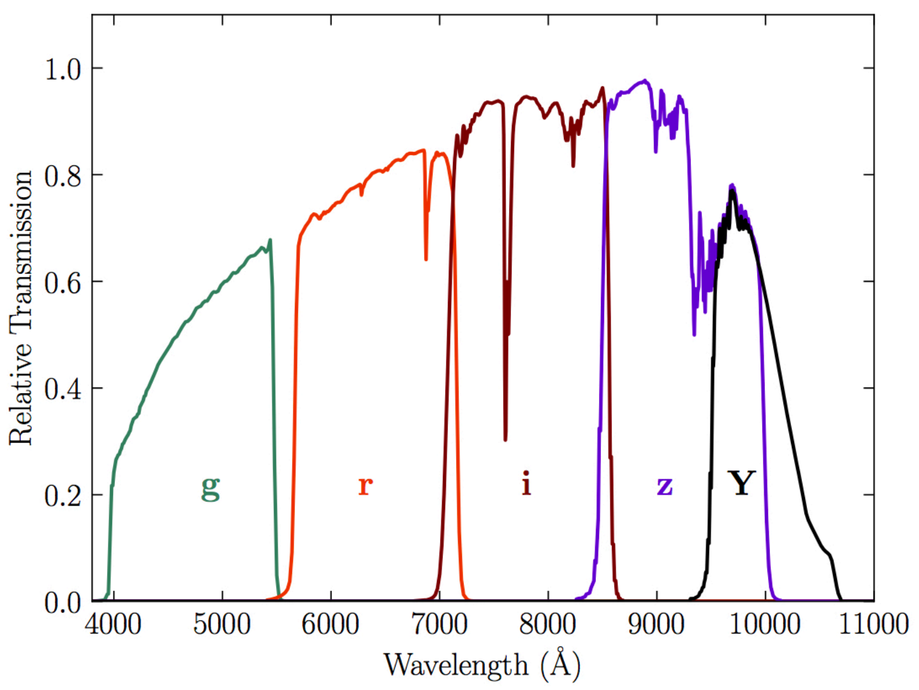
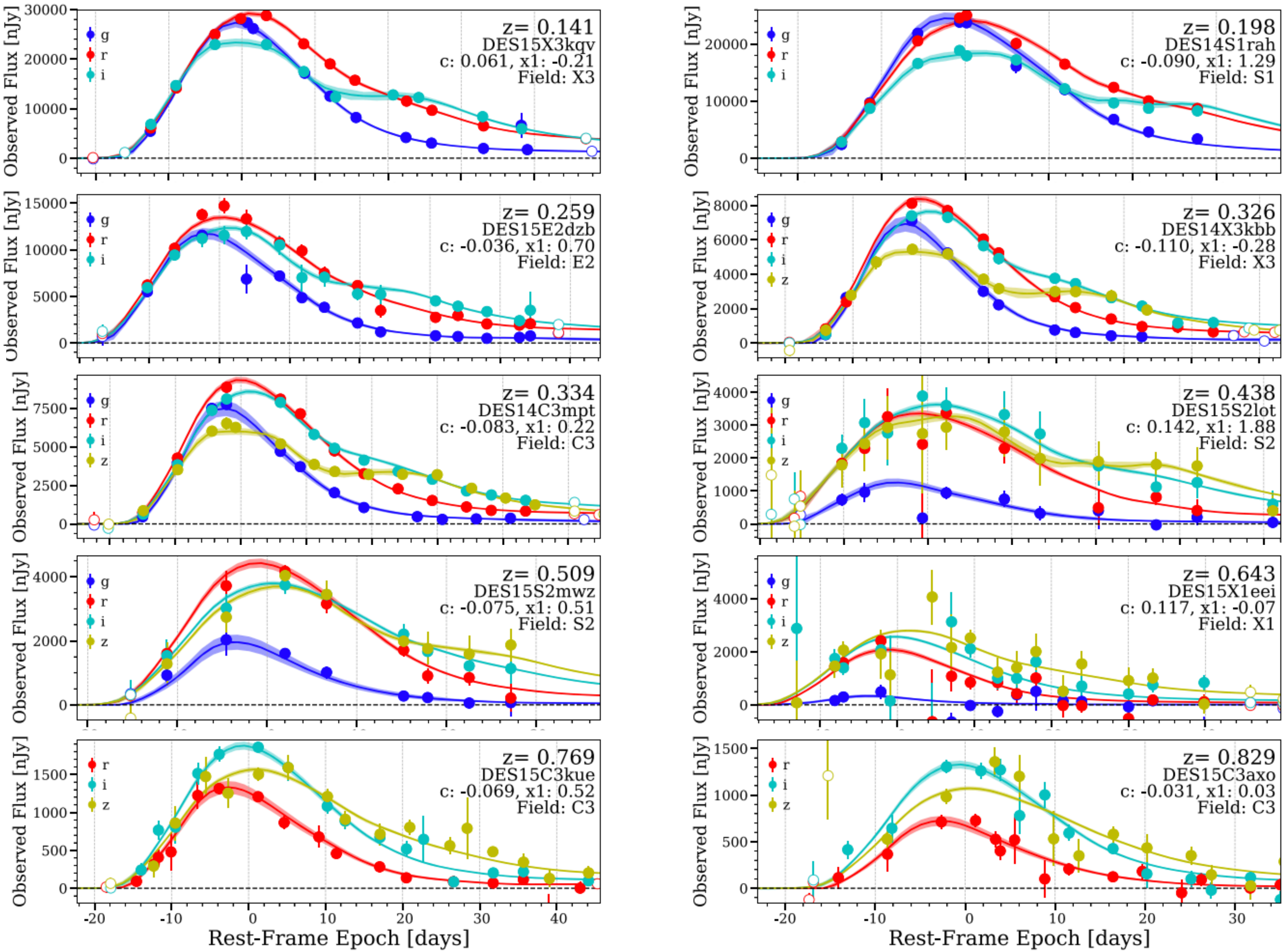




Relative Transmission
g
r
i
z
Y
Wavelength (Å)



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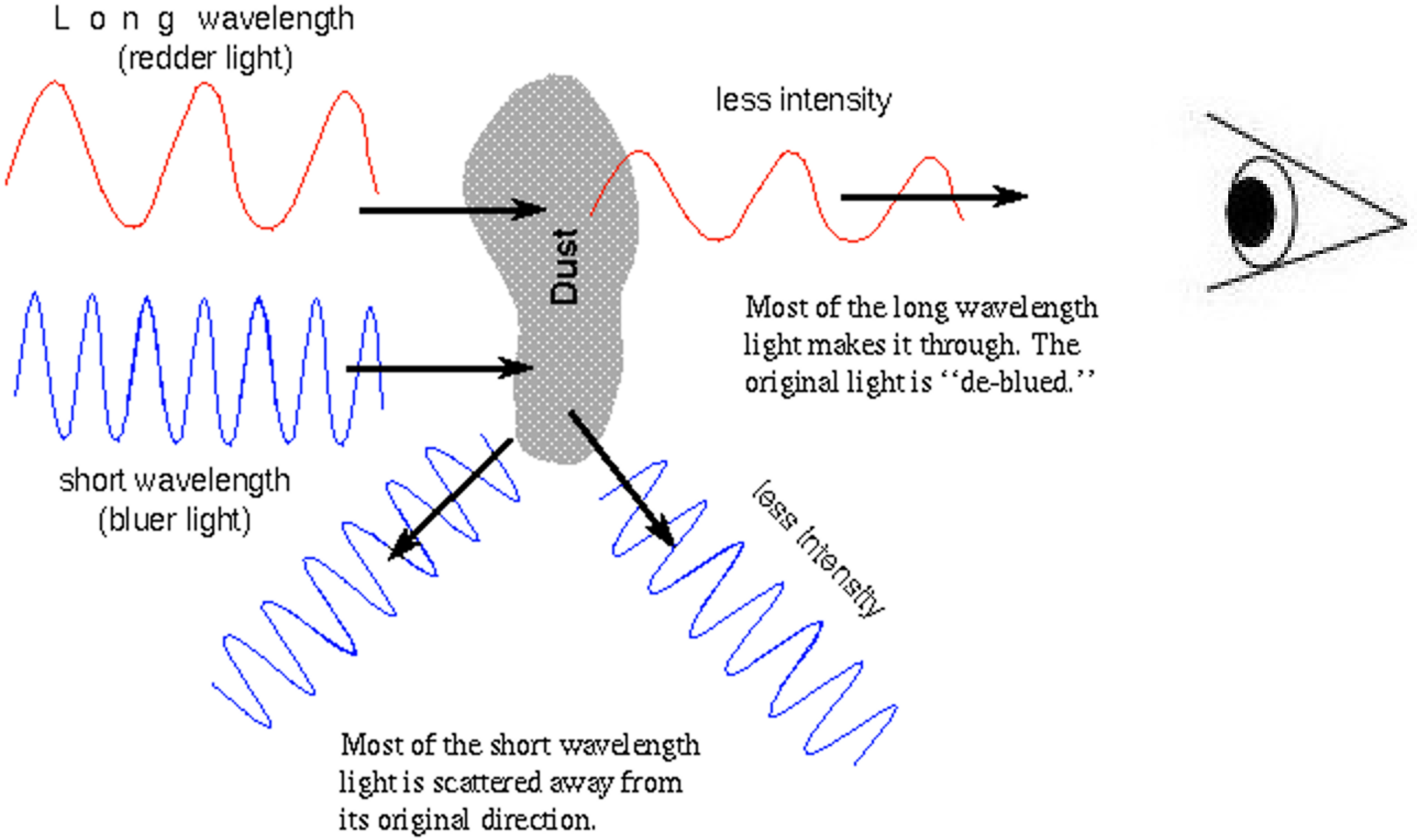
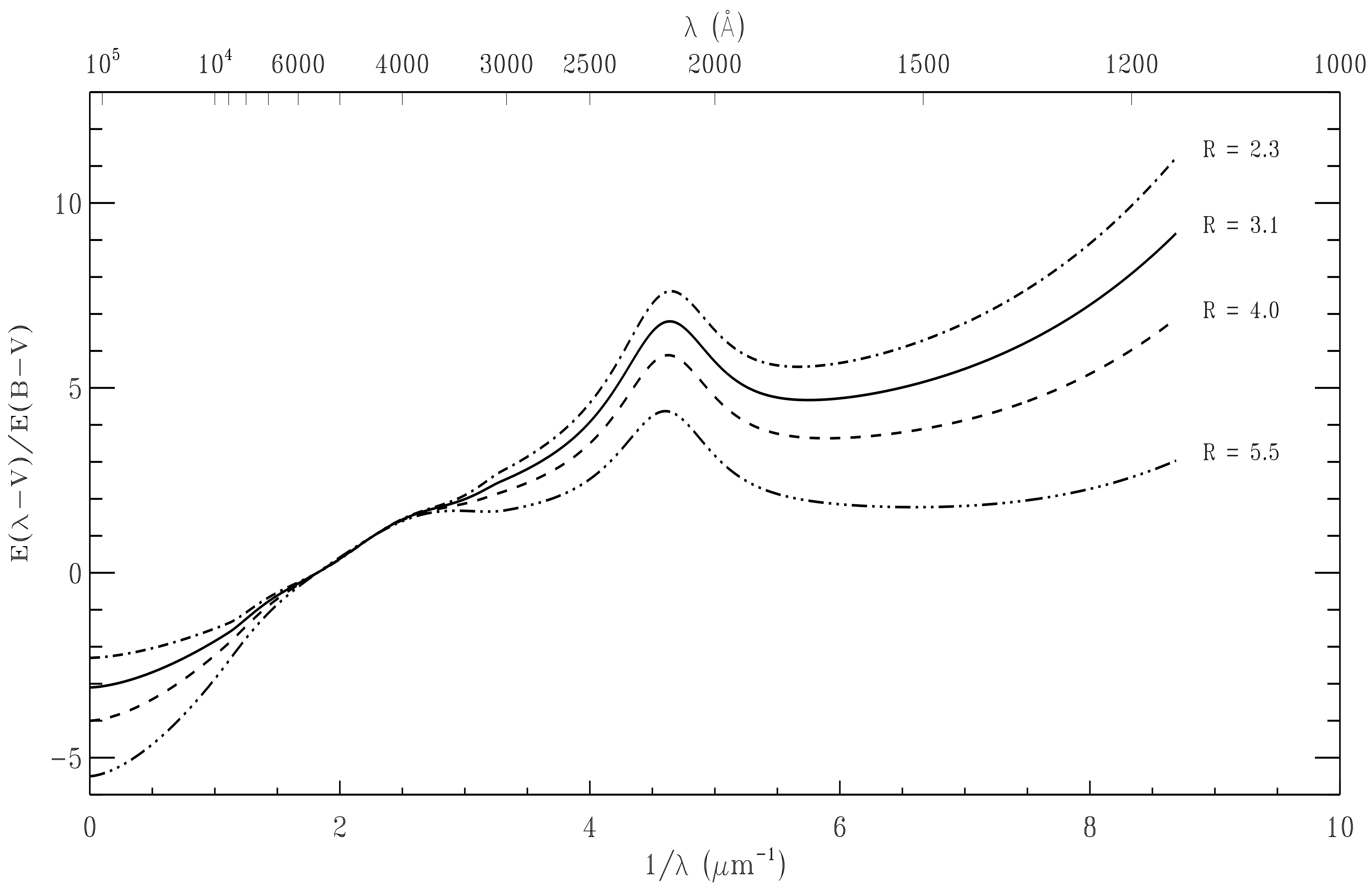
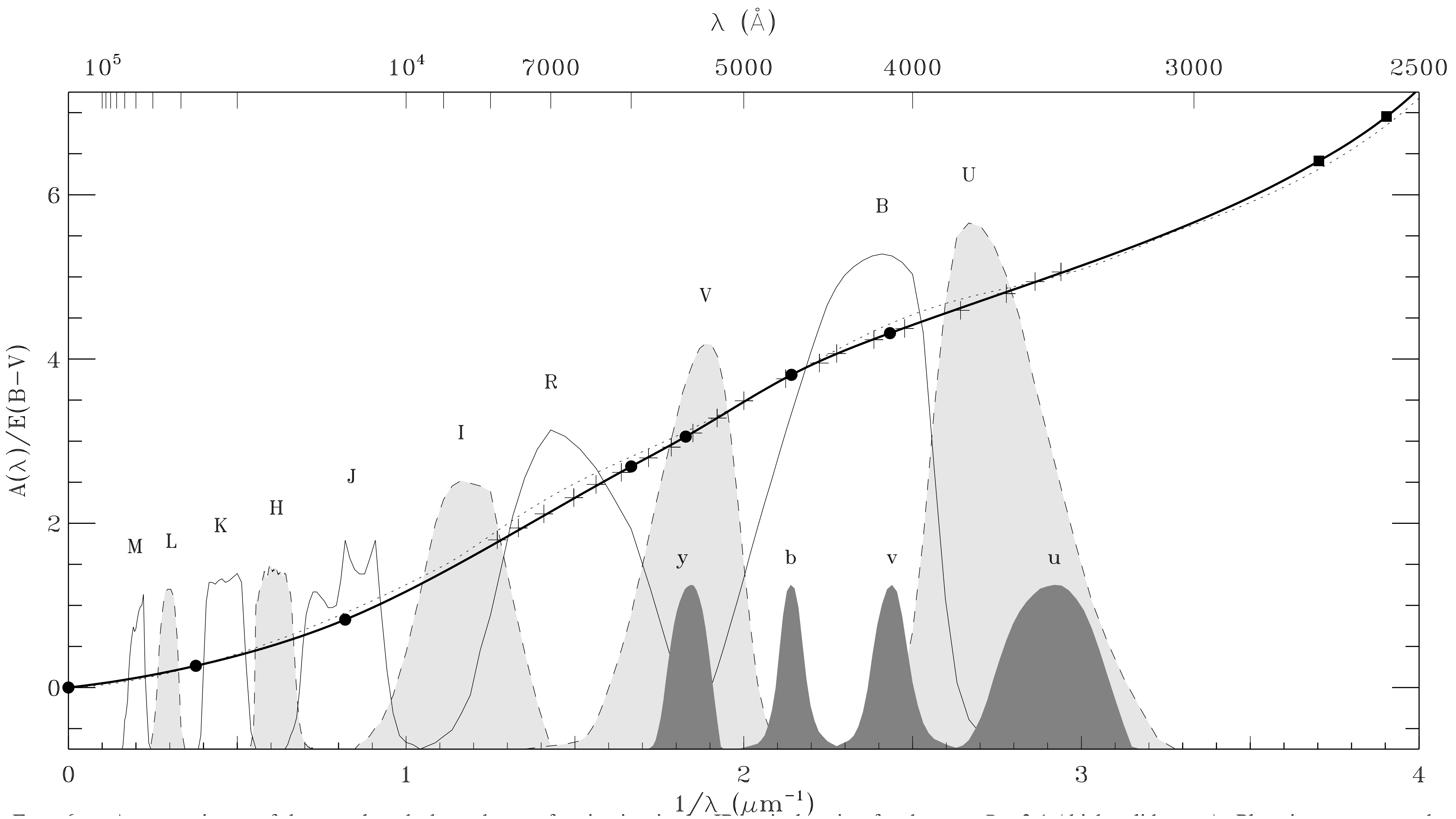
DES15X3kqv
c: 0.061, x1: -0.21
Field: X3
z= 0.198
DES14S1rah
c: -0.090, x1: 1.29
Field: S1
z= 0.259
DES15E2dzb
c: -0.036, x1: 0.70
Field: E2
z= 0.326
DES14X3kbb
c: -0.110, x1: -0.28
Field: X3
z= 0.334
DES14C3mpt
c: -0.083, x1: 0.22
Field: C3
z= 0.438
DES15S2lot
c: 0.142, x1: 1.88
Field: S2
z= 0.509
DES15S2mwz
c: -0.075, x1: 0.51
Field: S2
z= 0.643
DES15X1eei
c: 0.117, x1: -0.07
Field: X1
z= 0.769
DES15C3kue
c: -0.069, x1: 0.52
Field: C3
z= 0.829
DES15C3axo
c: -0.031, x1: 0.03
Field: C3
Observed Flux [nJy]
Rest-Frame Epoch [days]

