Pulsating stars and their fundamental parameters with ML

Anupam Bhardwaj (IUCAA)

Credit: NASA/STScI/A. Riess

AI/ML in A&A, IUCAA, January 08, 2025

Stellar variability and pulsation

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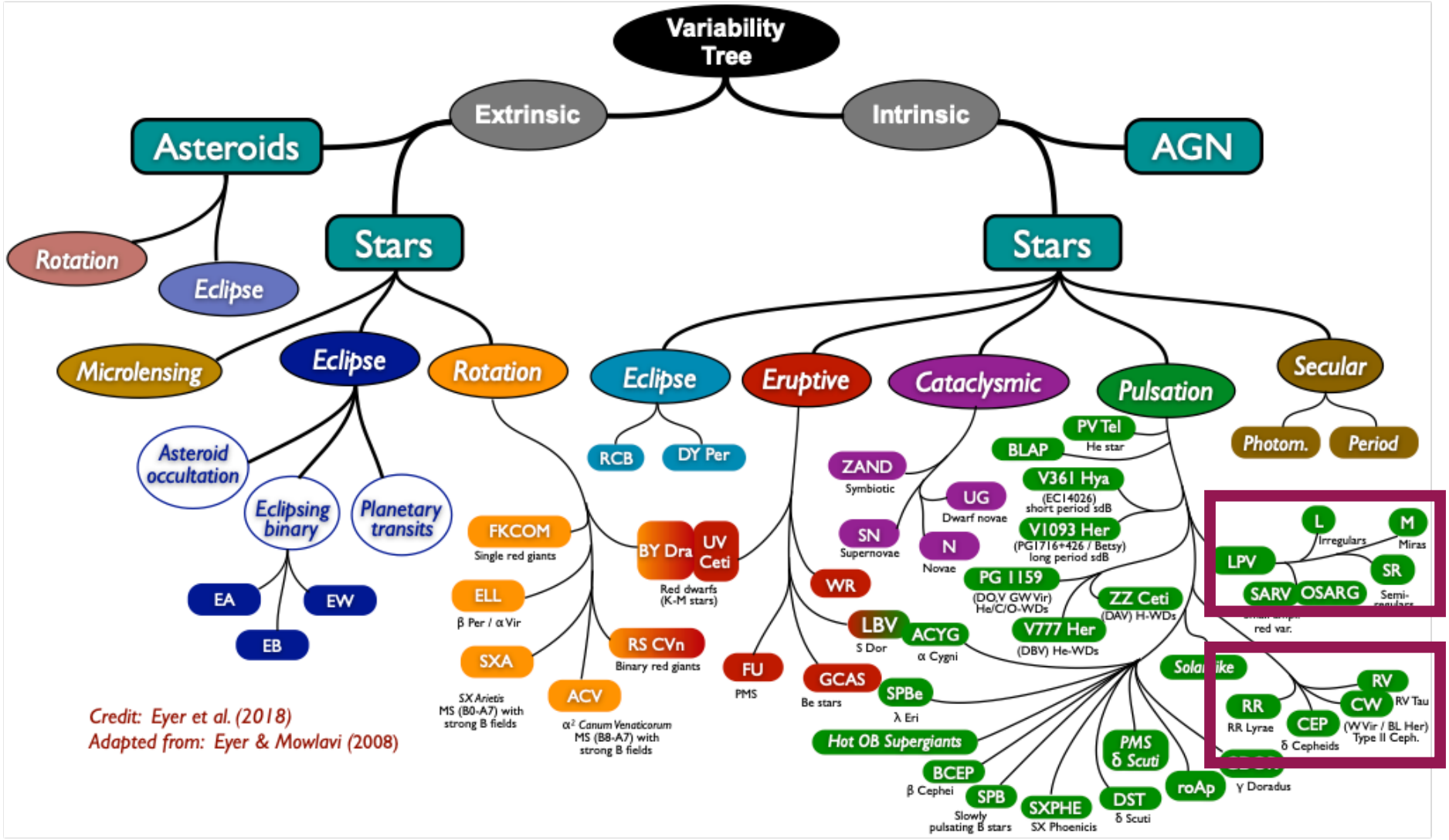

Pulsating variable stars

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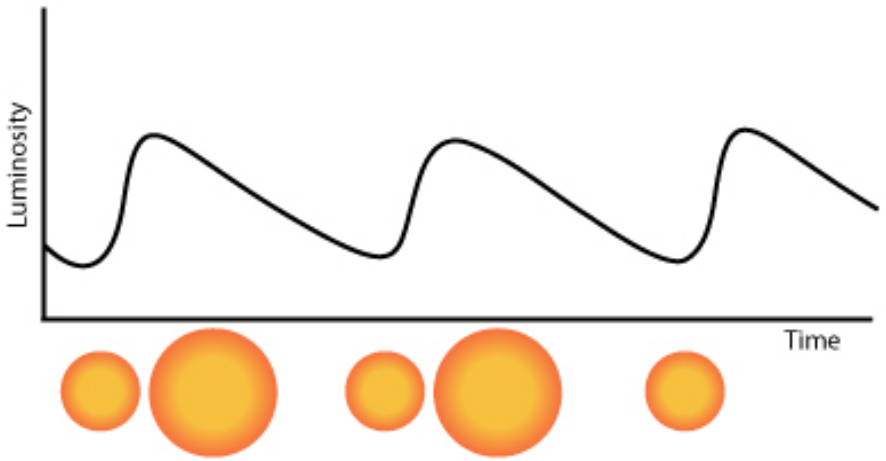
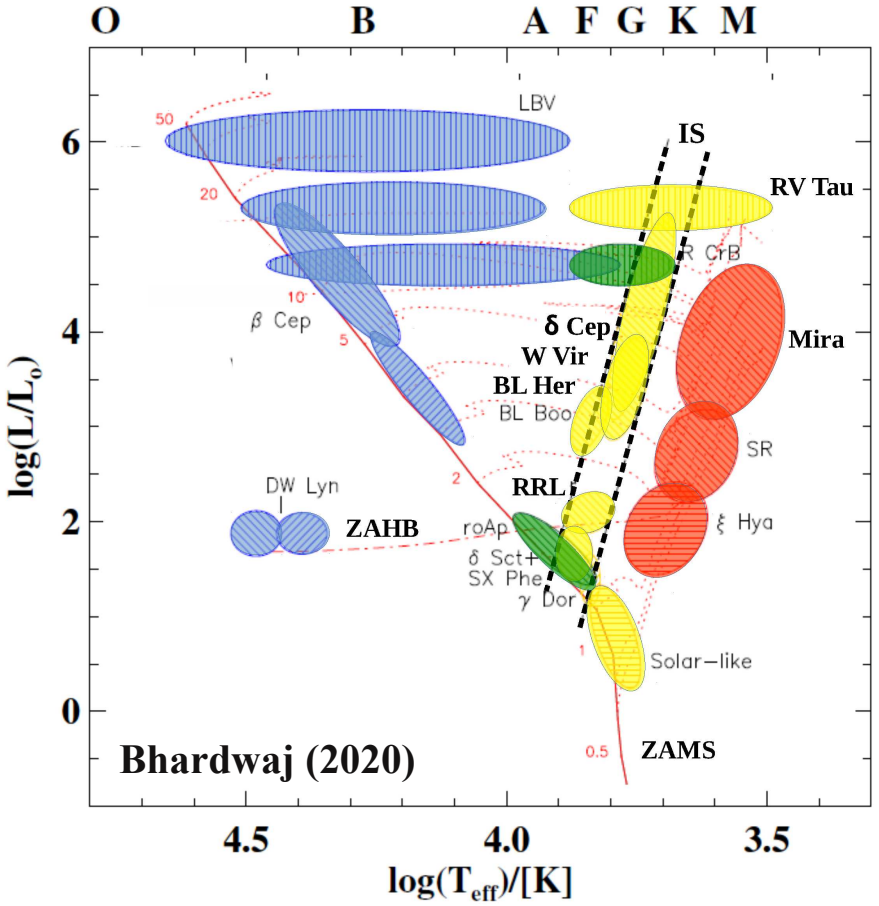
Within and beyond the "Instability Strip" in the HR diagram

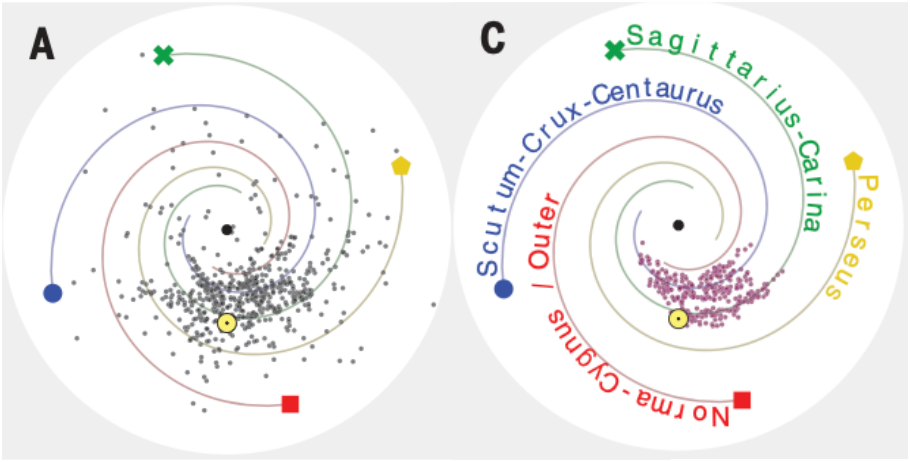
- Classical or Type I Cepheids
- Type II Cepheids
- Anomalous Cepheids
- RR Lyrae variables
- Miras



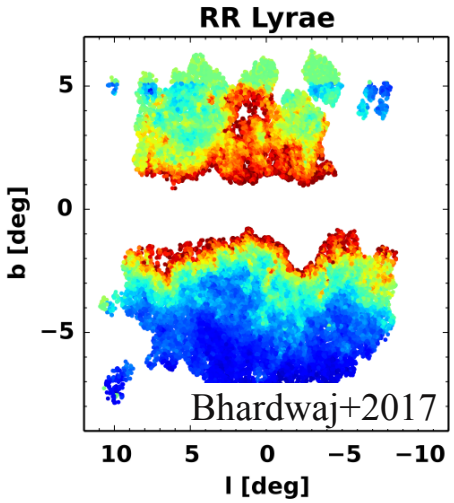


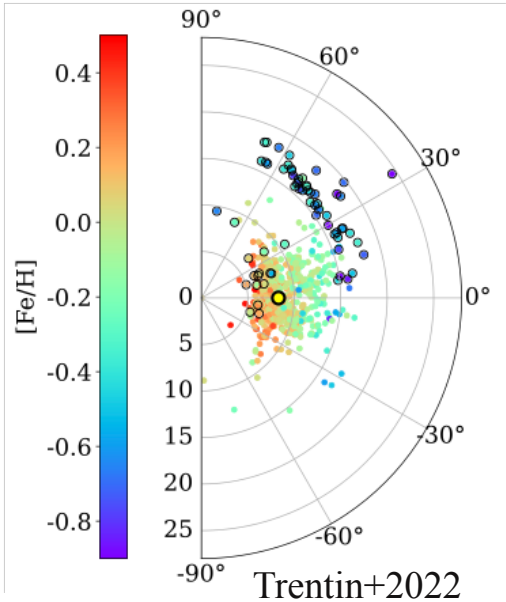
Pulsating variable stars

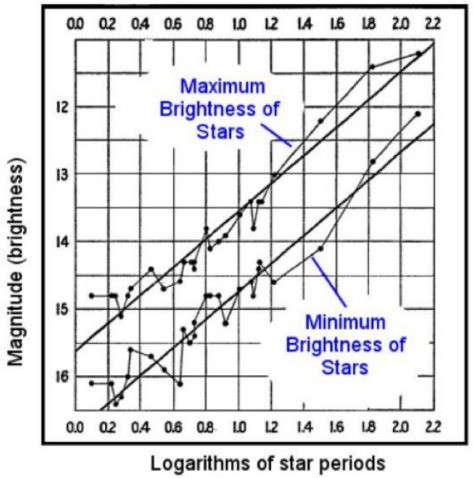
Stellar population tracers and distance indicators



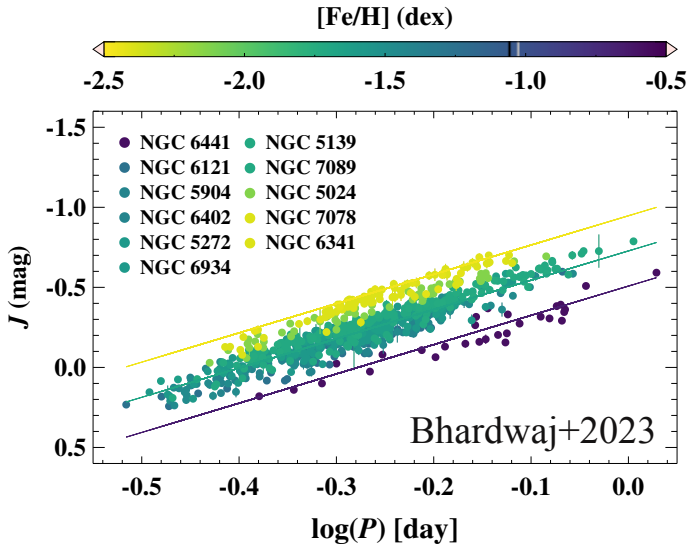
Skowron+2019

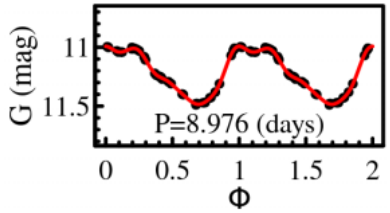


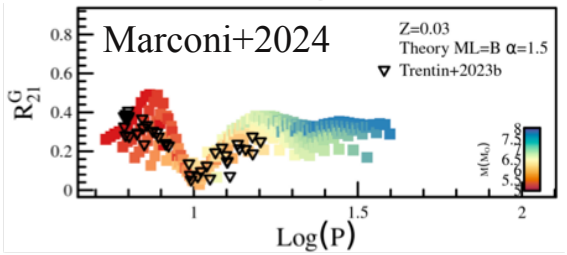




Classical Cepheids in the Magellanic Clouds
Leavitt and Pickering (1912)