Reddening and extinction



Extinction/reddening law





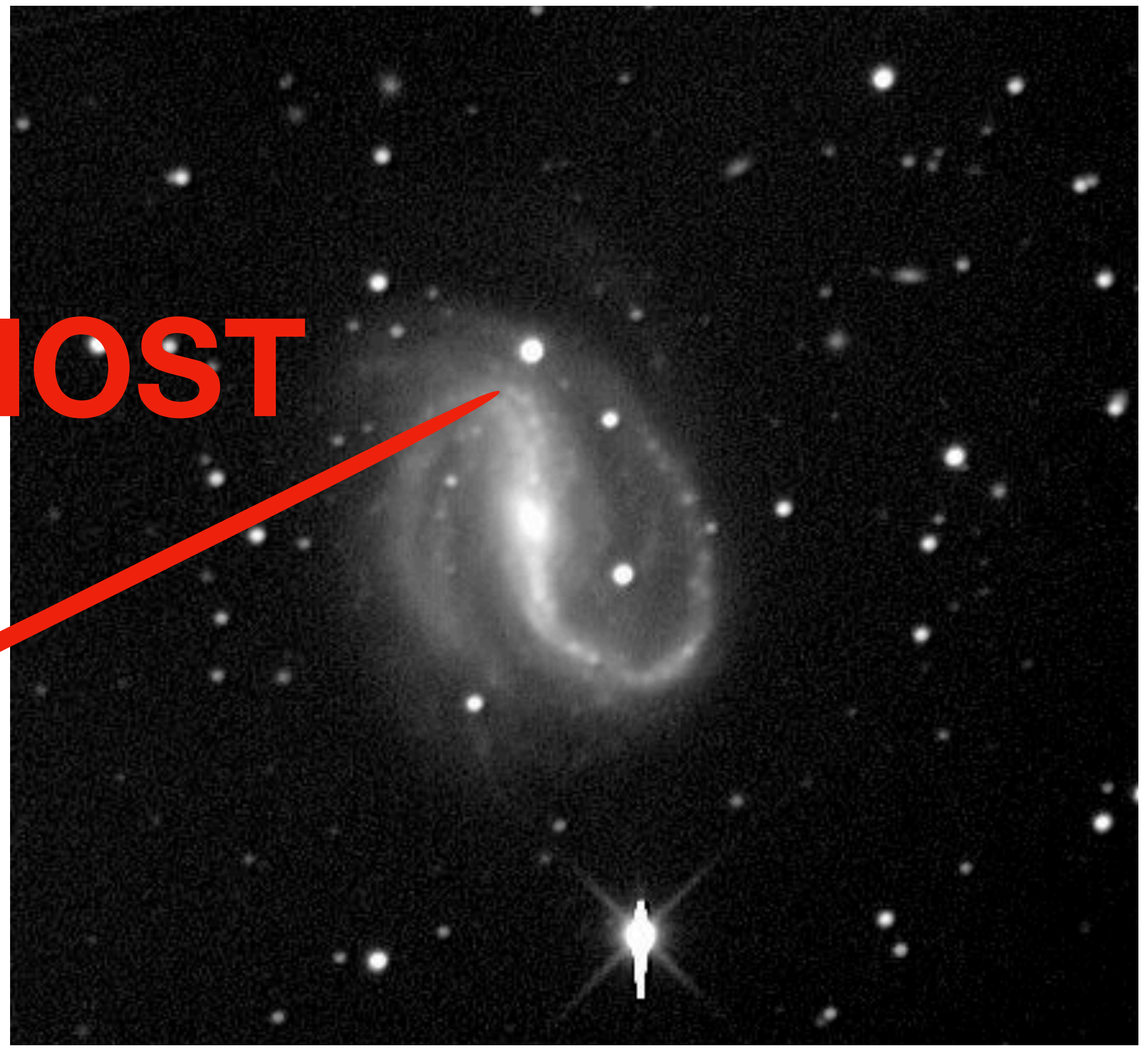
$$\boxed{R \equiv A(V)/E(B-V)}$$

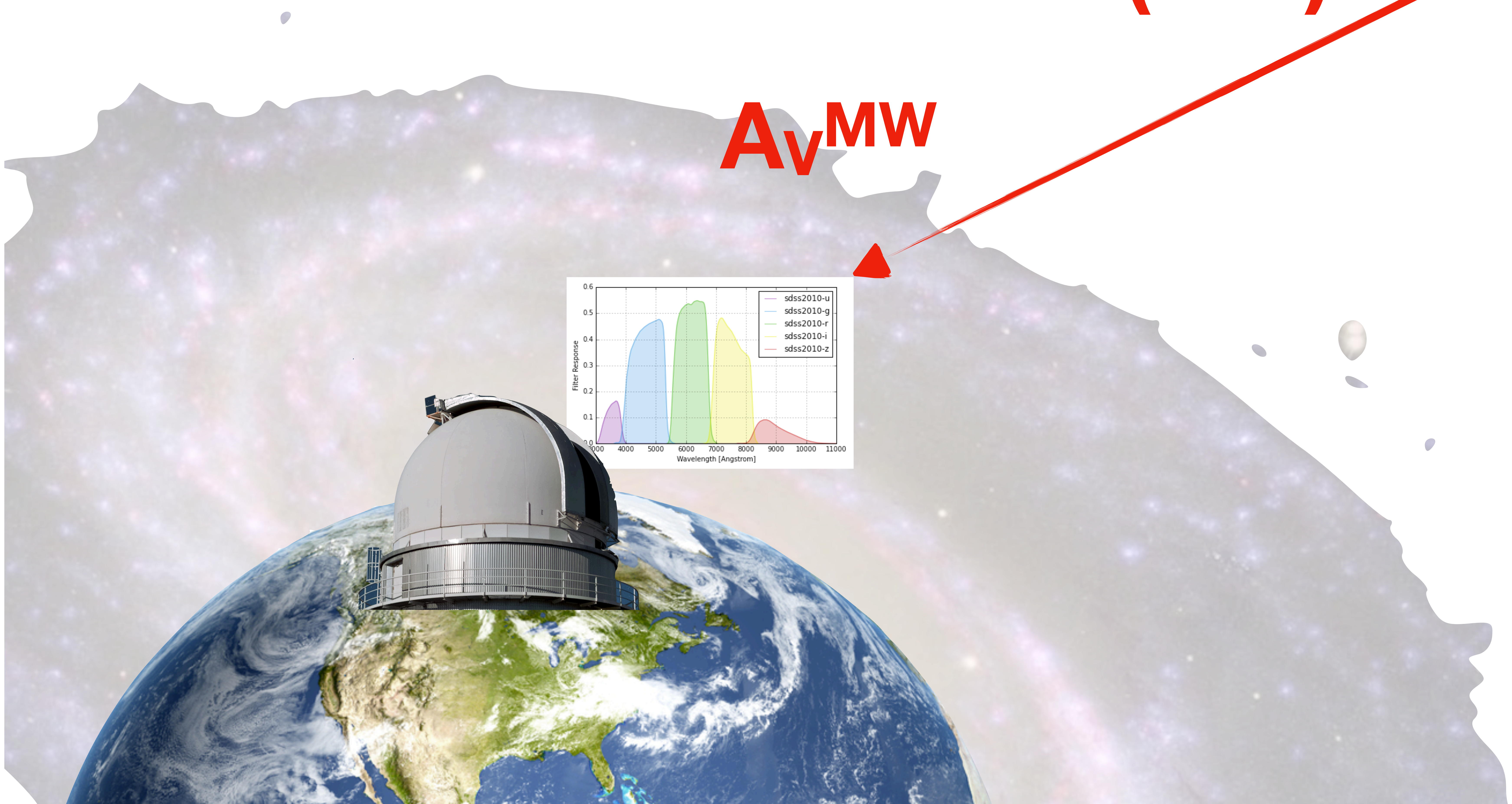
Several parametrizations:
Cardelli & O'Donnell (CCM), Fitzpatrick, etc.

In the MW the average CCM measured from our position to other stars is
R=3.1 (2.5-5.5)
This value is generally assumed for other environments and galaxies.

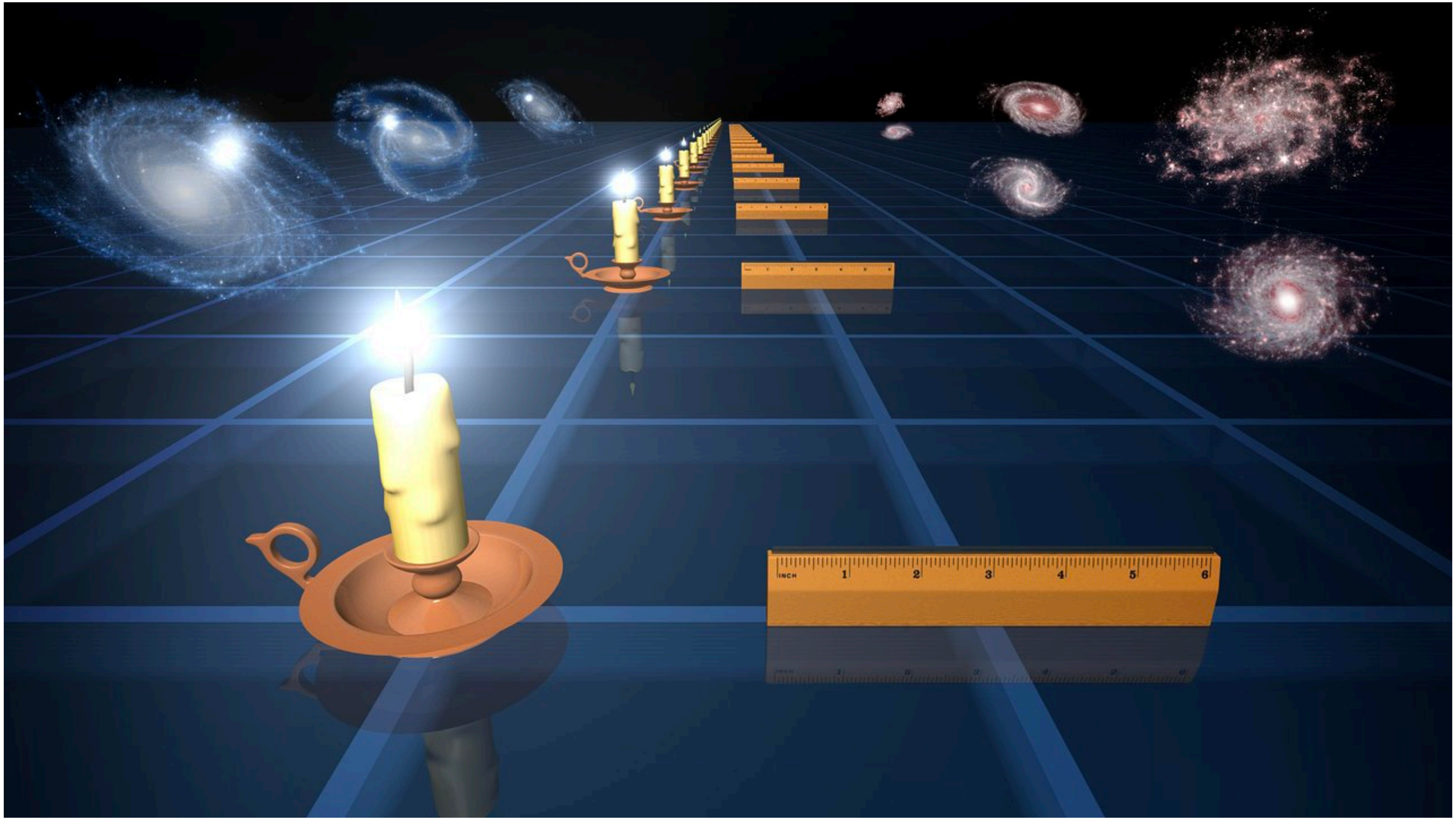
Reddening and extinction

Basics





Type Ia supernova cosmology



SNIa cosmology

SNIa are the most precise extragalactic distance indicators (uncert. 5%)