Cosmic distance ladder

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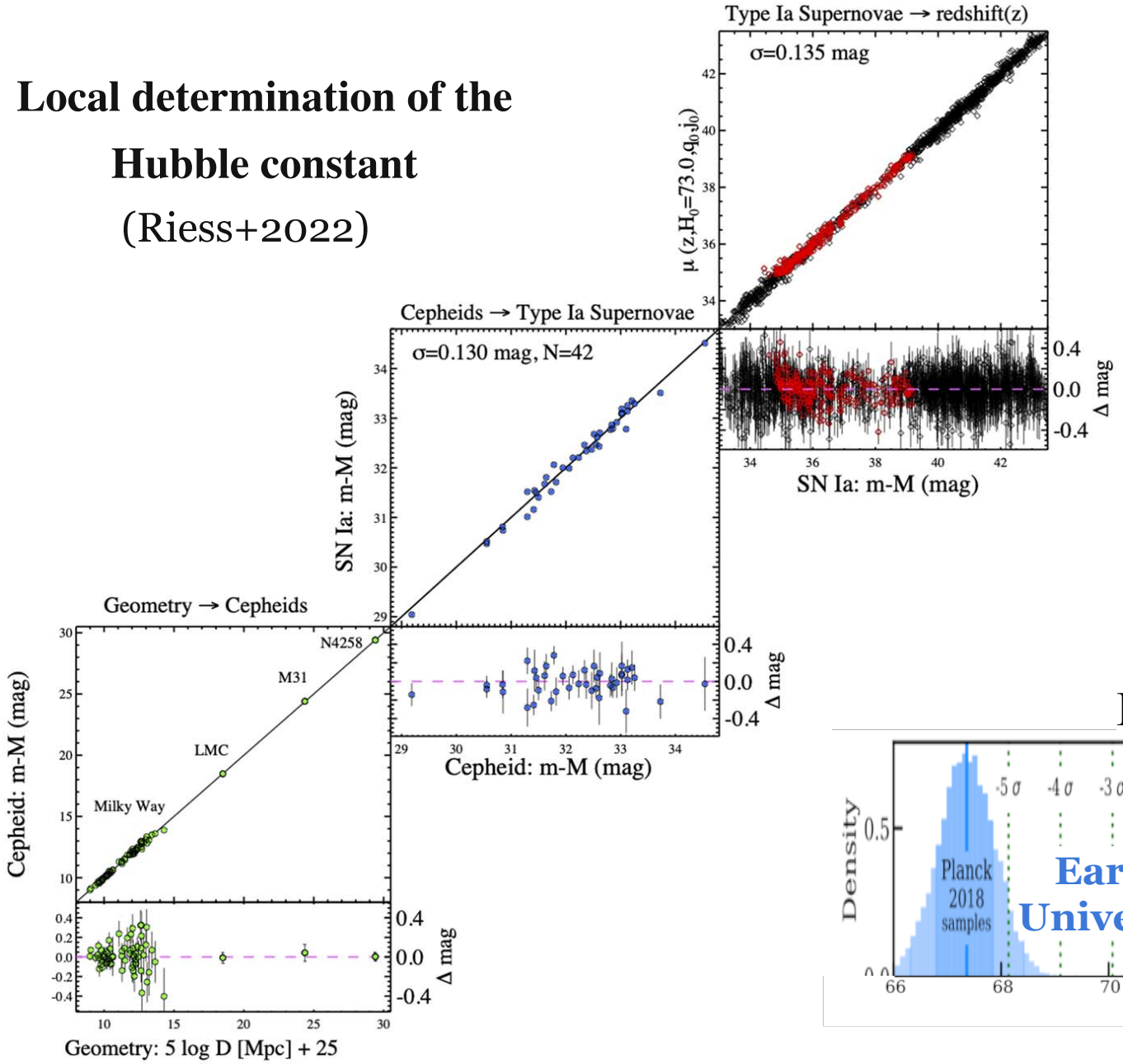
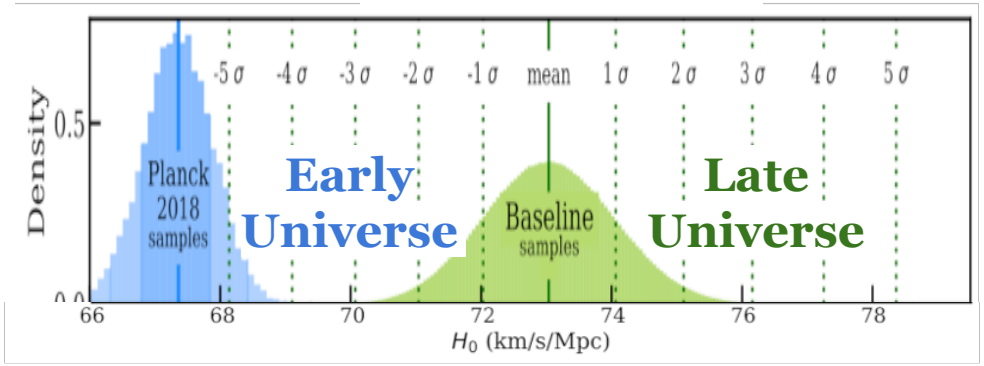
Local determination of the Hubble constant

(Riess+2022)



Hubble Tension



Cosmic distance ladder

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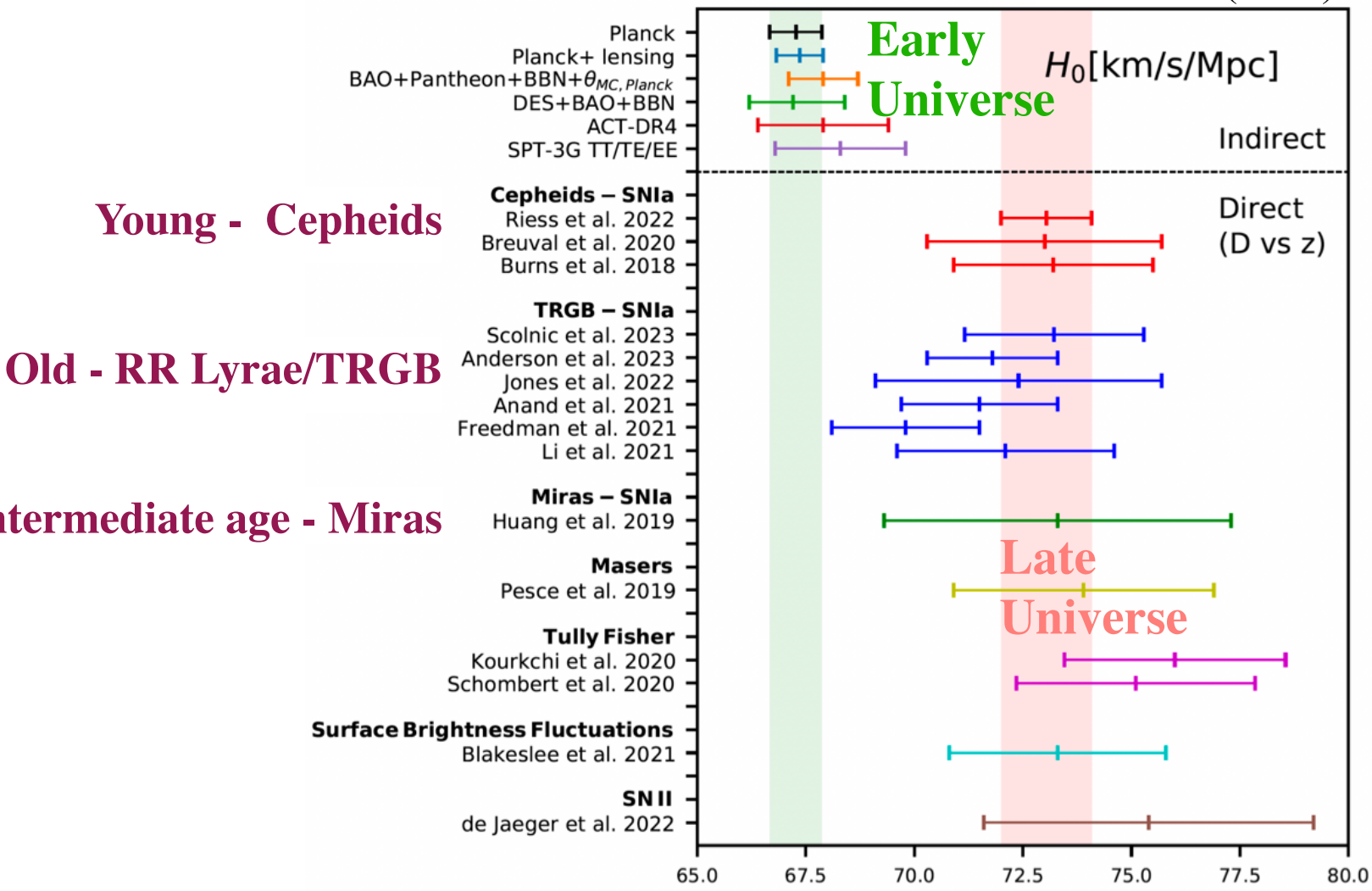
Based on standard candles of different ages and metallicities

Valentino+(2022)



Young - Cepheids

Old - RR Lyrae/TRGB

Intermediate age - Miras

Variable star numbers

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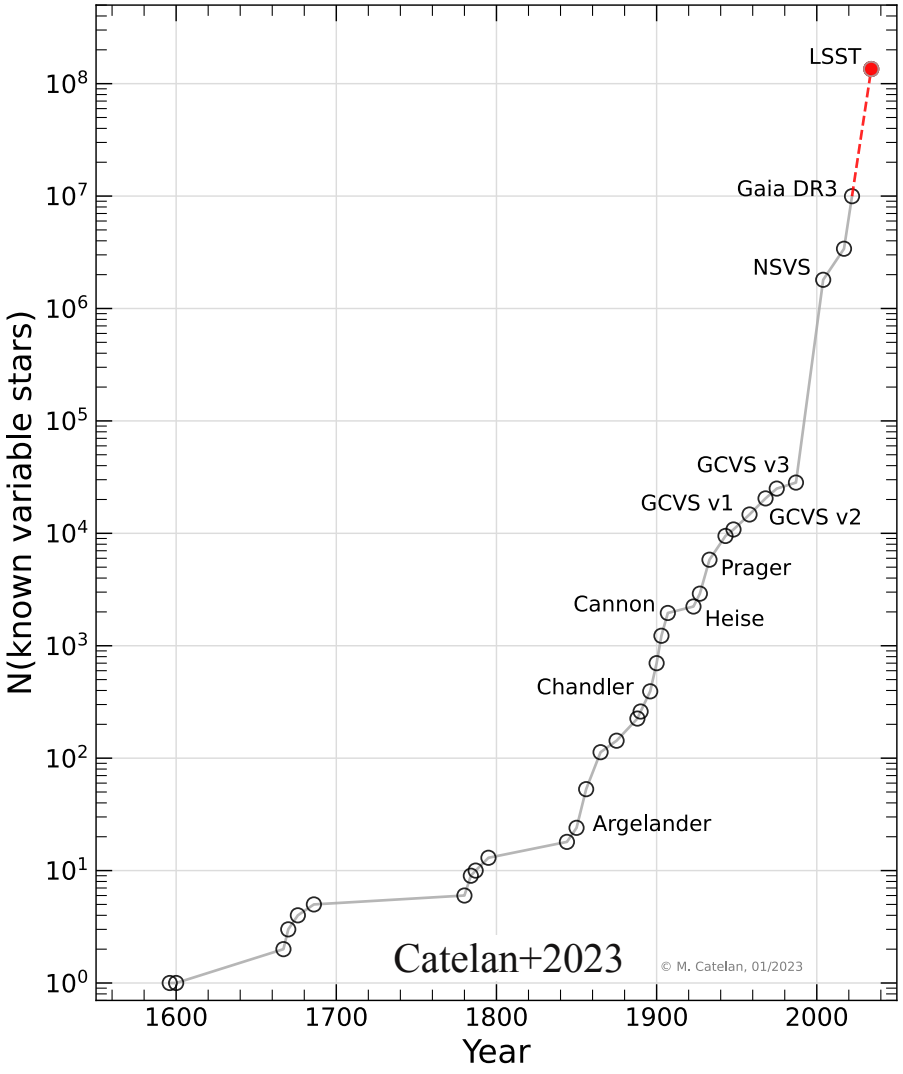
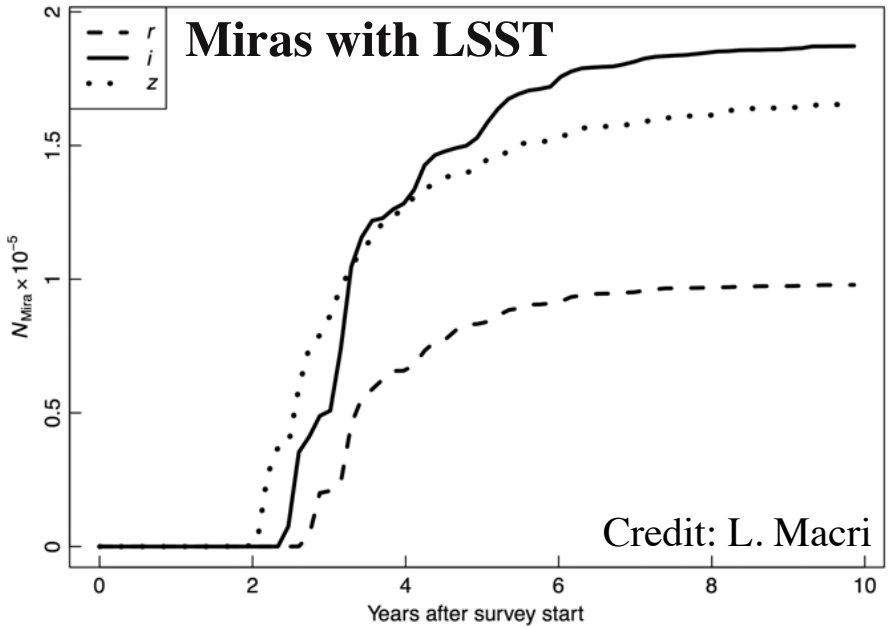
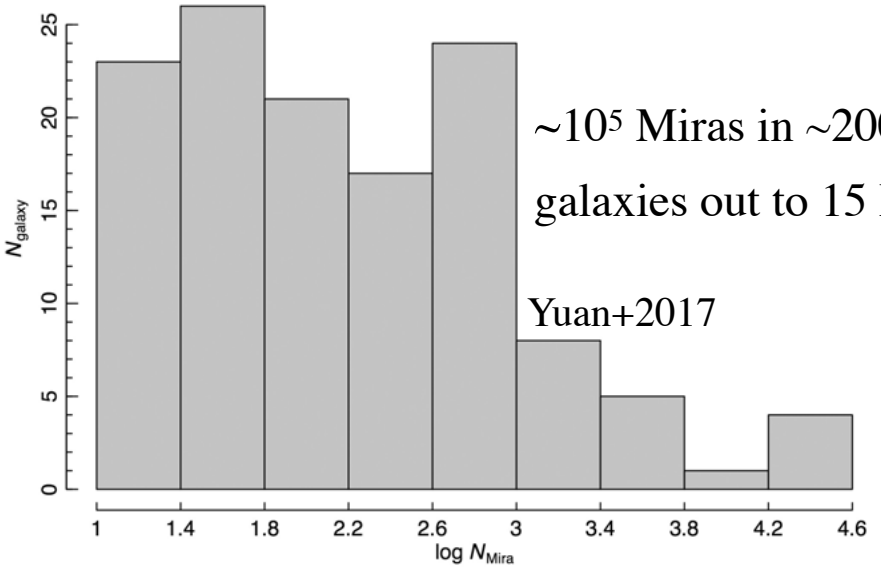
Now and with LSST…