Two empirical correlations:

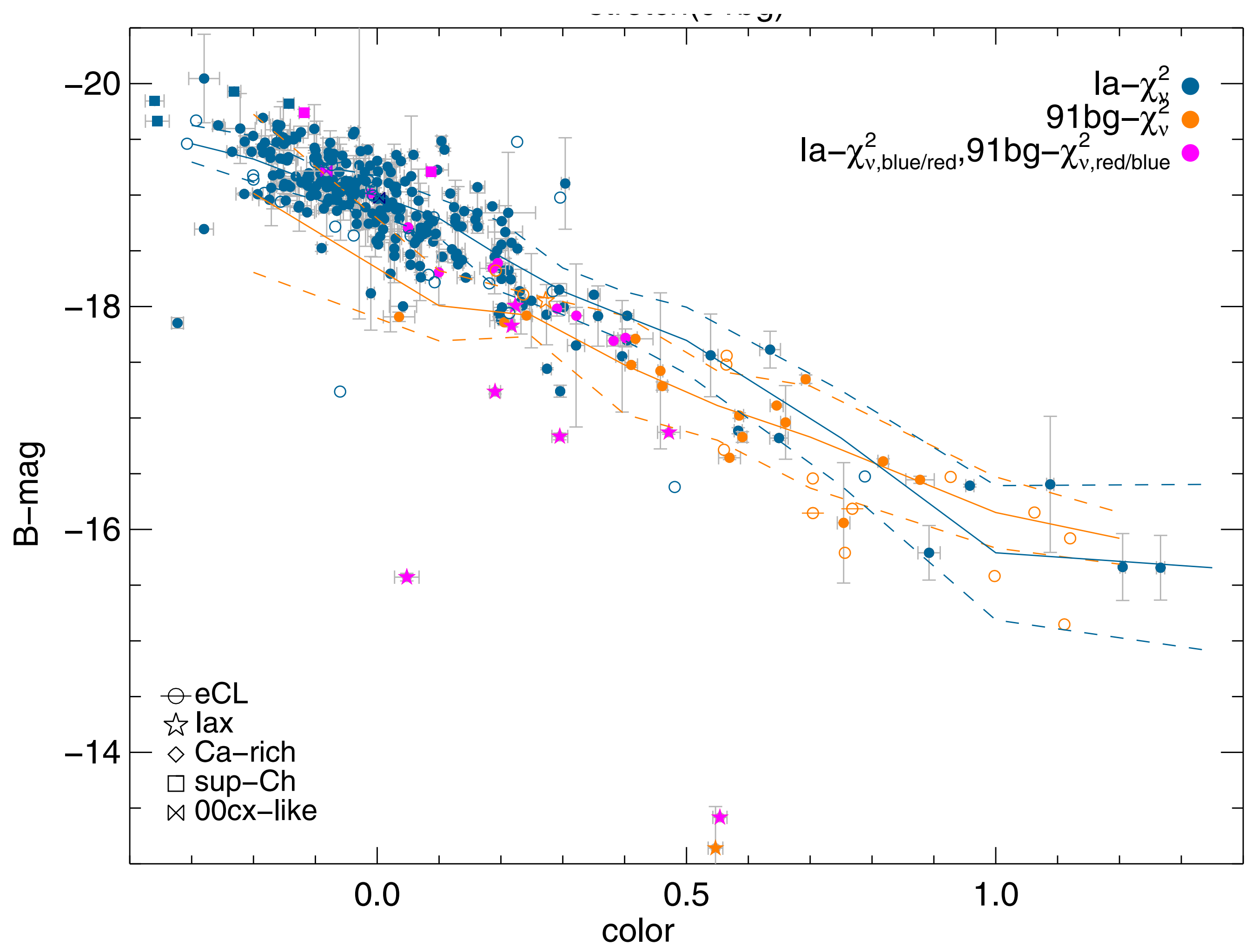
peak brightness vs brightness decay

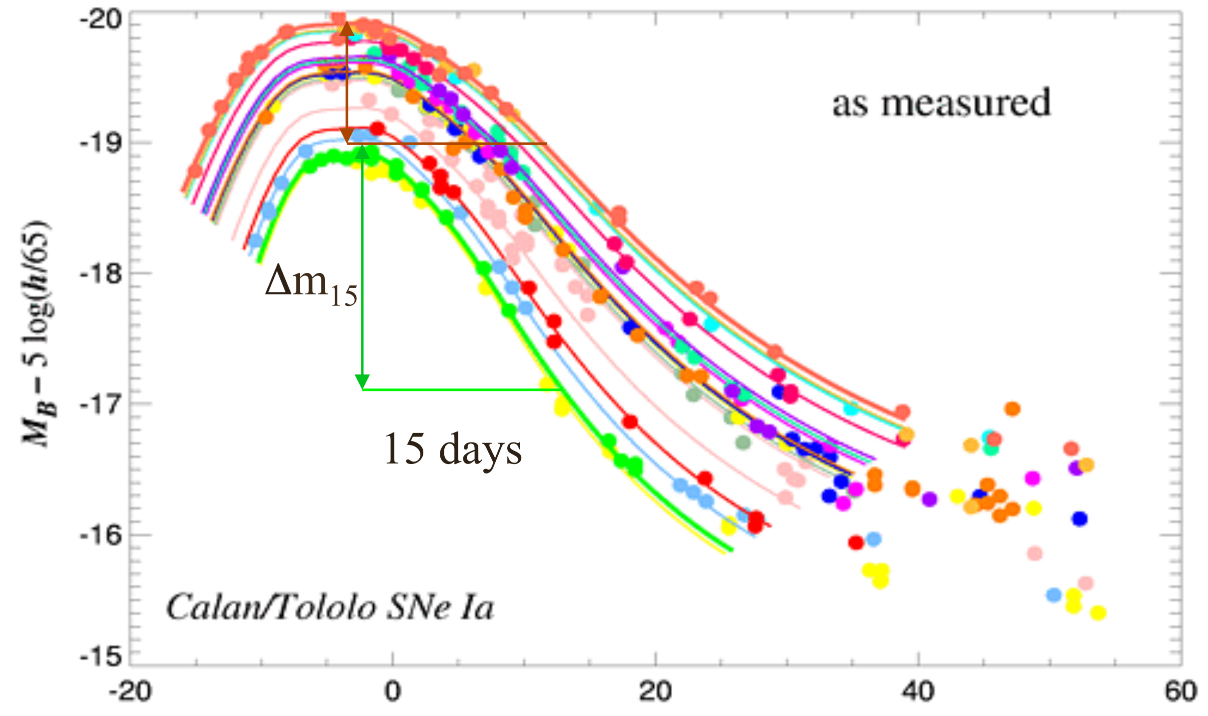
peak brightness vs color

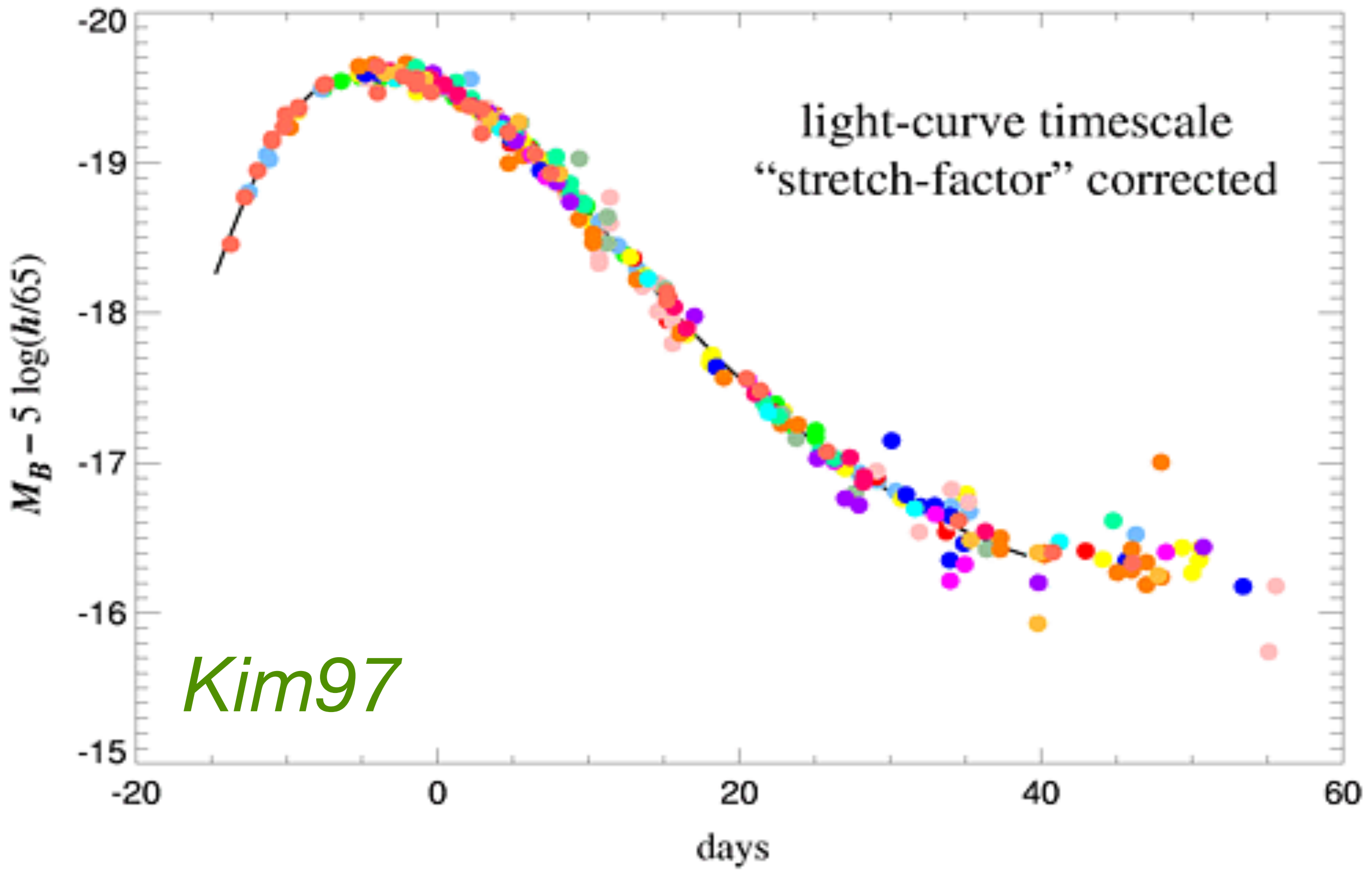
Standardized peak brightness

$$\mu(z)_{\rm SN} = m(z) - M = (m_{\rm obs} \color{red}{+\alpha x1} \color{blue}{-\beta c} \color{black}{- A_{\rm MW} + K_{x,y}) - M}$$

$$\mu(z)_{\rm model} = 5\log_{10}(d_L/10pc) \qquad d_L(z) = (1+z)\frac{c}{H_0}\int_0^z \frac{dz}{\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda(a+z)^{3(1+w)}}}$$