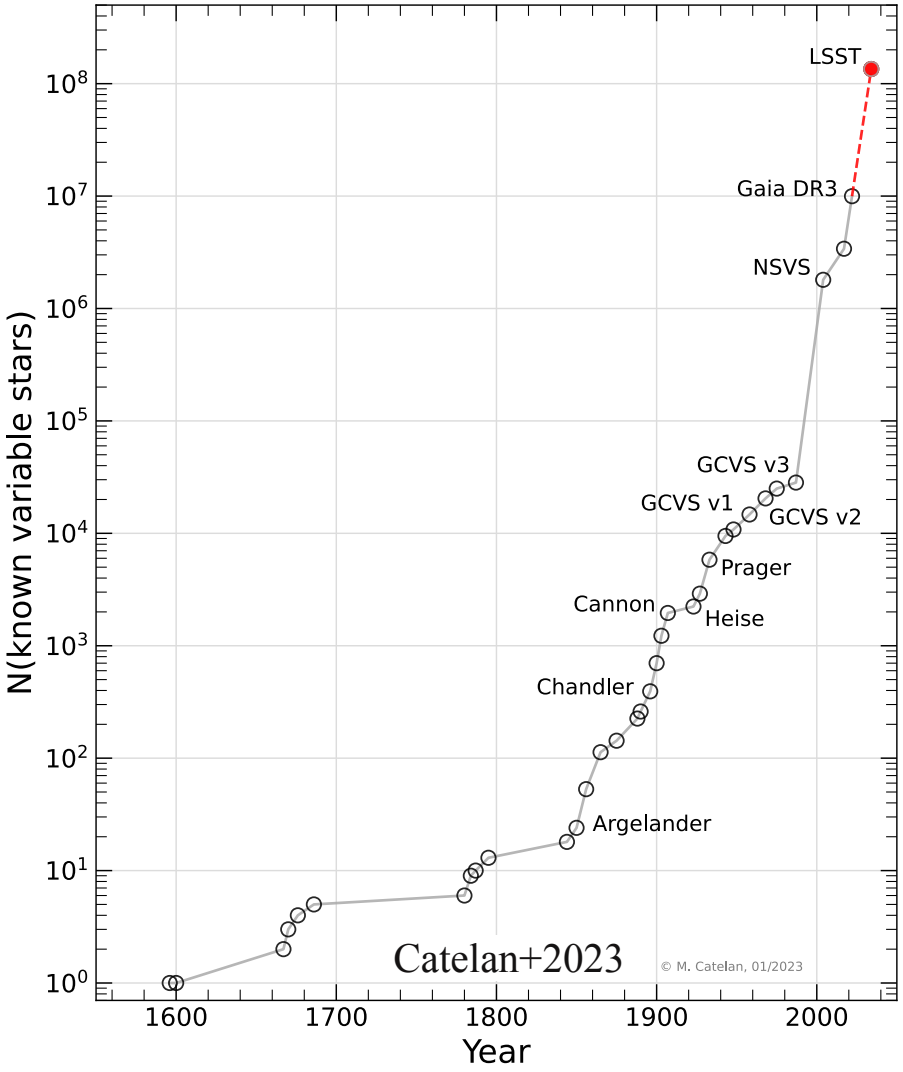


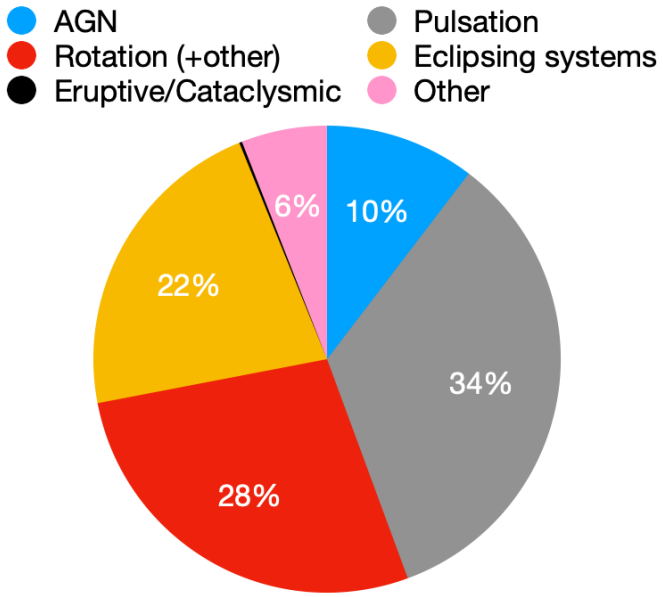


Variable star numbers

IUCAA

Now and with LSST…



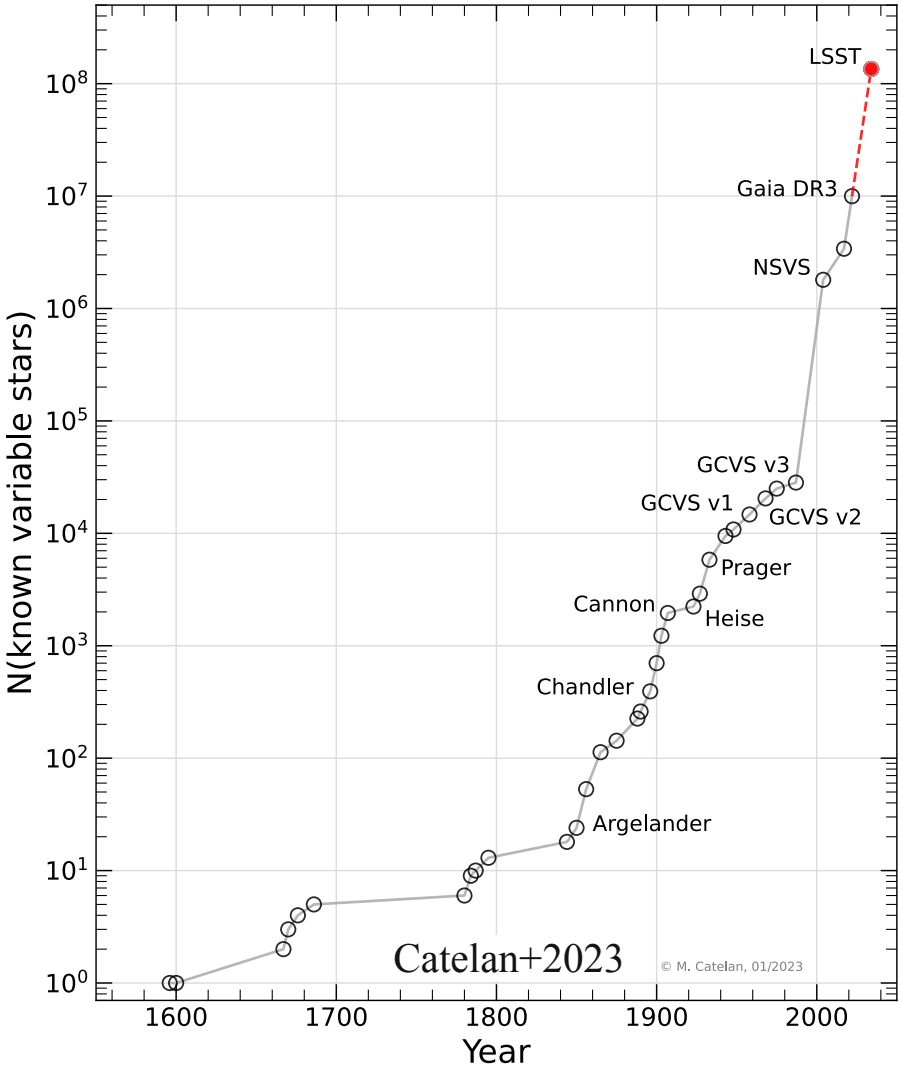


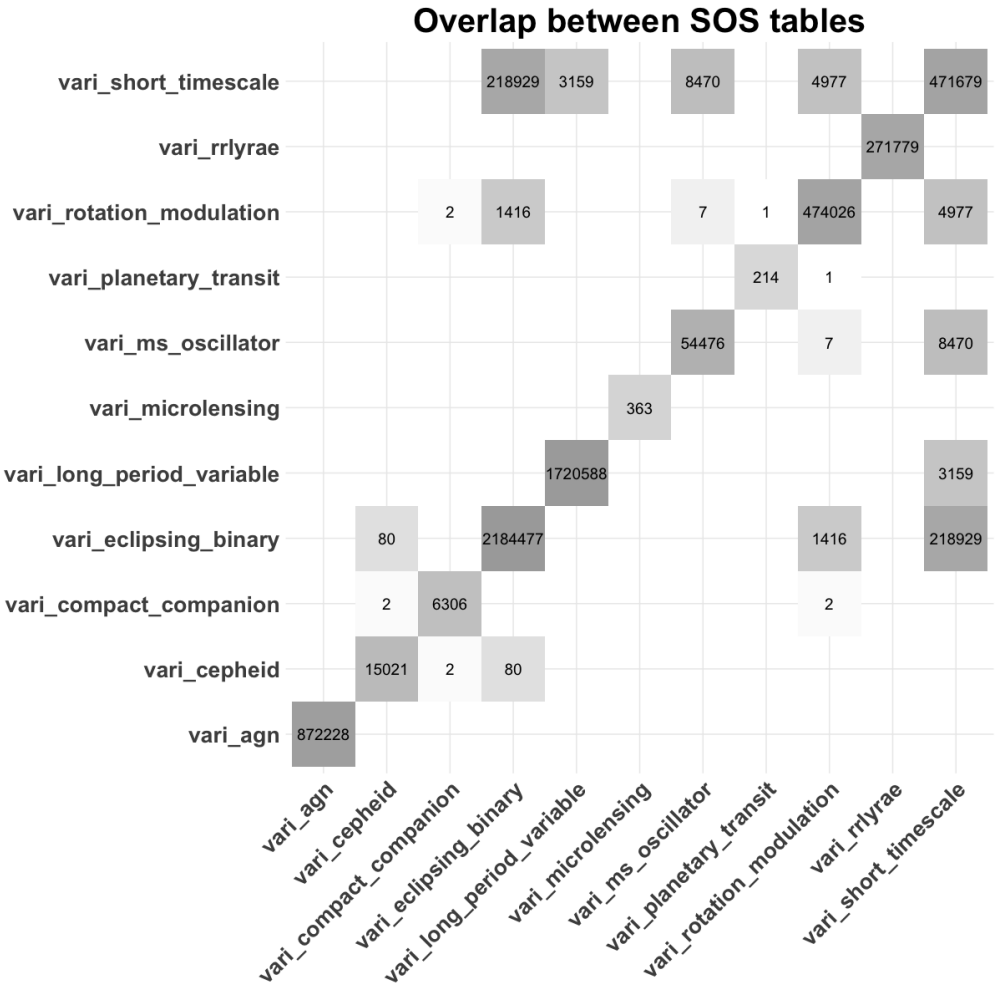
Gaia DR3

Eyer+2022

Variable star numbers

Now and with LSST…

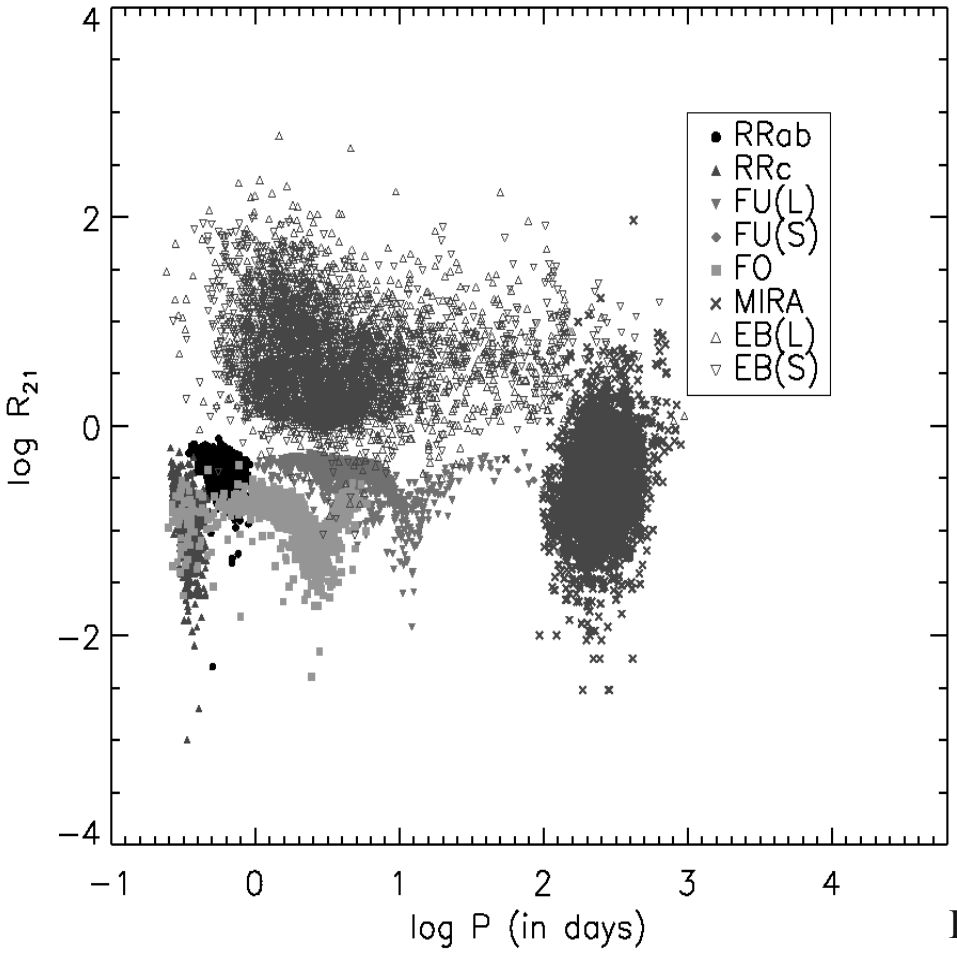


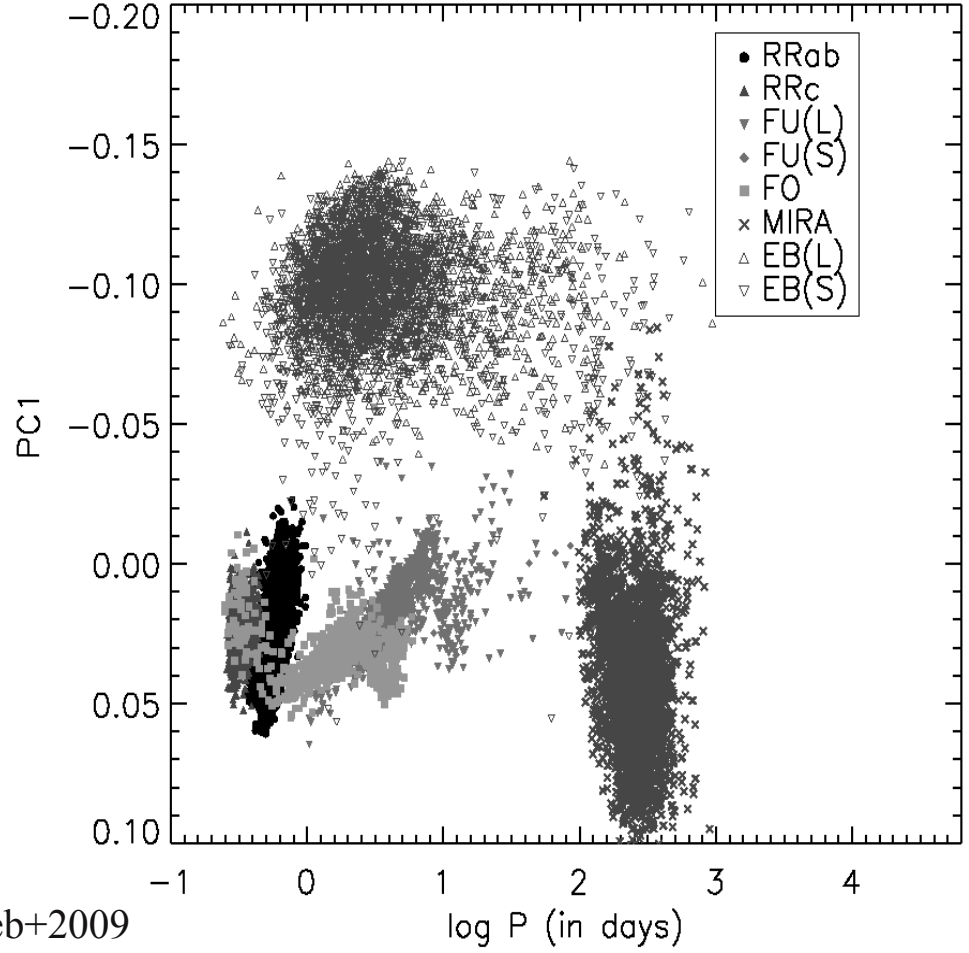


Eyer+2022

Variable star classification

Traditional Fourier/PCA analysis for periodic variable stars





Deb+2009

Variable star classification

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Year	Catalog / Survey	Title
2013	Gaia Mission (Preliminary Data)	*Gaia: The astrometric and photometric mission*
2016	OGLE-IV	*The OGLE-IV Catalog of Galactic and Magellanic Cloud Variables*
2017	GCVS 5th Edition	*General Catalogue of Variable Stars, 5th Edition*
	CRTS	*The Catalina Real-Time Transient Survey: Variable Stars in the Catalina Sky Survey*
2018	Gaia DR2	*Gaia Data Release 2: The astrometric solution*
	Pan-STARRS1	*The Pan-STARRS1 Transients and Variable Stars*
	VVV	*VVV Variable Star Catalog*
	VMC	*The VISTA Magellanic Clouds Survey: Variable Stars and Their Evolutionary Pathways in the Magellanic Clouds*
2019	ZTF	*The Zwicky Transient Facility Bright Transient and Variable Star Catalog*
	ASAS-SN	*The ASAS-SN Catalog of Variable Stars*
2020	TESS	*TESS Variable Star Catalog: Early Results from the First Year of Data*
2022	Gaia DR3	*Gaia Data Release 3*
2025 (expected)	LSST	*Variable Stars in the LSST Era*

ChatGPT

Variable star classification

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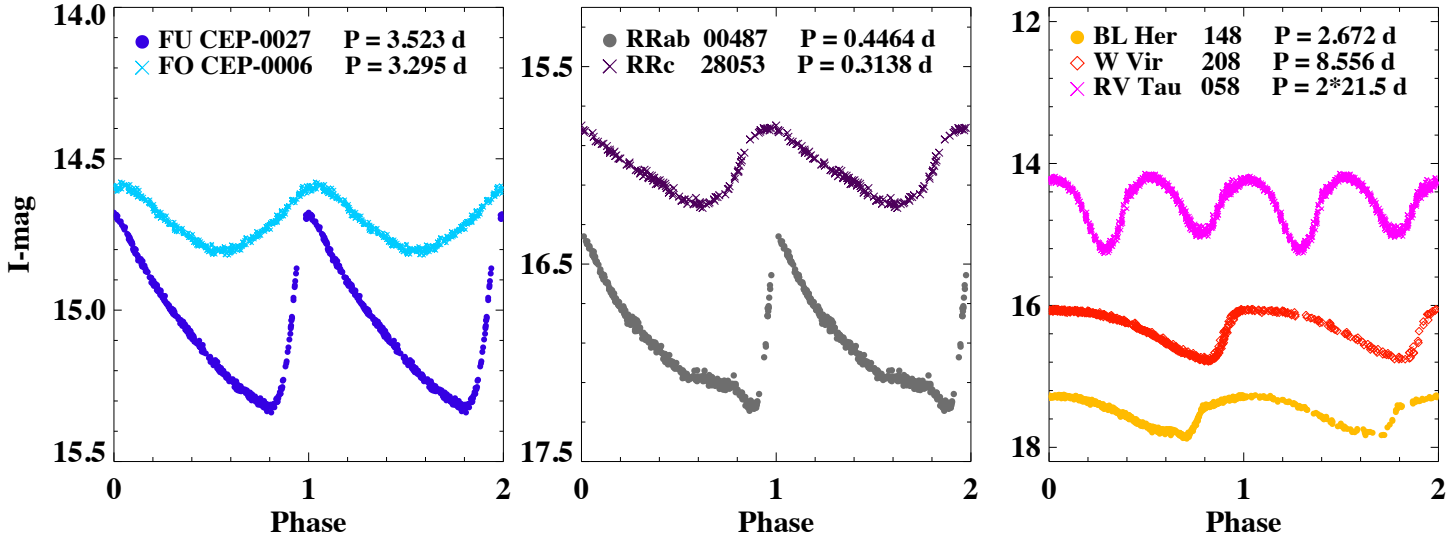
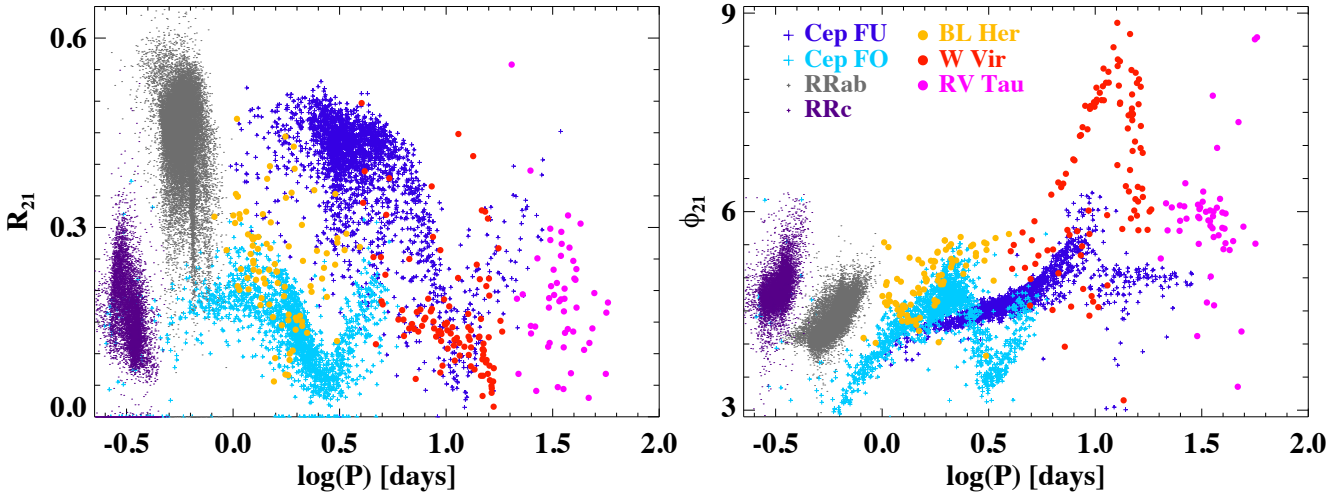
Light curves of periodic variables





Variable star classification

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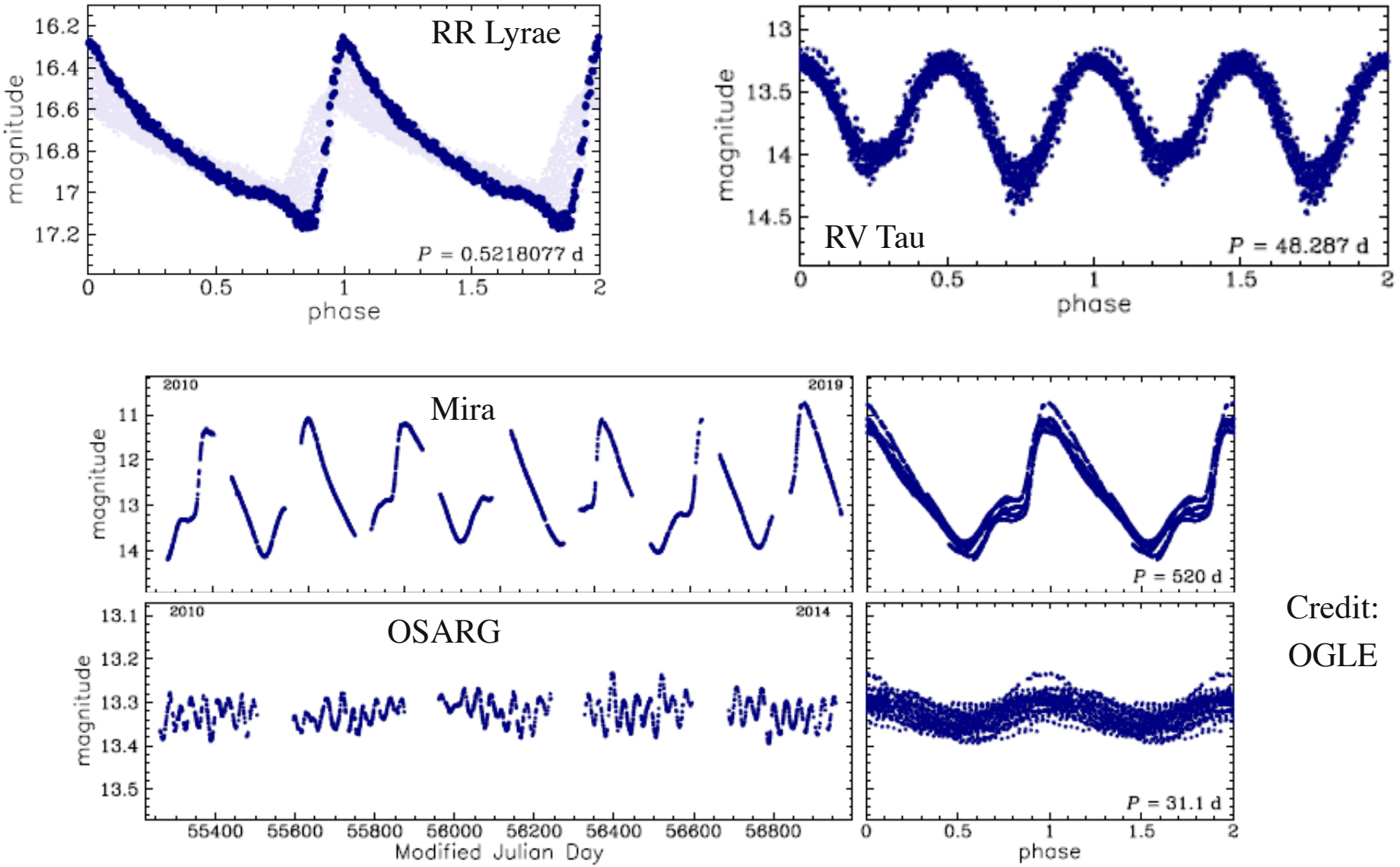
Light curves of periodic variables



Credit: OGLE

Variable star classification

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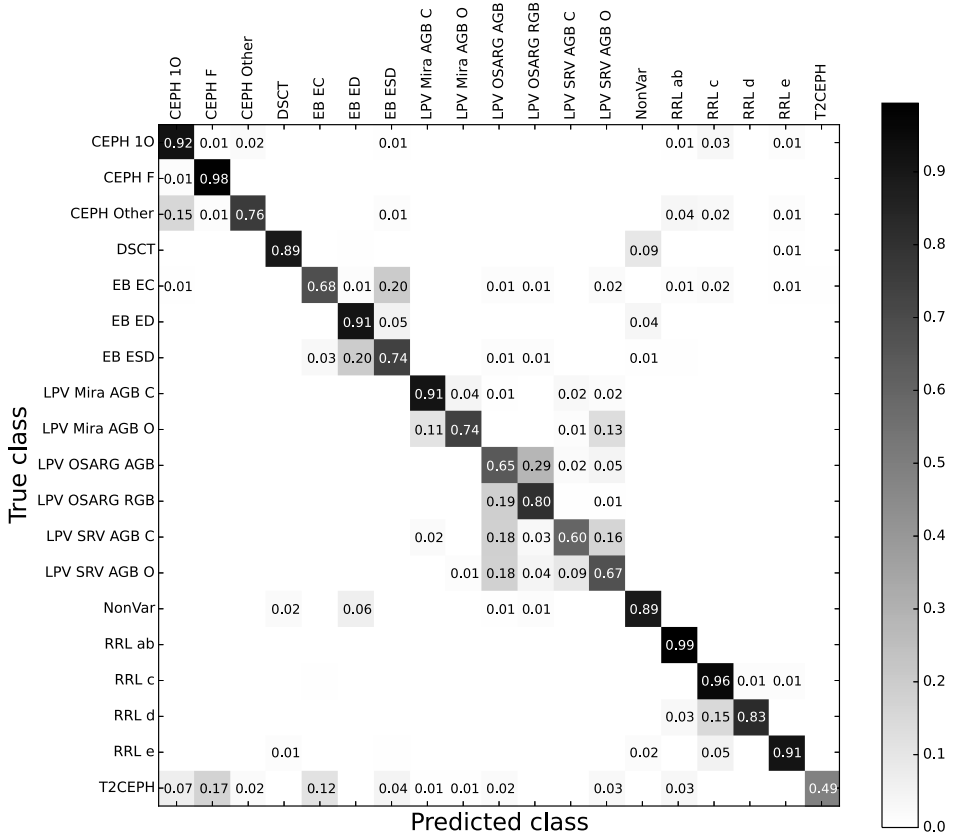
Random-Forest classifier — Light curve features

Feature	Description	Estimated by LC
Period	Photometric period determined by the Lomb-Scargle perioddogram	Y
Parallax	Photometric parallax provided by *Gaia*DR3	
Error	Parallax uncertainty provided by *Gaia* DR3	
$(B_P - R_P)_0$	$(G_{BP} - G_{RP})_0$, dereddened color determined based on *Gaia* DR3	
M_{W_G}	G-band (330 nm to 1050 nm) absolute Wesenheit magnitudes determined based on *Gaia* DR3	
Amp.	Normalized peak-to-peak amplitude determined from the eighth-order Fourier fitting of the LCs	Y
γ_2	Kurtosis $=\frac{\frac{1}{n}\sum_{i=1}^{n}(x_i-\bar{x})^4}{(\frac{1}{n}\sum_{i=1}^{n}(x_i-\bar{x})^2)^2} - 3$	Y
γ_1	Skewness $= \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i-\bar{x})^3}{(\frac{1}{n}\sum_{i=1}^{n}(x_i-\bar{x})^2)^3}/2$	Y
Q_{31}	The normalized difference betweeen 3rd quartile (75%) and 1st quartile (25%) in LCs	Y
W	Shapiro-Wilk normality test statistics	Y
K	Stetson K index, calculated using LCs	Y
Std	The normalized weighted standard deviation of the LCs	Y
R_{21}	a_2/a_1, 2nd to 1st amplitude ratio obtained from the eighth-order Fourier fitting	Y
R_{31}	a_3/a_1, 3rd to 1st amplitude ratio obtained from the eighth-order Fourier fitting	Y
ϕ_{21}	$\phi_2 - 2\phi_1$, the phase difference between 2nd to 1st phase obtained from the eighth-order Fourier fitting	Y
ϕ_{31}	$\phi_3 - 3\phi_1$, the phase difference between 3rd to 1st phase obtained from the eighth-order Fourier fitting	Y
$W_1 - W_3$	$W_1 - W_3$ color determined based on *WISE*	
$W_1 - W_4$	$W_1 - W_4$ color determined based on *WISE*	
M_{W_1}	The absolute W_1-band Wesenheit magnitude	

TESS (Gao+2024)

ALeRCE (Sánchez-Sáez+2021)

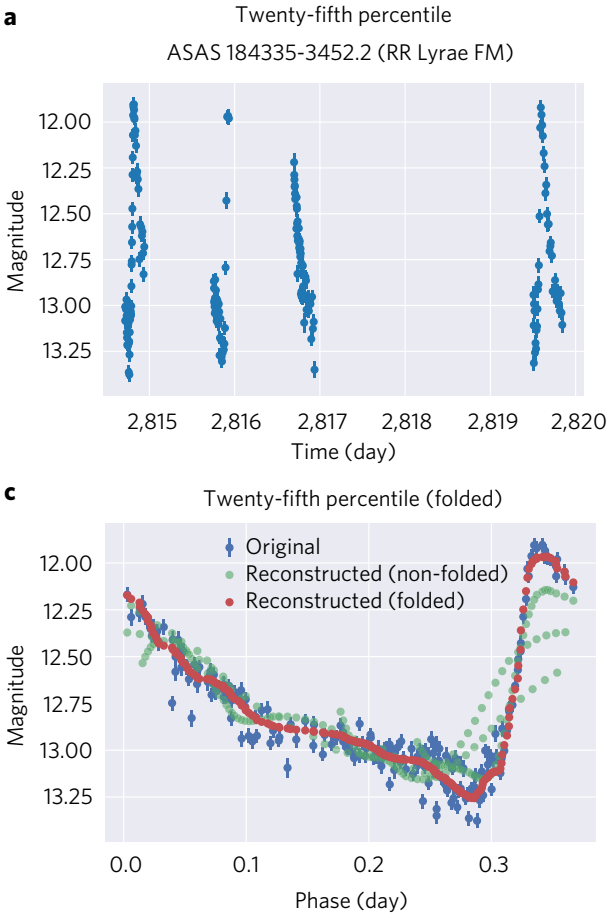
OGLE (Kim & Bailer-Jones+2016)

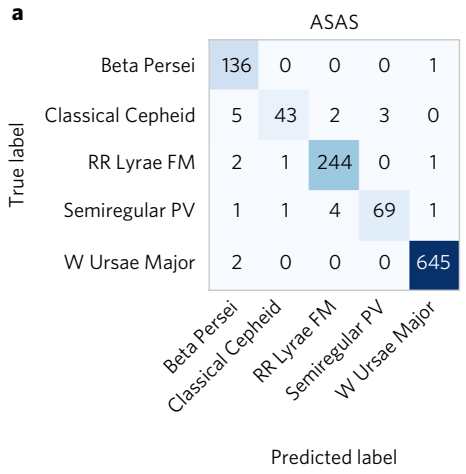


Variable star classification

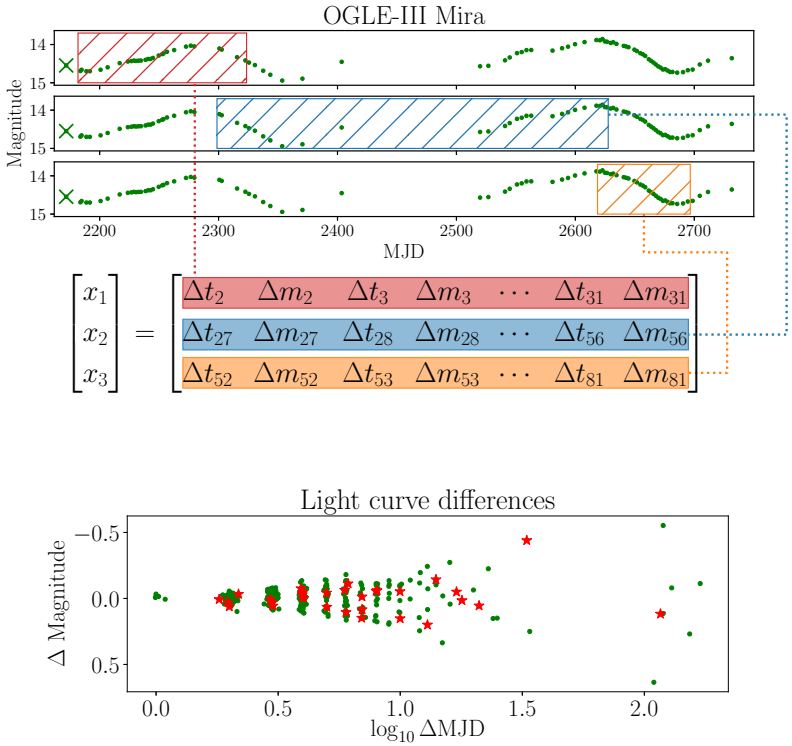
Recurrent Neural Networks

Encoder-decoder architecture (Naul+2018)





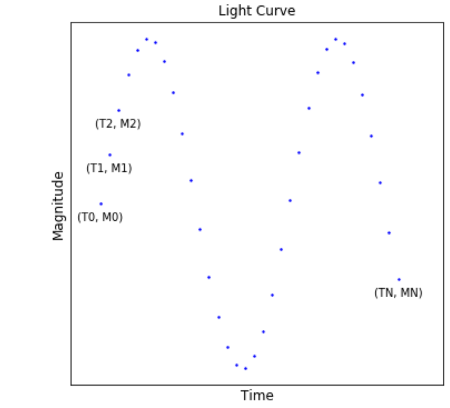
dmdt matrix — OGLE (Becker+2020)
CRTS (Kang+2023)