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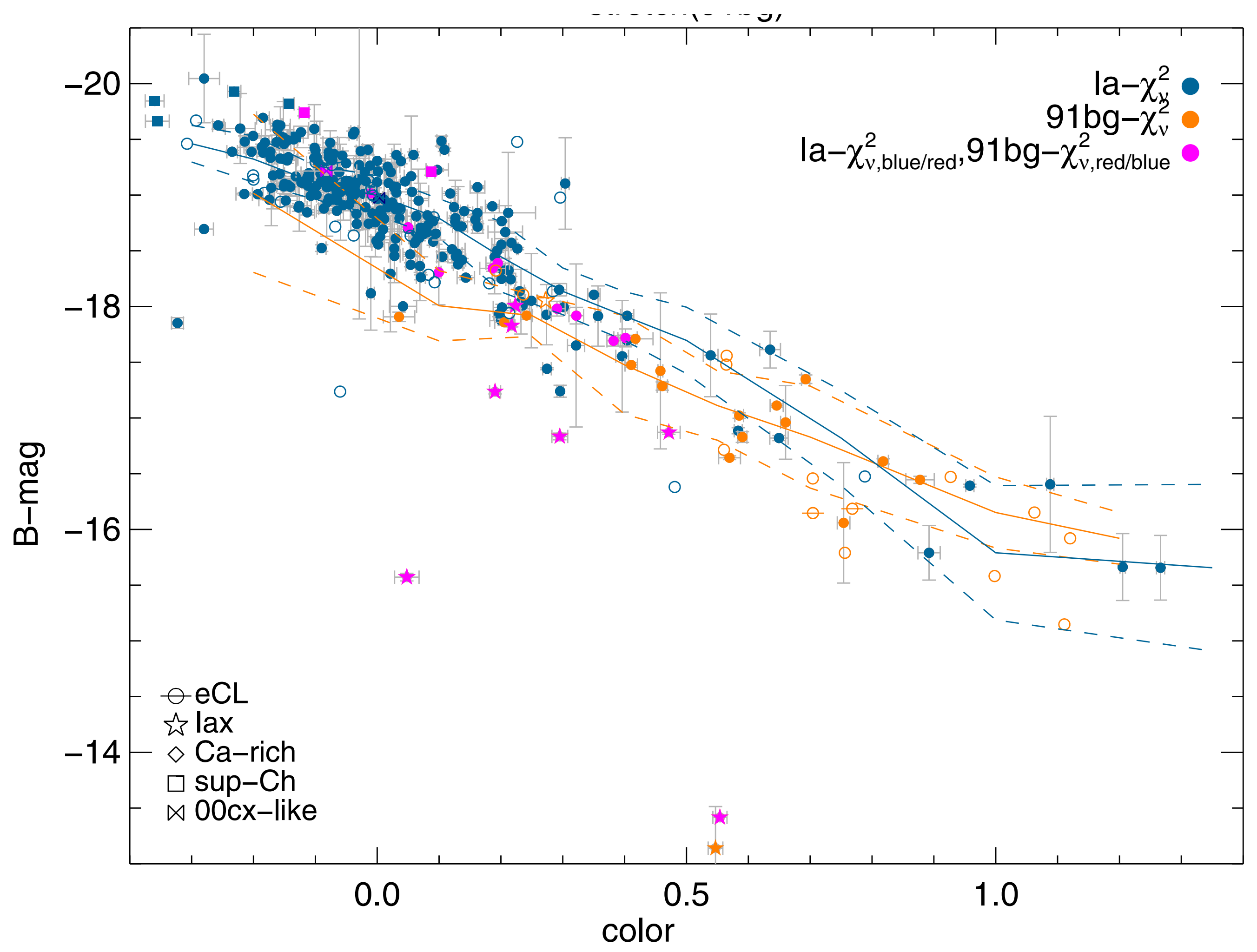
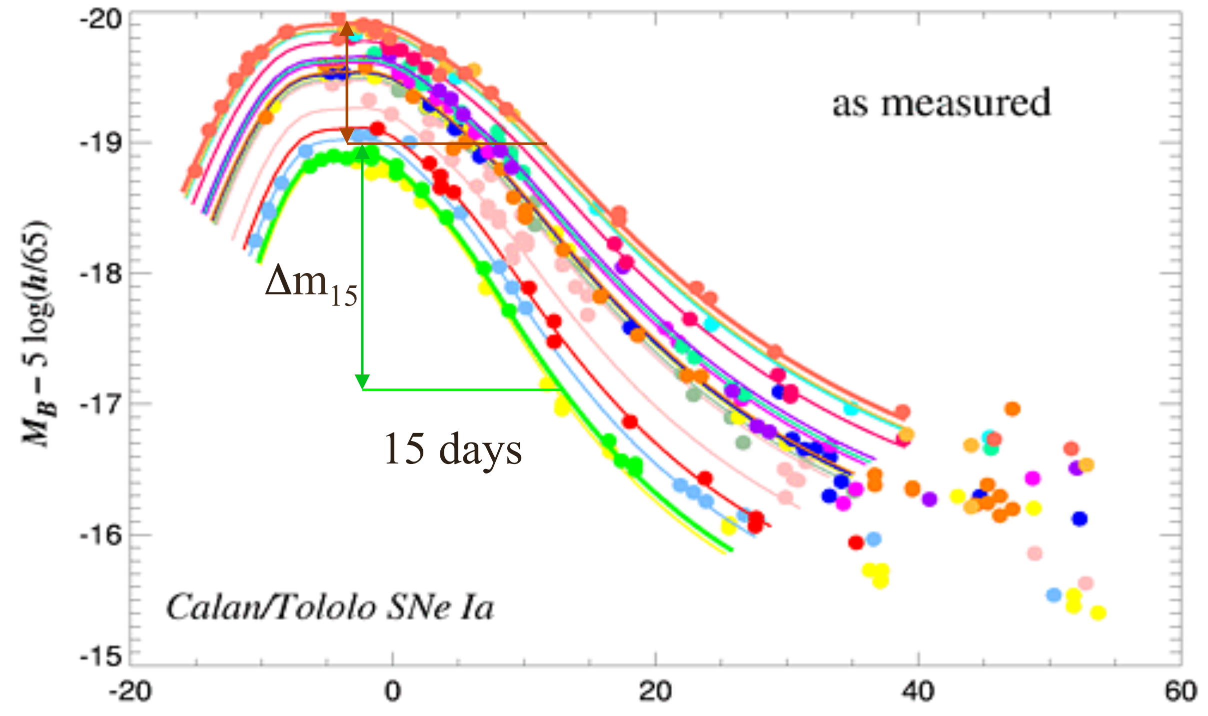
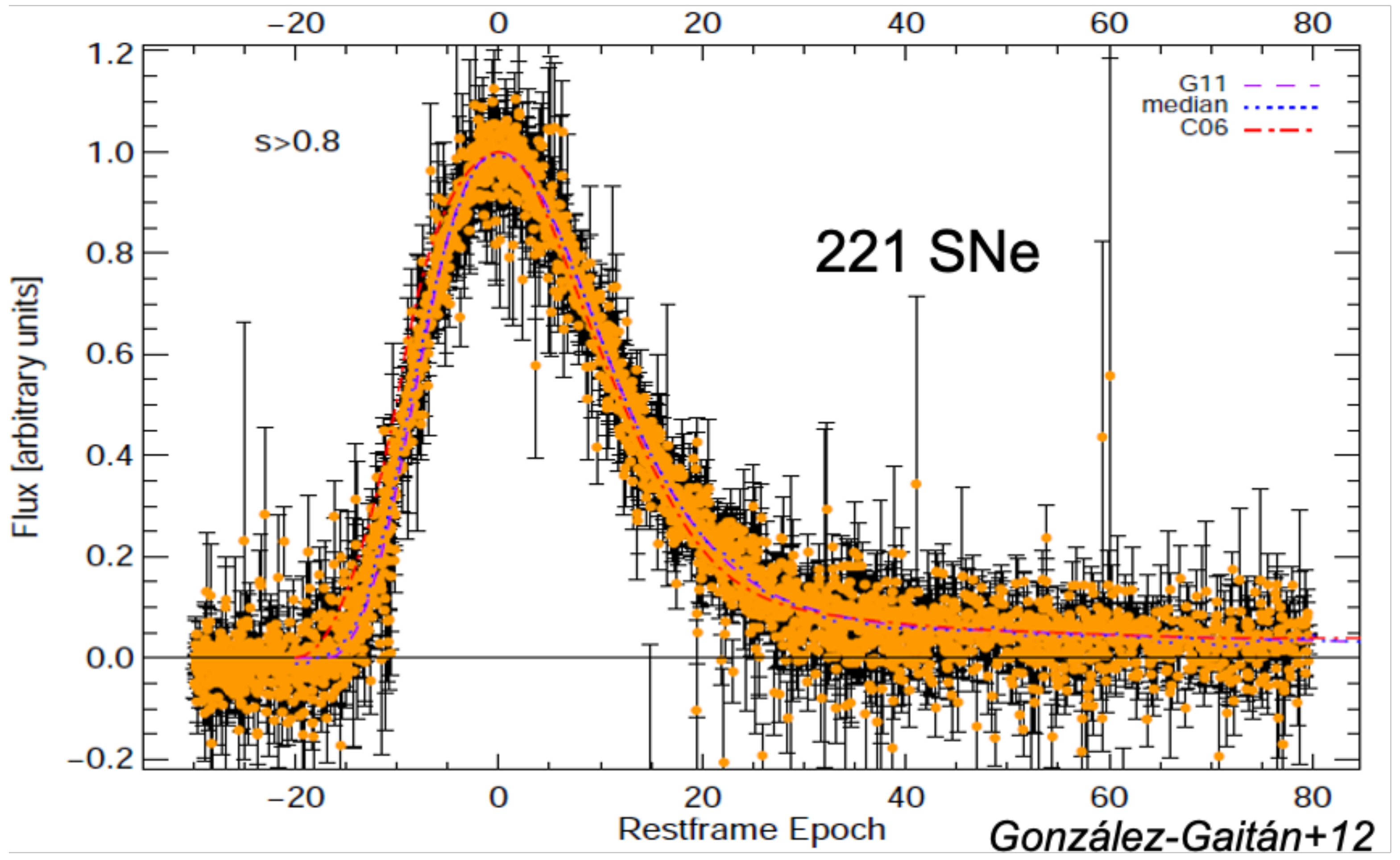






SNIa templates

LC parameters are measured from spectro-photometric templates f(t,λ)

SALT2 PCA from observed spectra: x0,x1,c

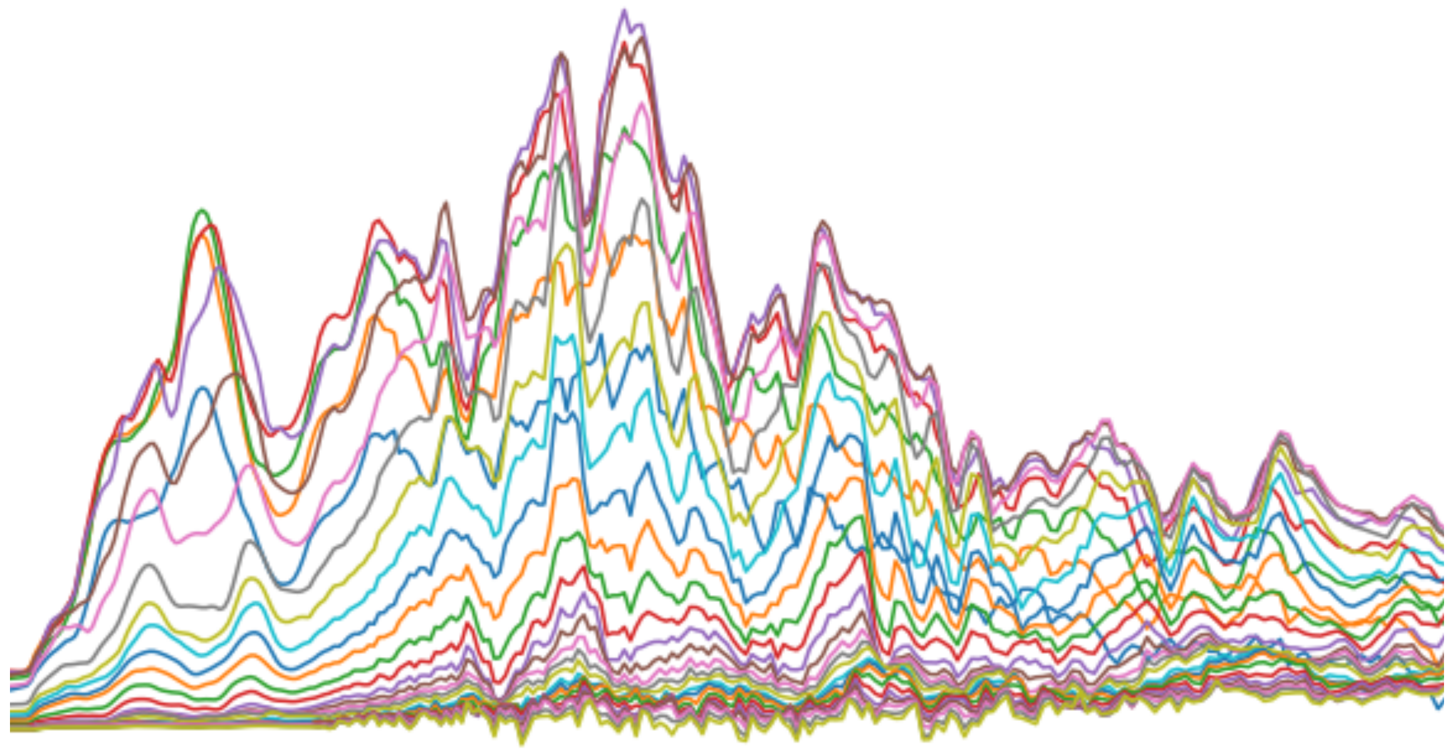
$$F(t,\lambda) = x_0(M_0(t,\lambda) + x_1 M_1(t,\lambda)) \times 10^{-0.4CL(\lambda)c}$$