Variable star classification

Convolutional neural networks (CNN)

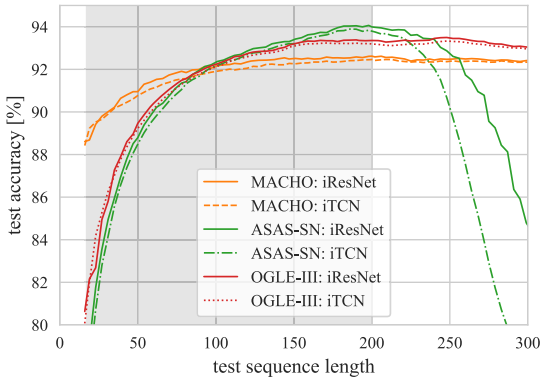
dmdt matrix based inputs (Aguirre+2019)



$$[\,T_0\,,\,T_1\,,\,\ldots,\,T_N\,]$$
$$[\,M_0,\,M_1,\,\ldots,\,M_N\,]$$

$$[\,0,\,(T_1-T_0)\,,\,\ldots,\,(T_N-T_{N-1})\,]$$
$$[\,0,\,(M_1-M_0),\,\ldots,\,(M_N-M_{N-1})\,]$$

$$[\,T'_0\,,\,T'_1\,,\,\ldots\,,\,T'_{N'}\,]$$
$$[\,M'_0,\,M'_1,\,\ldots,\,M'_{N'}\,]$$



Zhang+2021

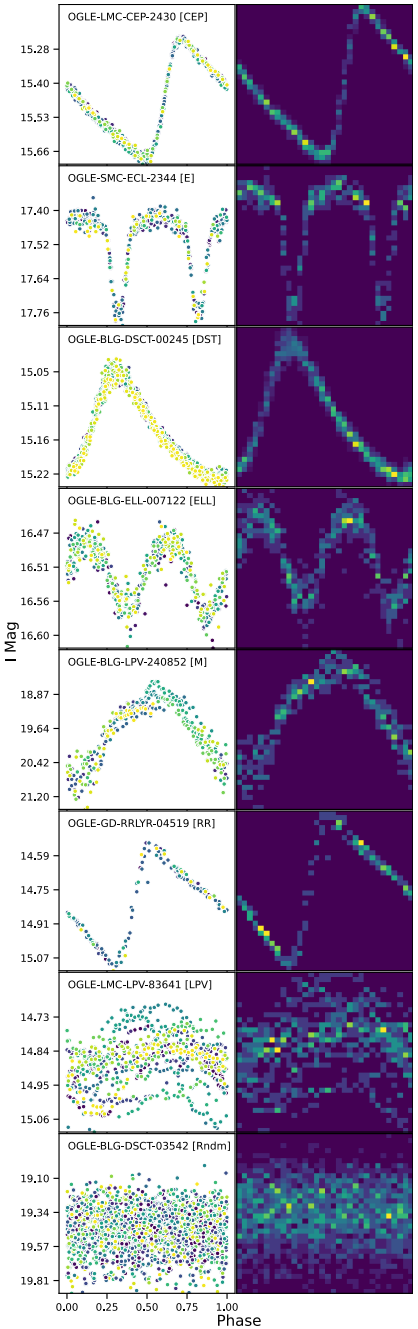
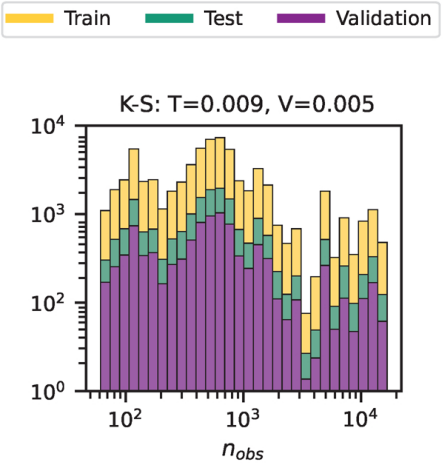


Image-based CNNs
Of OGLE light curves
Szklenár+2021,
Monsalves+2024

Dmdt-images
CRTS light curves
Mahabal+2017

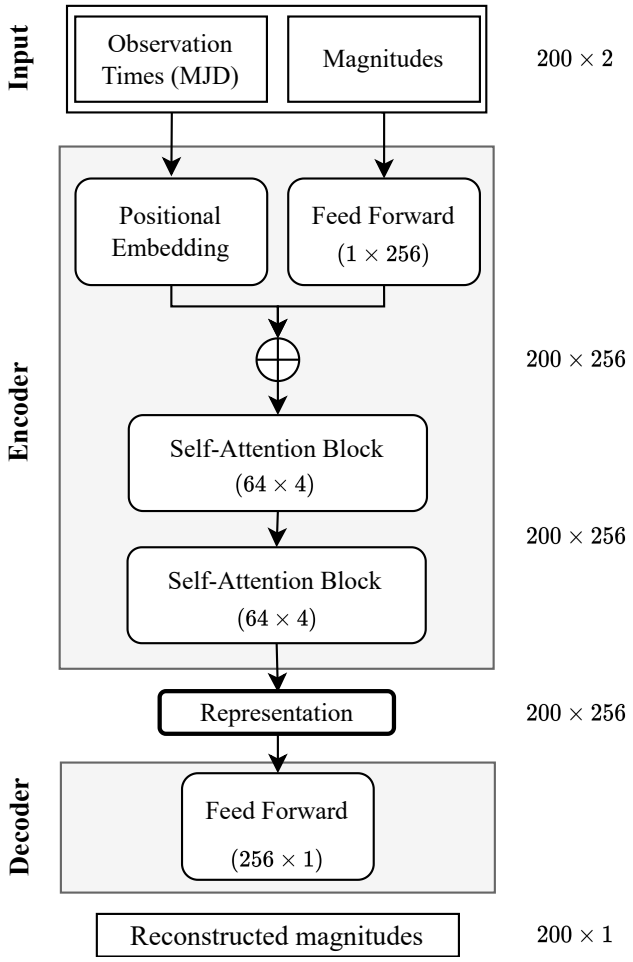


Monsalves+2024

Variable star classification

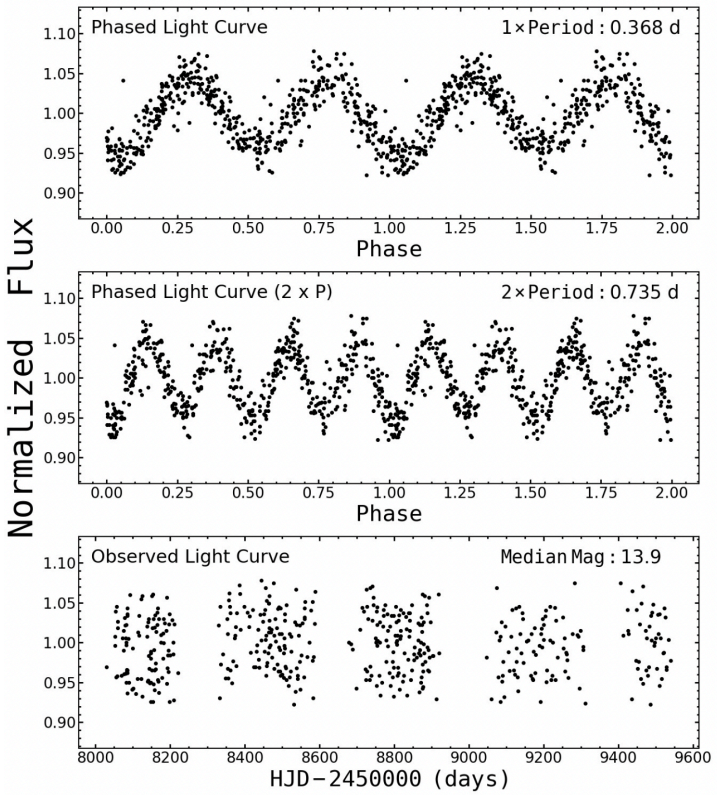
Transformer-based classifier

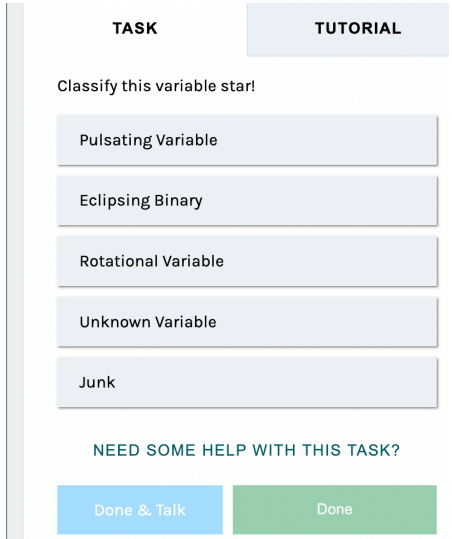
ASTROMER — (Donoso-Oliva+2023)

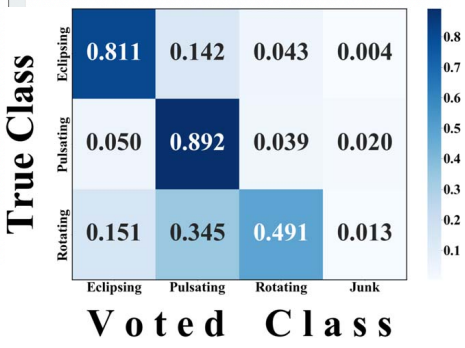


Citizen ASAS-SN data release

(Christy+2022)

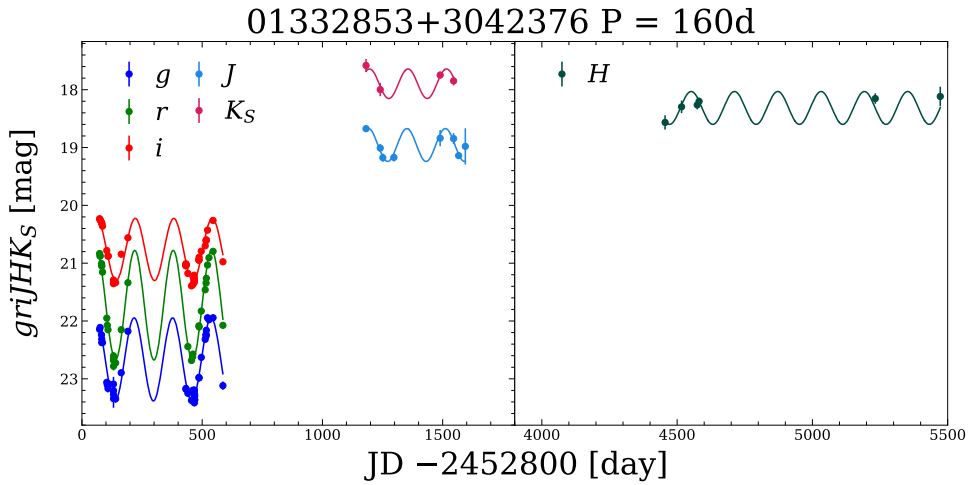


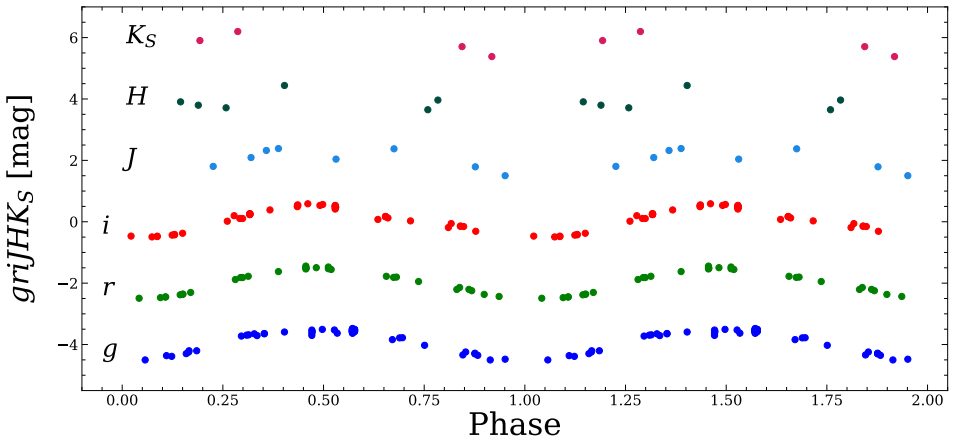




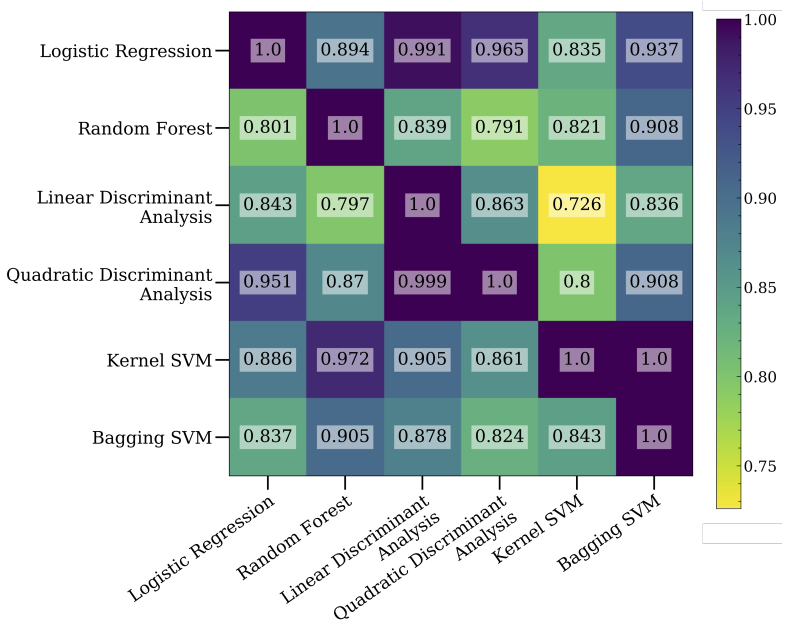
Variable star classification

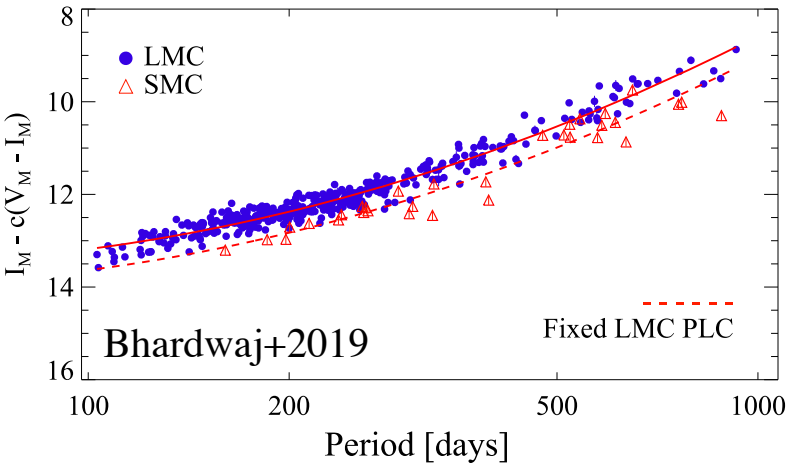
Specific object studies — Miras





Konchady+2019





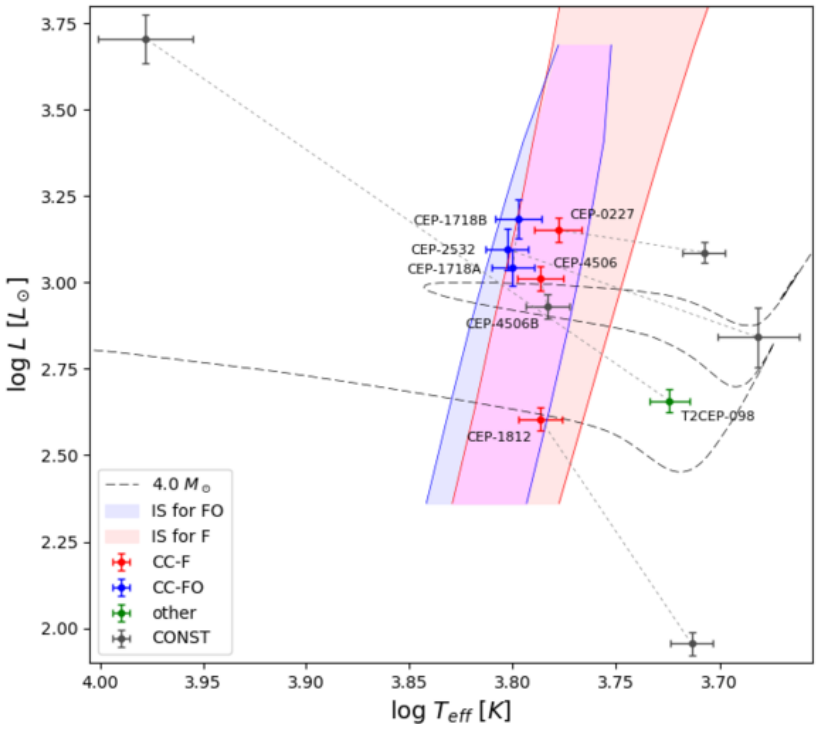
Fundamental parameters in an instant…

Cepheid mass discrepancy problem

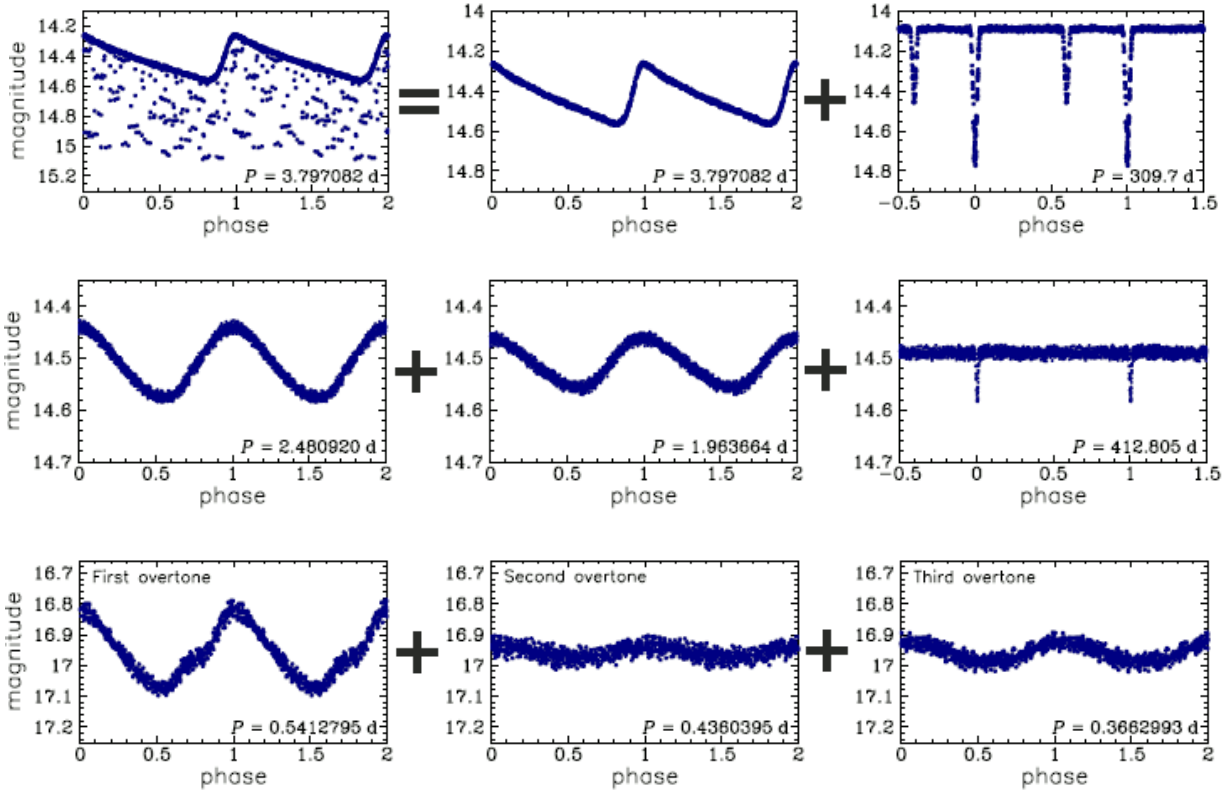
Mass-Luminosity relations

Period-mass-radius relations

Binary Cepheids (Pilecki+2019)

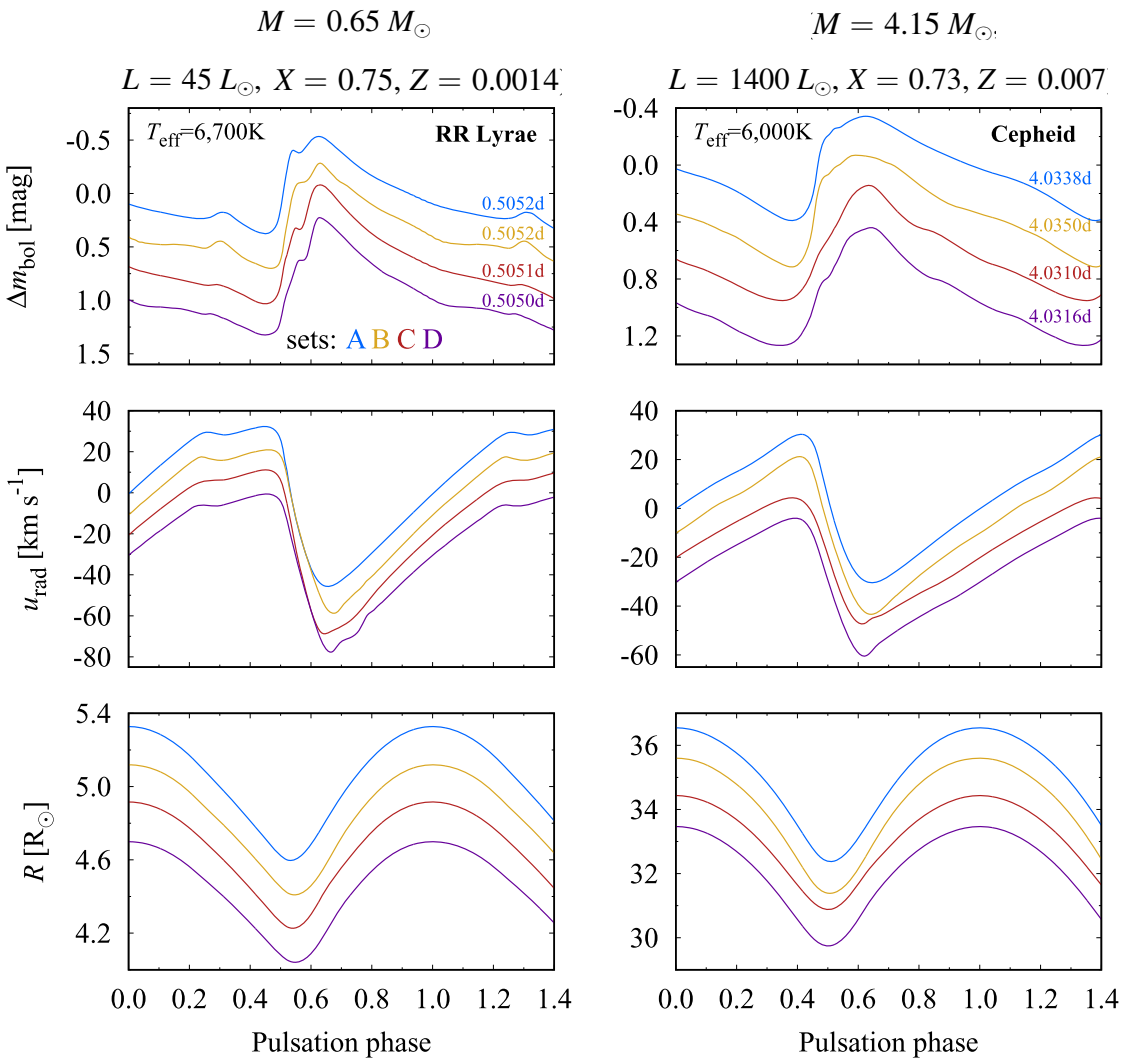


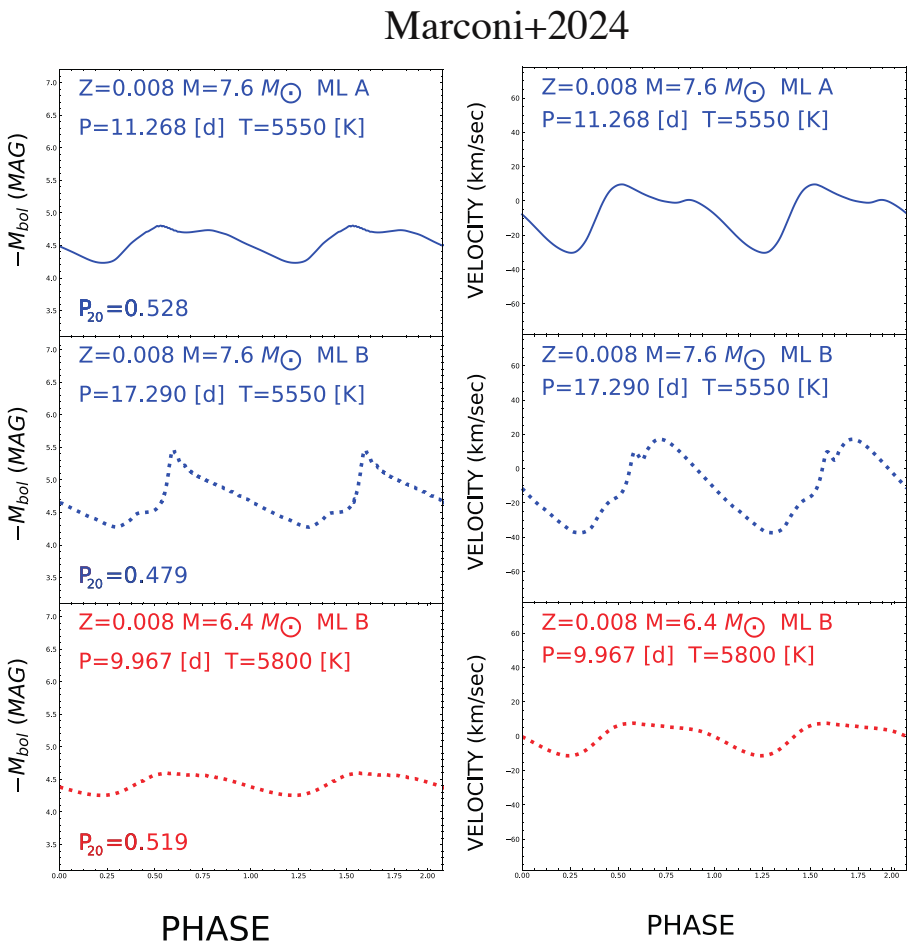
Dynamical mass of a classical Cepheid to an unprecedented 1% accuracy OGLE-LMC-CEP-0227 (Pietrzyński et al. 2010, Naturę)