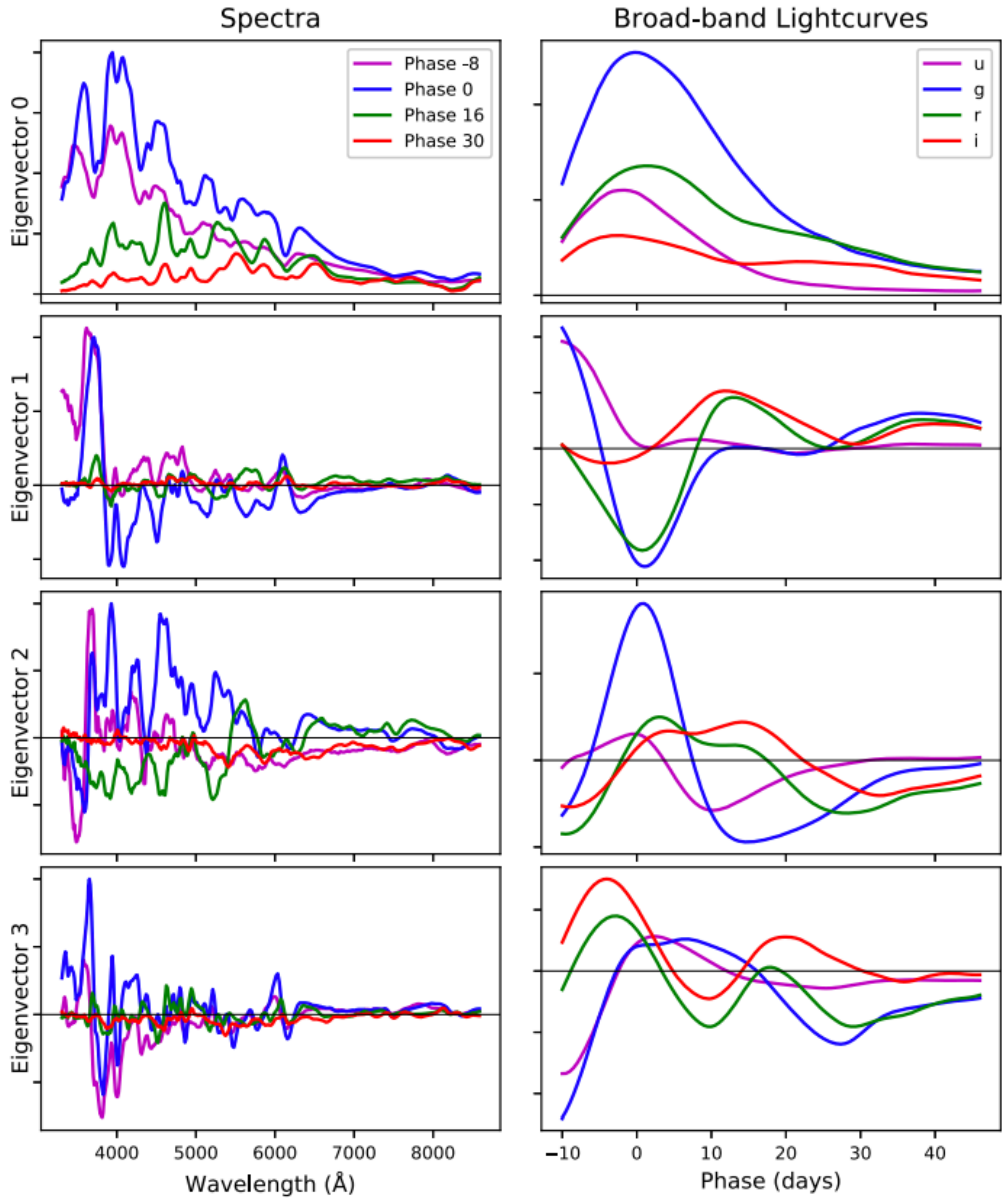
Hsiao MLCS2k2

SNEMO Saunders19

Trained on SNFactory SN IFS EMPCA of 2,7,15 components

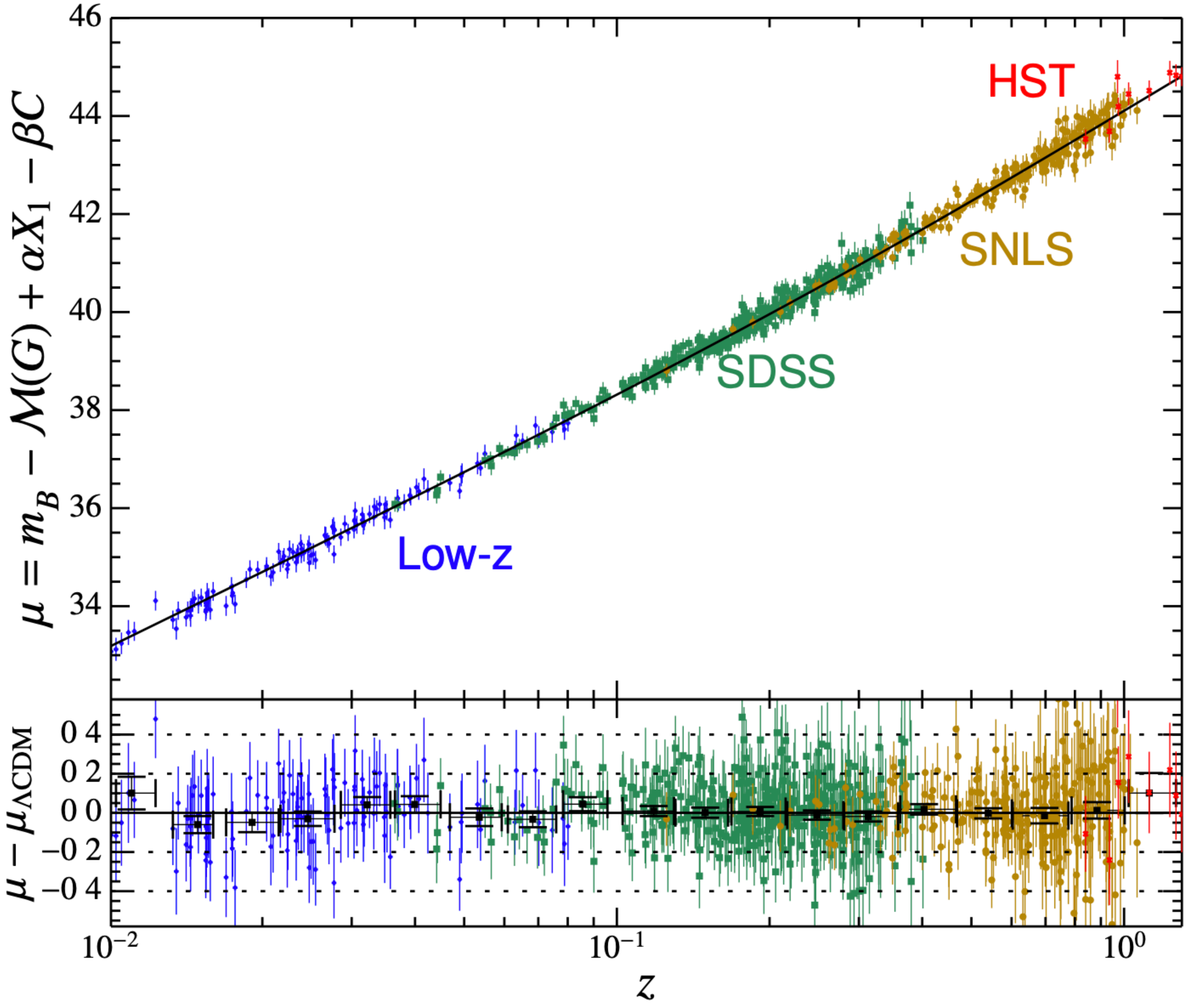
$$F_{\mathrm{SN}}(p,\lambda) = c_{\mathrm{SN},0}\left(e_0(p,\lambda) + \sum_{i=1}^{N} c'_{\mathrm{SN},i} e_i(p,\lambda)\right)$$





Modern SNIa cosmology surveys

Betoule 14

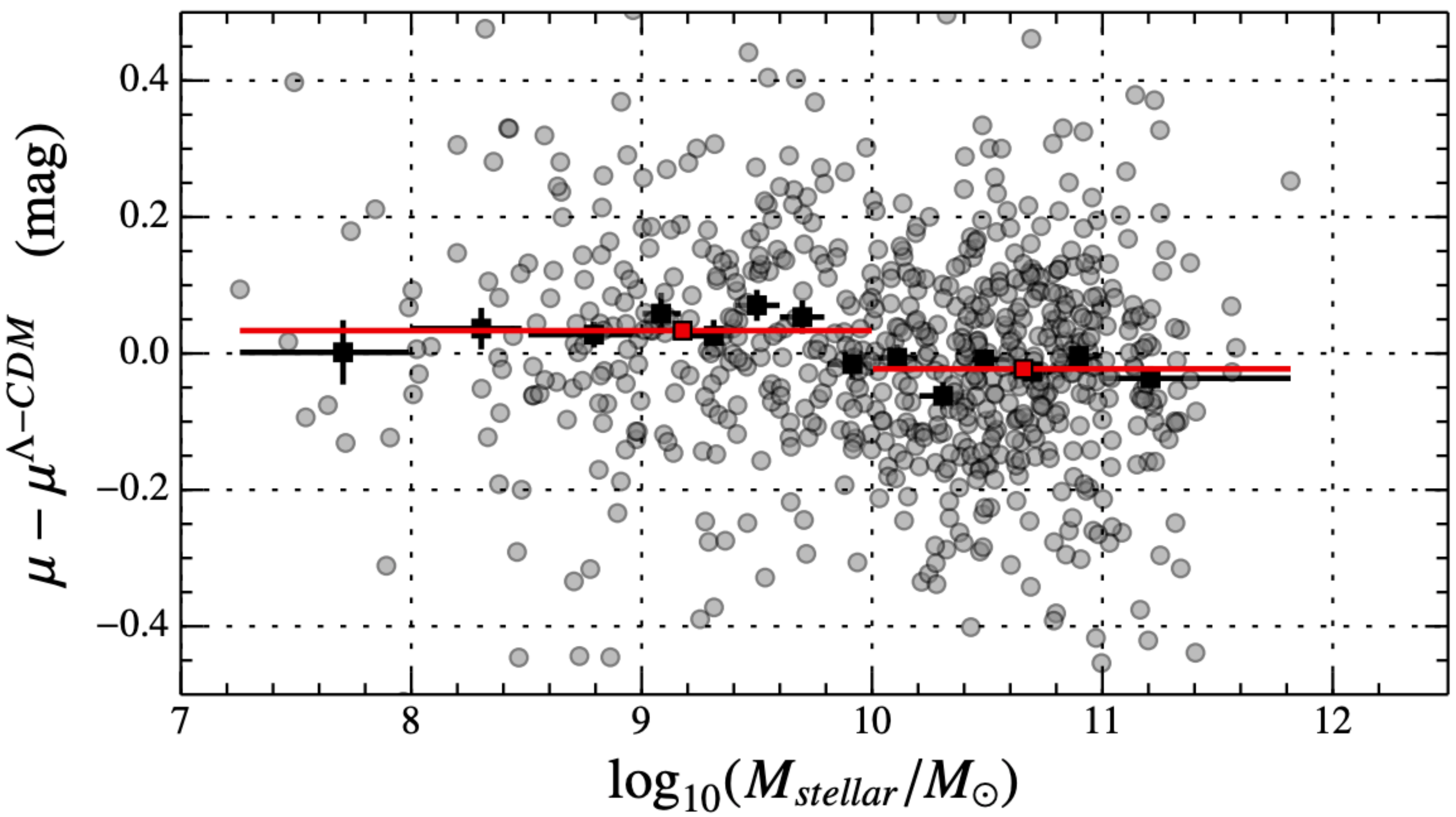


Hubble Residual

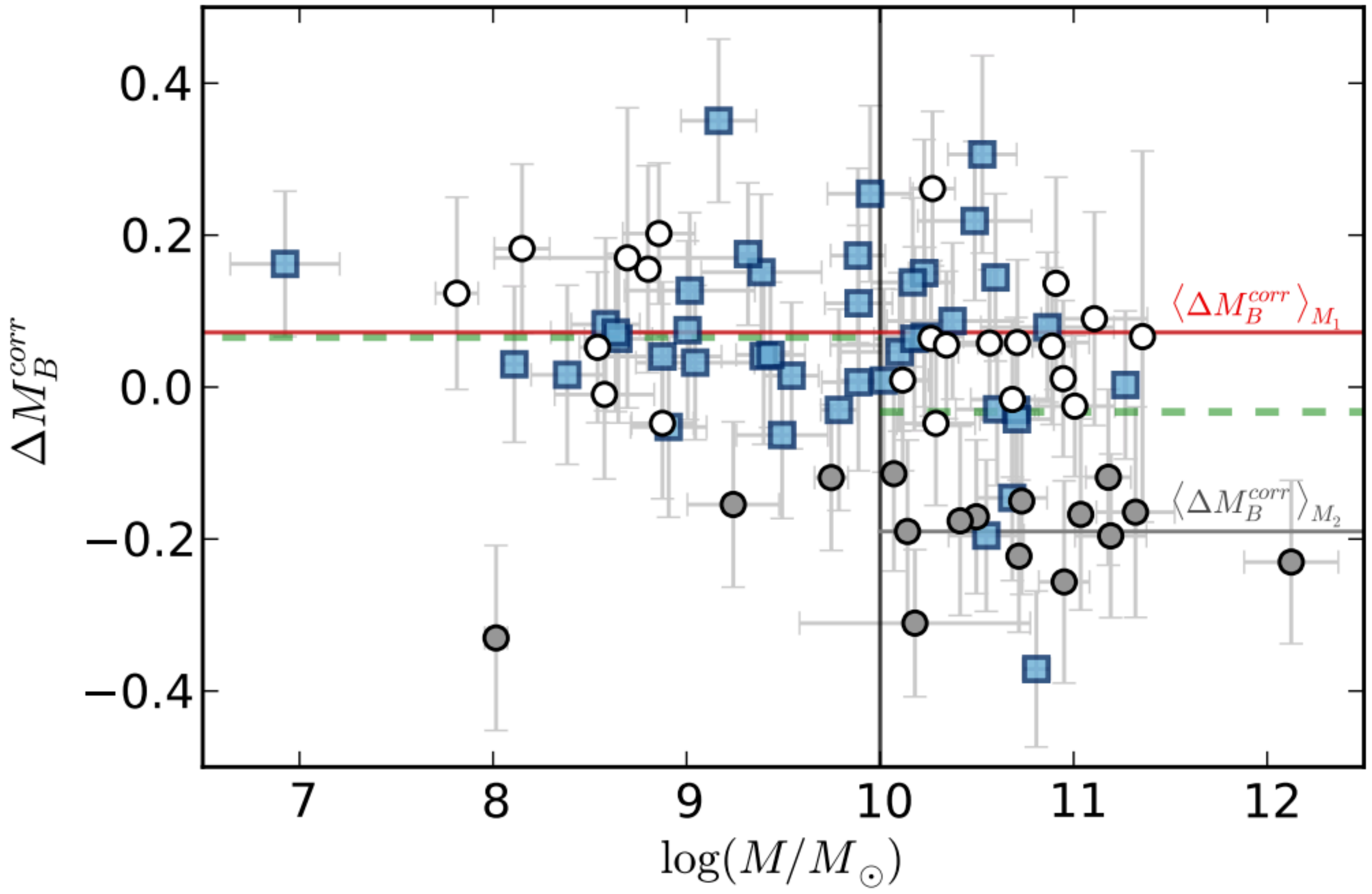
Source	Number
Cálan/Tololo	17
CfAI	7
CfAII	15
CfAIII[a]	55
CSP[a]	13
Other low-z	11
SDSS[a]	374
SNLS	239
HST	9
Total	740

SNIa environment

Sullivan+10



Rigault+13



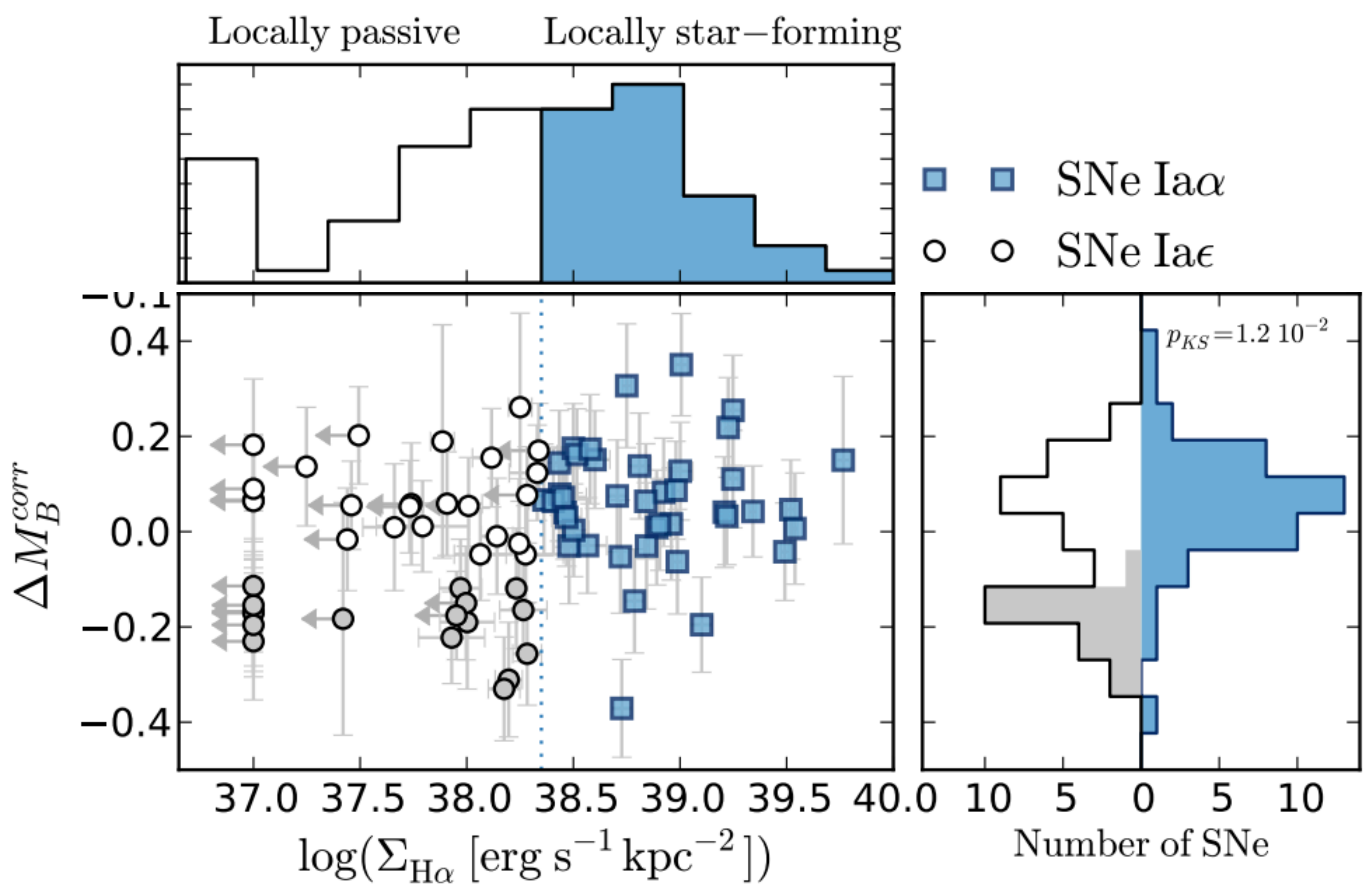
Recent (>2010) a dependence was found between HR and properties of the SN host galaxy

Two different populations, one associated to young and other to old populations, that evolve with z!

But mass should be just a proxy for another other parameter…

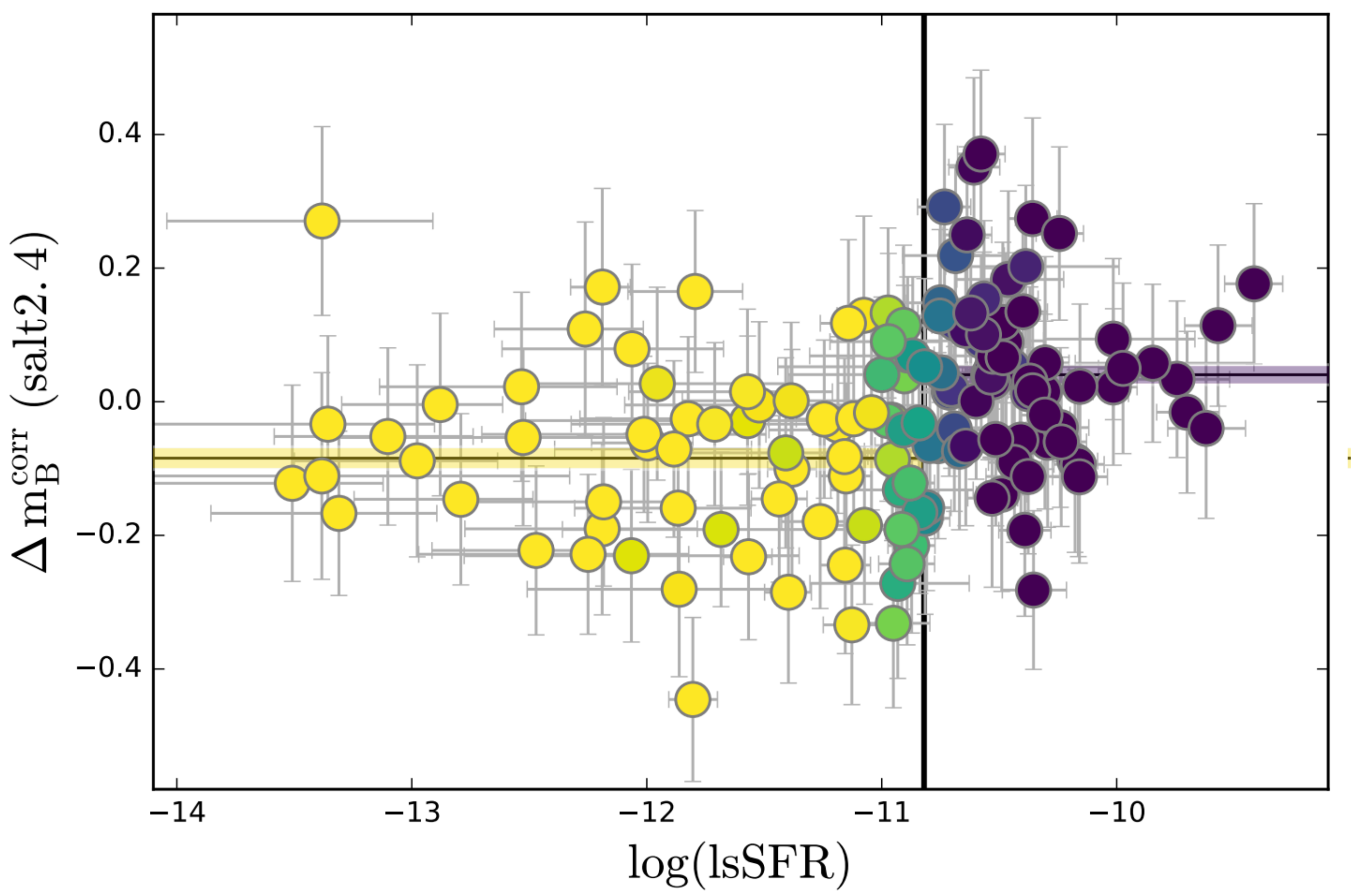
MASS STEP TERM ADDED

Local SNIa environment



SFR *Rigault et al. 2013*

IFS ~1kpc

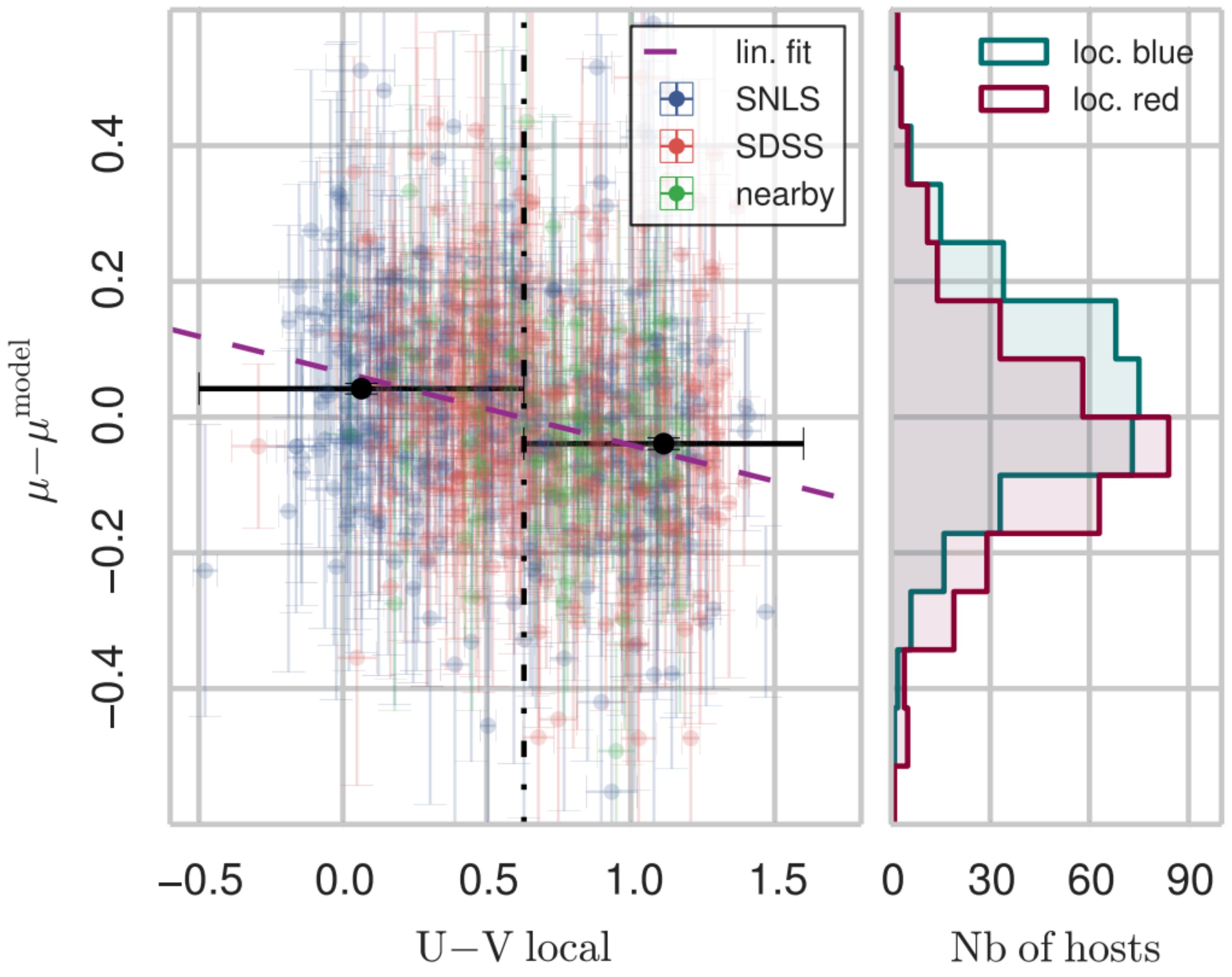


lsSFR *Rigault et al. 2018*

Phot ~1.5kpc

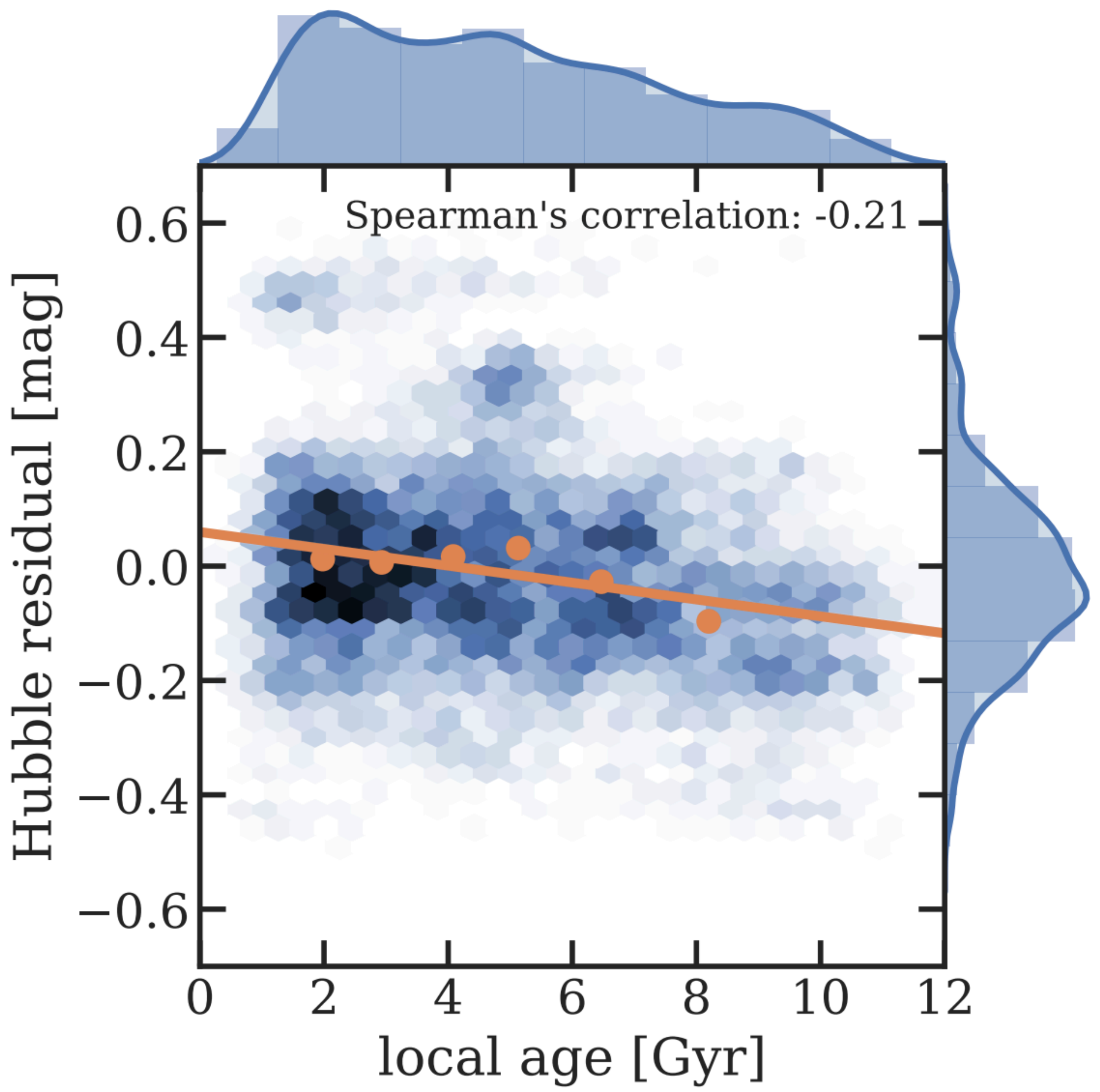
U-V *Roman et al. 2017*

Phot ~3kpc



Age *Rose et al 2019*

Phot ~5arcsec



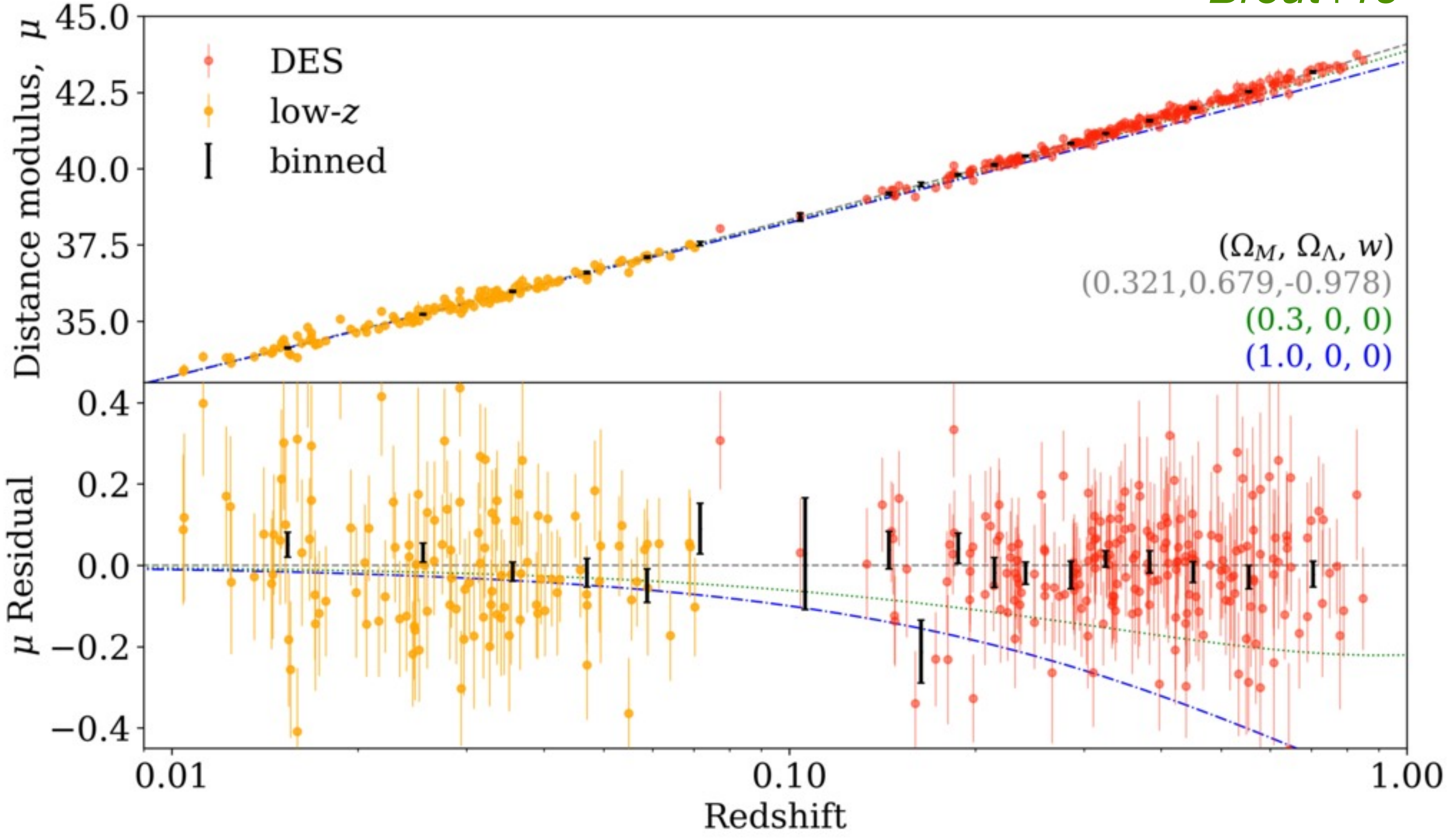
Modern age

Dark Energy Survey

207 SNe Ia 0.1<z<1.0 in the same photometric system

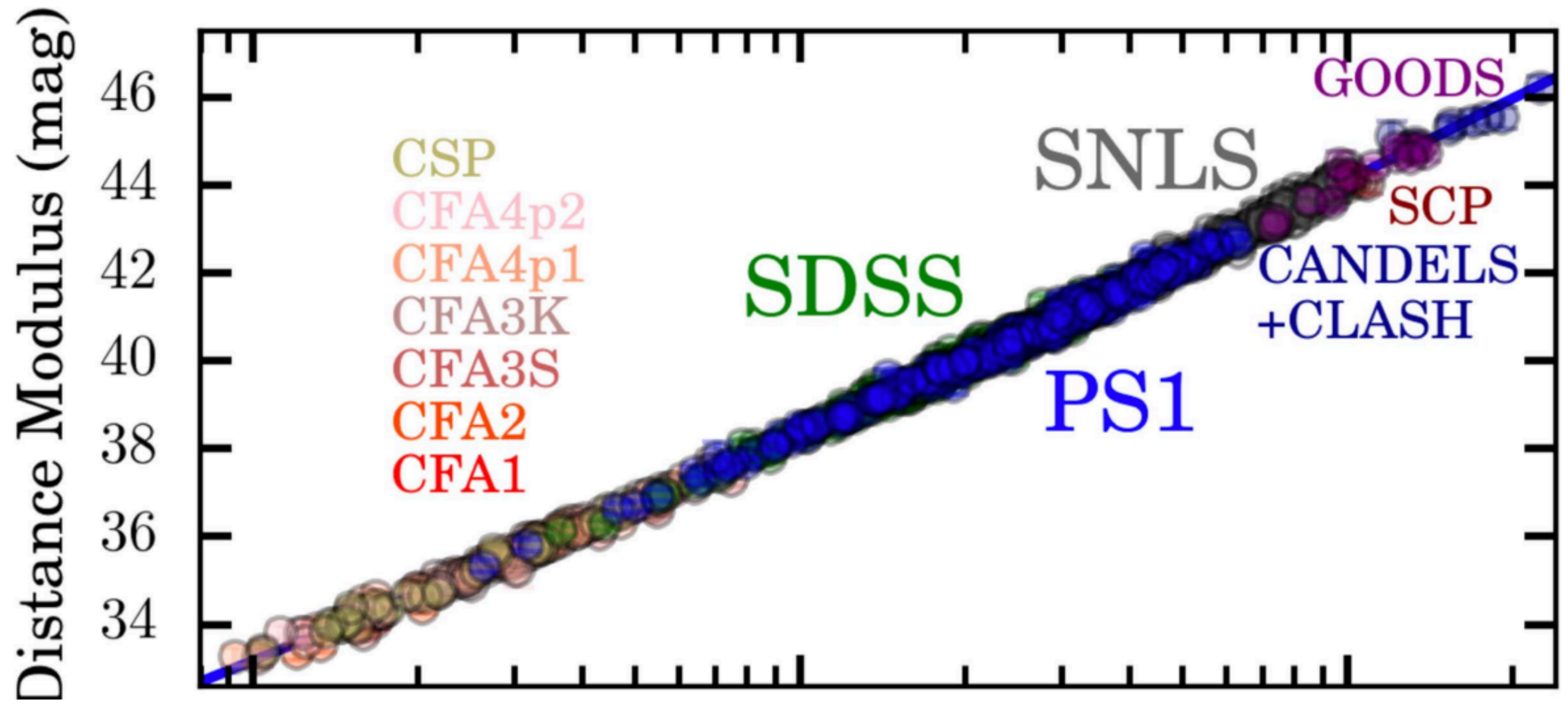
5YR sample with photometric SNIa coming

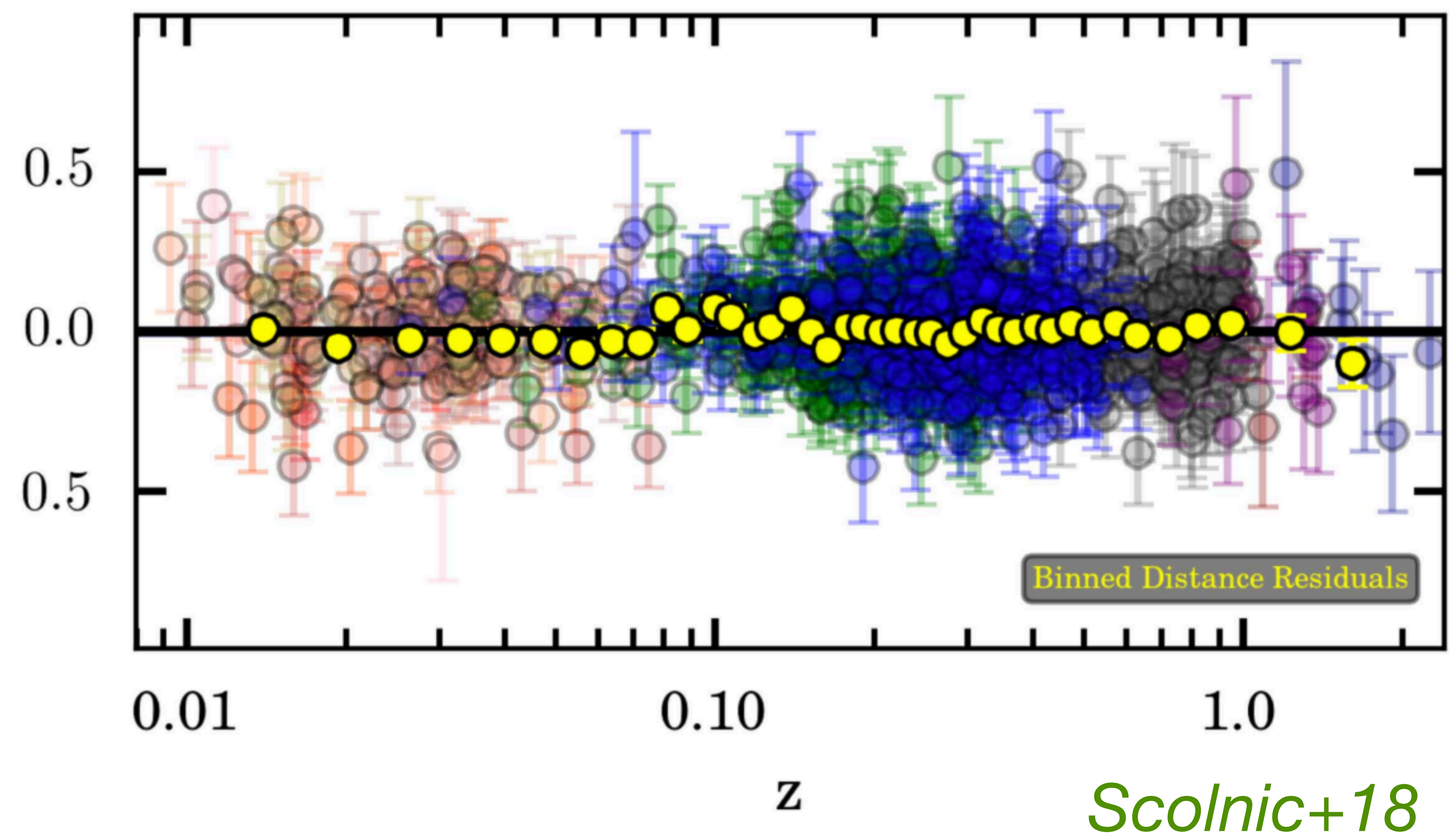
Brout+19



Pan-STARRS

Combined with previous data: PANTHEON





Scolnic+18

BEAMS with Bias Corrections (BBC)

Correcting Type Ia Supernova Distances for Selection Biases and Contamination in Photometrically Identified Samples

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[1] Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA; kessler@kicp.uchicago.edu
[2] Department of Astronomy and Astrophysics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, USA
Received 2016 October 14; revised 2017 January 12; accepted 2017 January 12; published 2017 February 8

Abstract

We present a new technique to create a bin-averaged Hubble diagram (HD) from photometrically identified SN Ia data. The resulting HD is corrected for selection biases and contamination from core-collapse (CC) SNe, and can be used to infer cosmological parameters. This method, called "BEAMS with Bias Corrections" (BBC), includes two fitting stages. The first BBC fitting stage uses a posterior distribution that includes multiple SN likelihoods, a Monte Carlo simulation to bias-correct the fitted SALT-II parameters, and CC probabilities determined from a machine-learning technique. The BBC fit determines (1) a bin-averaged HD (average distance versus redshift), and (2) the nuisance parameters α and β, which multiply the stretch and color (respectively) to standardize the SN brightness. In the second stage, the bin-averaged HD is fit to a cosmological model where priors can be imposed. We perform high-precision tests of the BBC method by simulating large (150,000 event) data samples corresponding to the Dark Energy Survey Supernova Program. Our tests include three models of intrinsic scatter, each with two different CC rates. In the BBC fit, the SALT-II nuisance parameters α and β are recovered to within 1% of their true values. In the cosmology fit, we determine the dark energy equation of state parameter w using a fixed value of Ω_M as a prior: averaging over all six tests based on $6 \times 150{,}000 = 900{,}000$ SNe, there is a small w-bias of 0.006 ± 0.002. Finally, the BBC fitting code is publicly available in the SNANA package.

Key words: cosmological parameters – supernovae: general

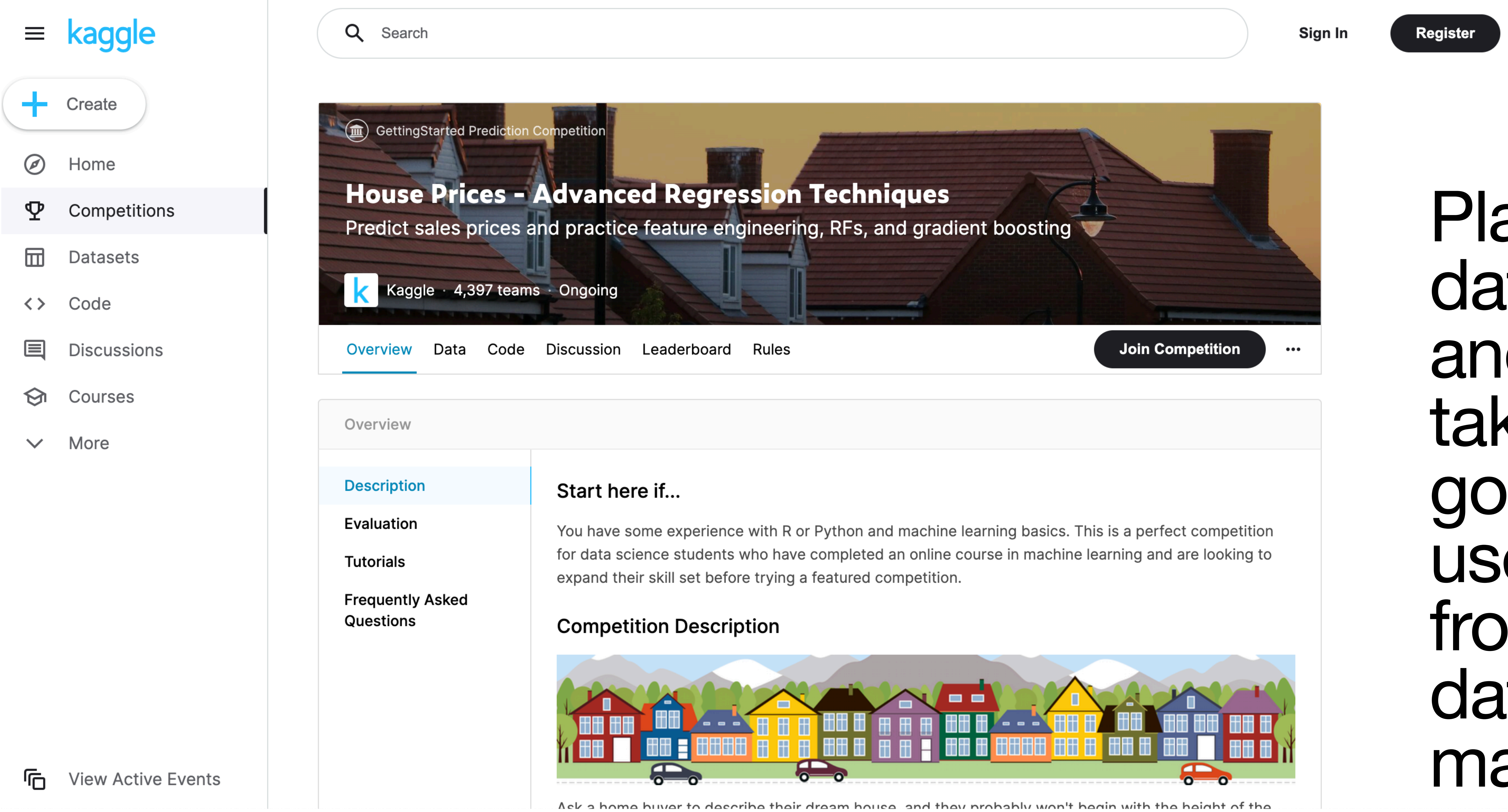
$$
\begin{aligned}
\mu^\star &= m_B^\star + \alpha x_1^\star - \beta c^\star - M_0 \\
&= (m_B - \bar{\delta}_{m_B}) + \alpha(x_1 - \bar{\delta}_{x_1}) - \beta(c - \bar{\delta}_c) - M_0
\end{aligned}
$$

For any given event, we cannot exactly determine the true parameter bias (δ) because of variations caused by intrinsic scatter and measurement noise. We therefore interpolate the bias ($\bar{\delta}$) in a 5D space of $\{z, x_1, c, \alpha, \beta\}$.

A correction for missing objects (Malmquist bias, faint…)

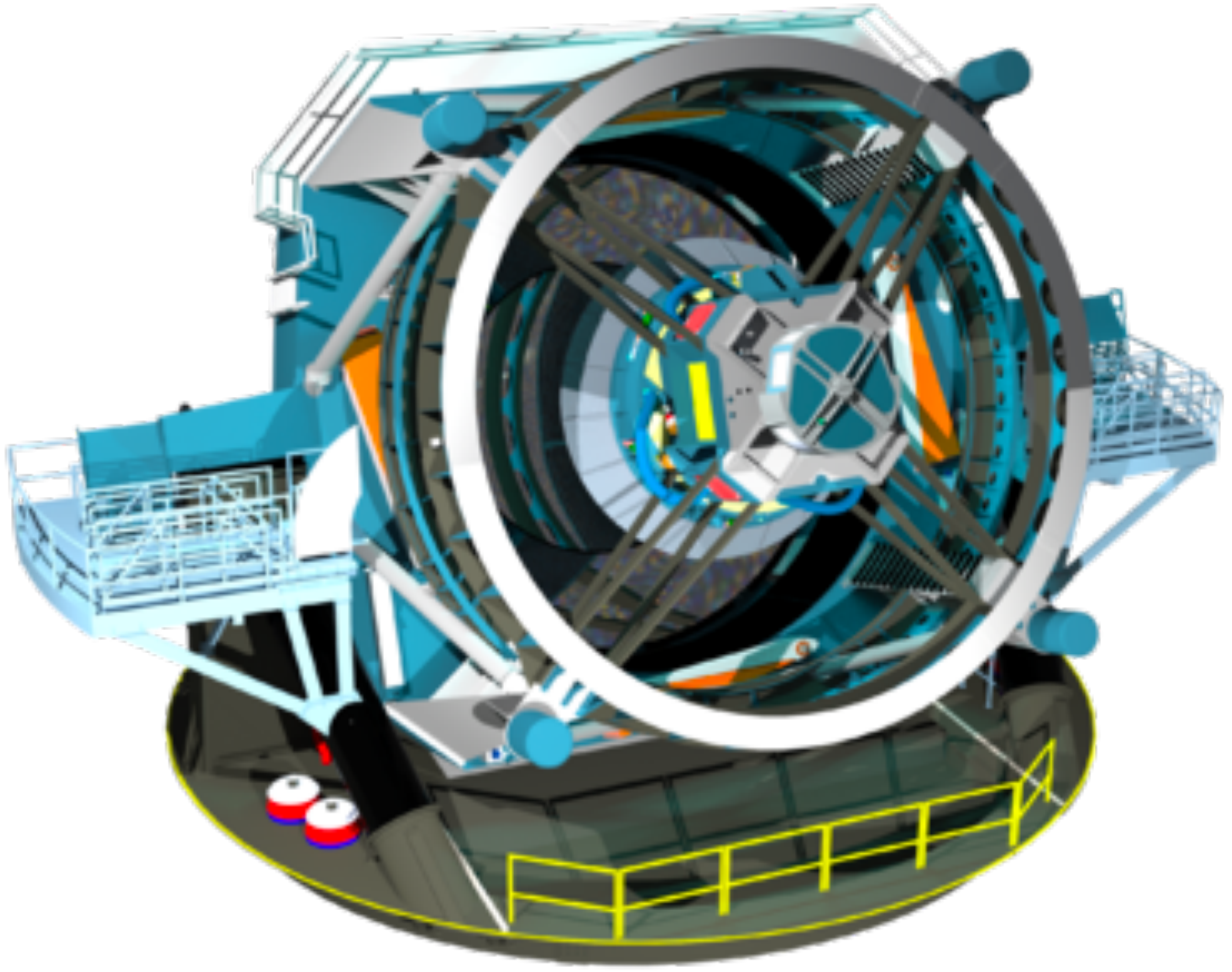
Kaggle

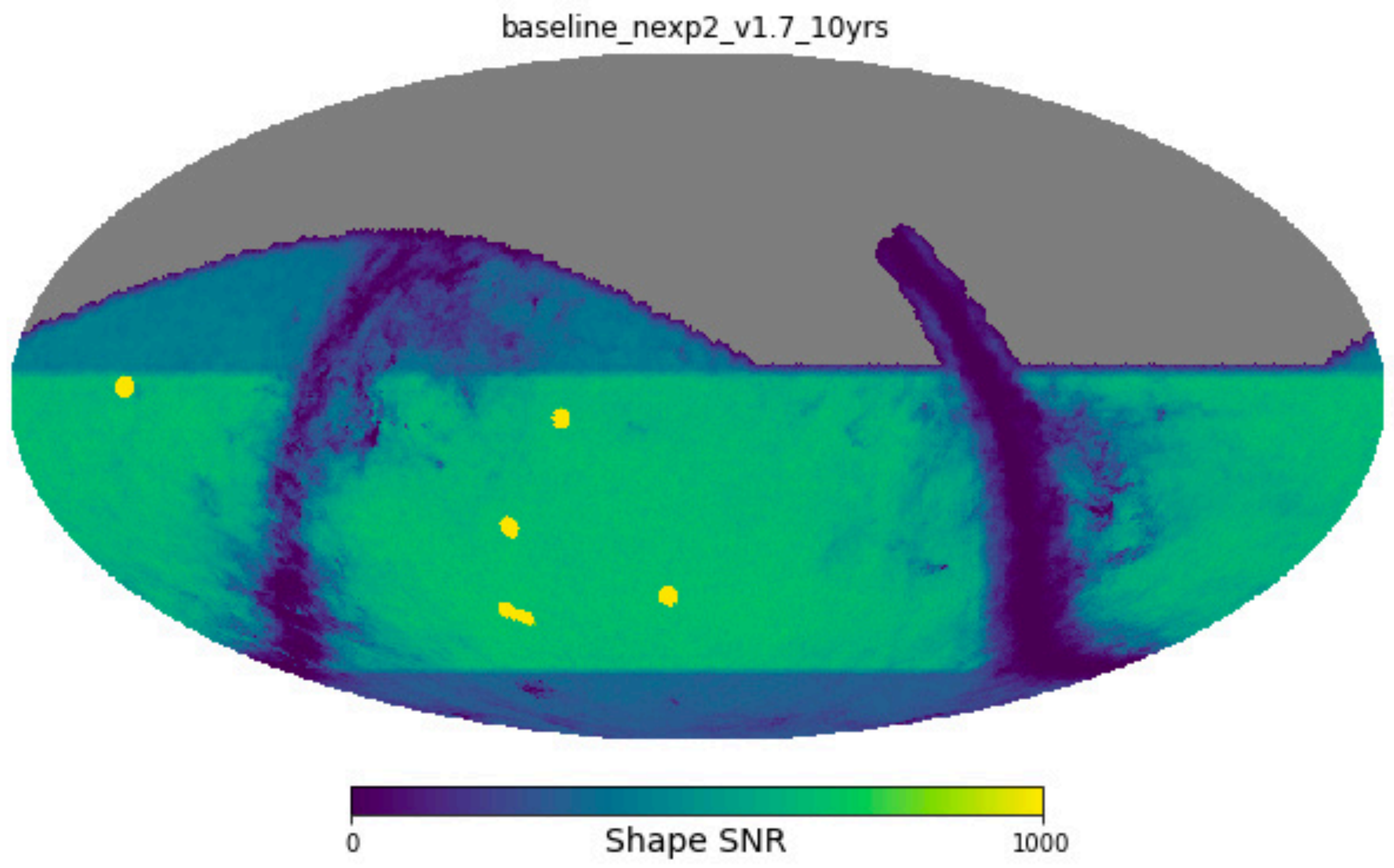
www.kaggle.com



Platform where datasets are stored and competitions take place with the goal of extracting all useful information from them using data science and machine learning

The Photometric LSST Astronomical Time-series Classification Challenge (PLAsTiCC)





Legacy Survey of Space and Time (LSST)

8.4m telescope at Cerro Pachón (Chile)

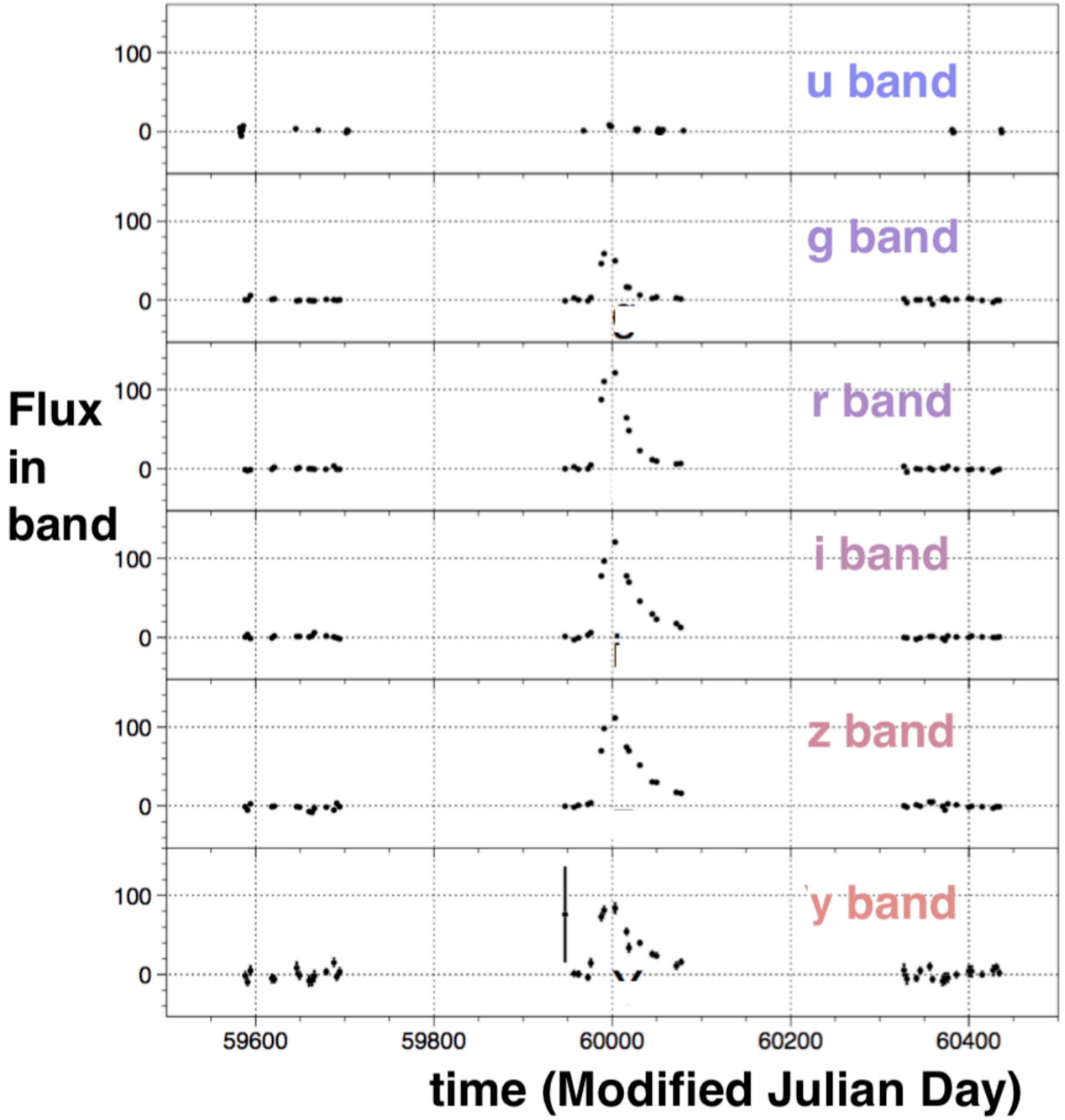
10 year survey of 18000 deg2 southern sky in *ugrizy*

Wide-Fast-Deep and Deep Drilling Fields

Plasticc is a simulation of transient data as it will be found by LSST during ~2 years

15 different classes of transients included

The Photometric LSST Astronomical Time-series Classification Challenge (PLAsTiCC)



Legacy Survey of Space and Time (LSST)

8.4m telescope at Cerro Pachón (Chile)

10 year survey of 18000 deg2 southern sky in *ugrizy*

Wide-Fast-Deep and Deep Drilling Fields

Plasticc is a simulation of transient data as it will be found by LSST during ~2 years

15 different classes of transients included