Predicted fundamental parameters

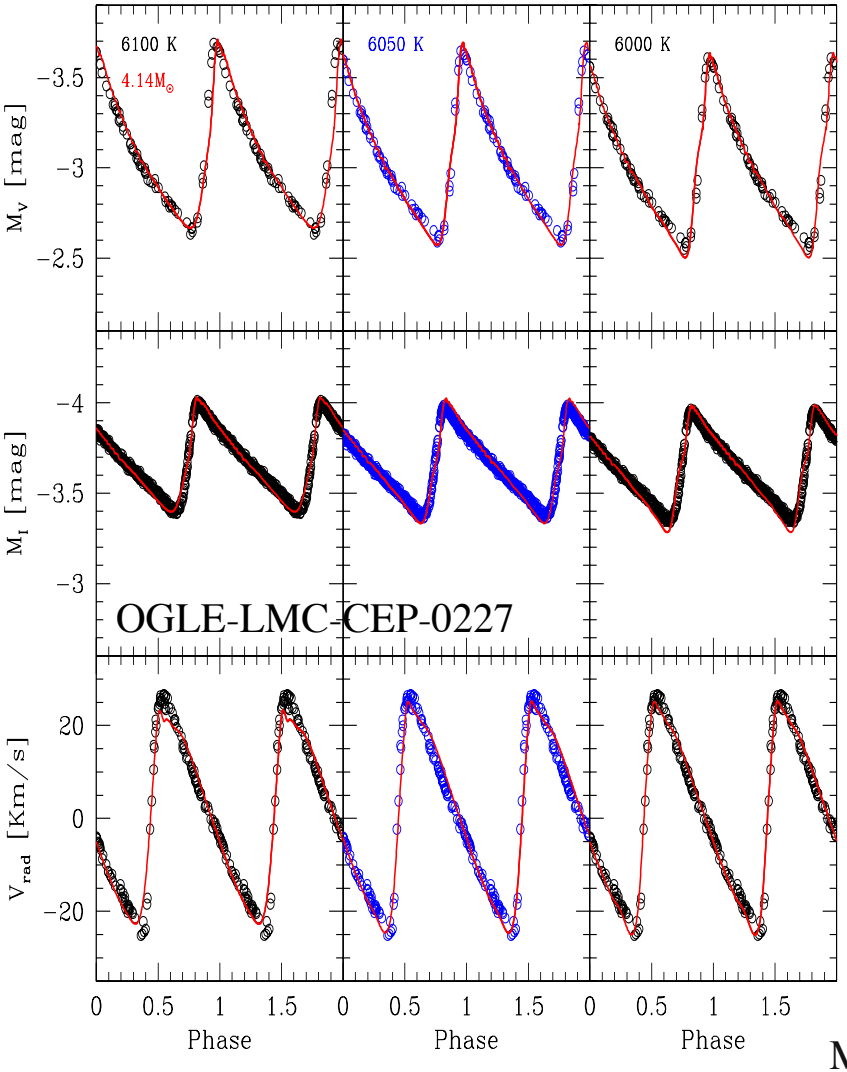
Non-linear time-dependent hydrodynamical models can reproduce light and radial velocity variations of Cepheid and RR Lyrae variables (Bono+2000, Marconi+2015, Paxton+2019)

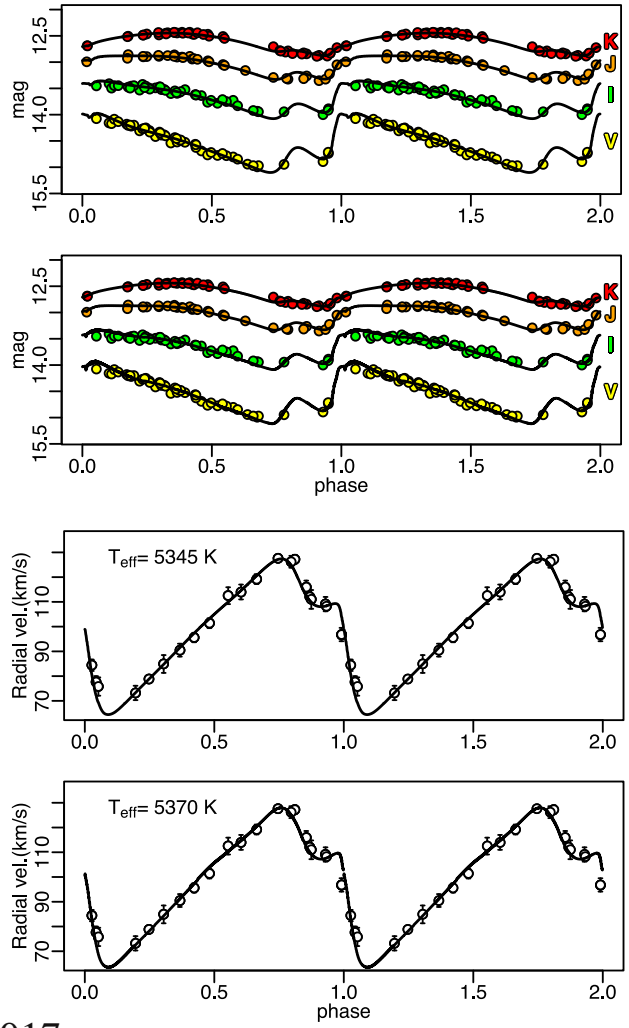




Predicted fundamental parameters

Model fitting approach





Marconi+2013, 2017

Predicted fundamental parameters

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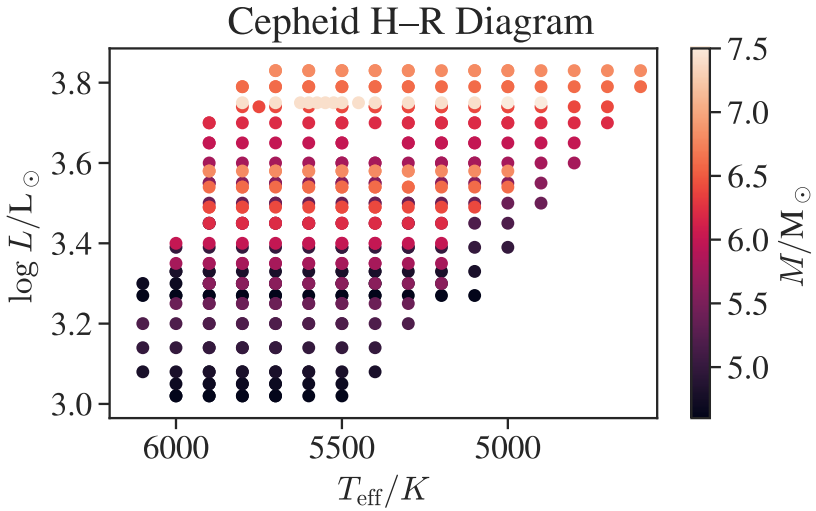
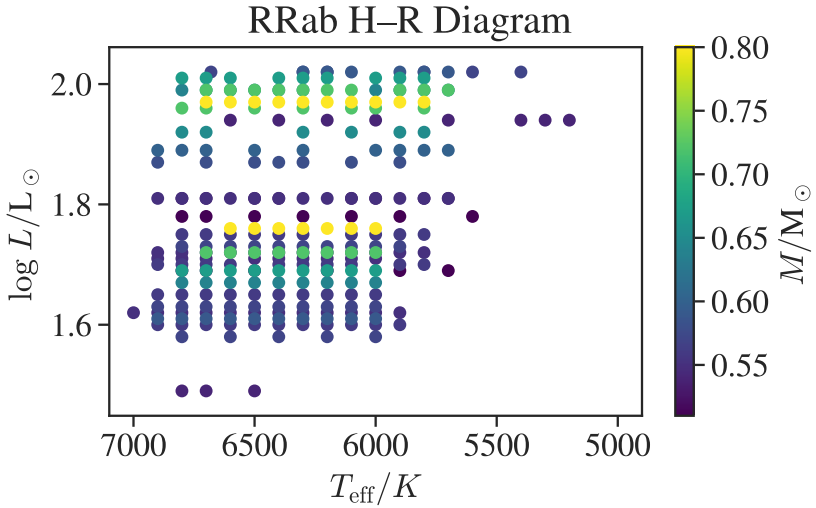
Model fitting approach to ensemble based analyses





Light curve structure parameters

$$M(t) = A_0 + \sum_{k=1}^{N} A_k \cos\left(k\omega t + \phi_k\right)$$

I- and V-band amplitudes, acutenesses, skewnesses, and the coefficients A_1, A_2, and A_3.

$$f(M, L, R, T_{\rm eff}, \ldots) = [\text{period, light curve structure}]$$

$$g = f^{-1}$$

$$g(\text{period, light curve structure}) = [M, L, R, T_{\rm eff}, \ldots]$$

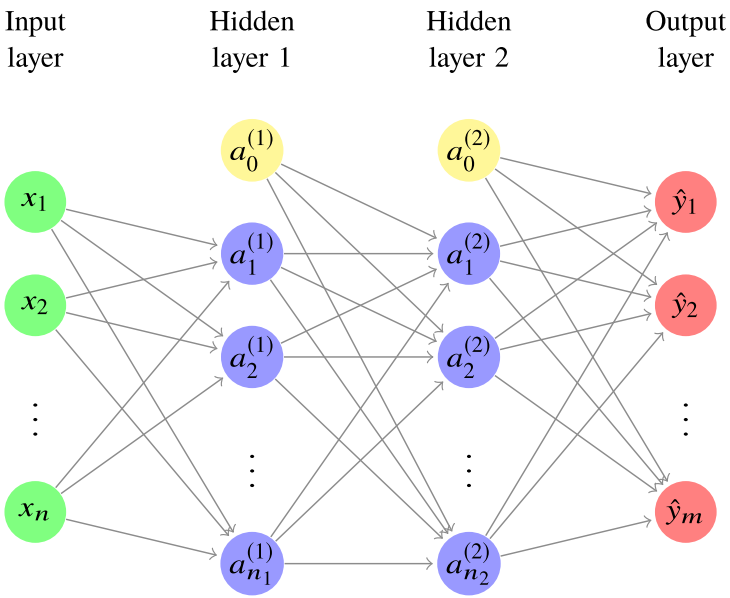
Bellinger, Kanbur, Bhardwaj+2020

Predicted fundamental parameters

IUCAA

Ensemble based analyses

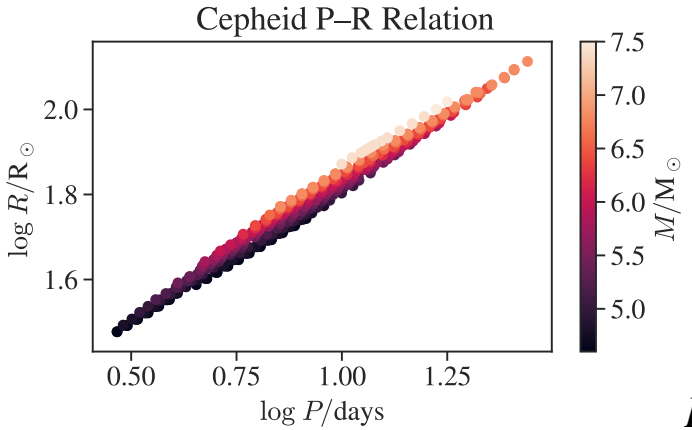
ANN trained on the theoretical models

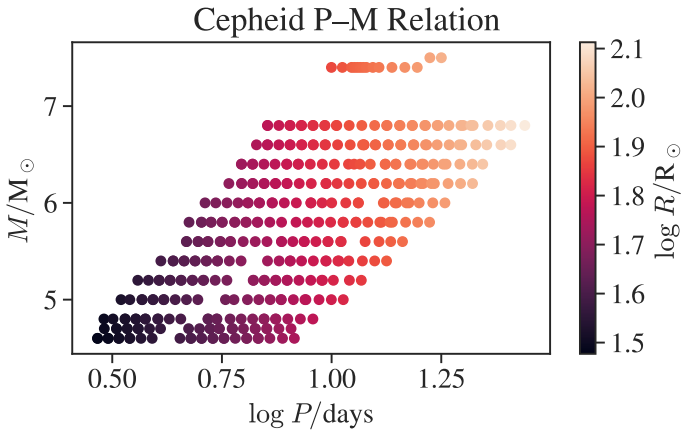


Two-fold cross-validation

Bellinger, Kanbur, Bhardwaj+2020

Model assessment





Linear model

$$y = a + b \log P$$

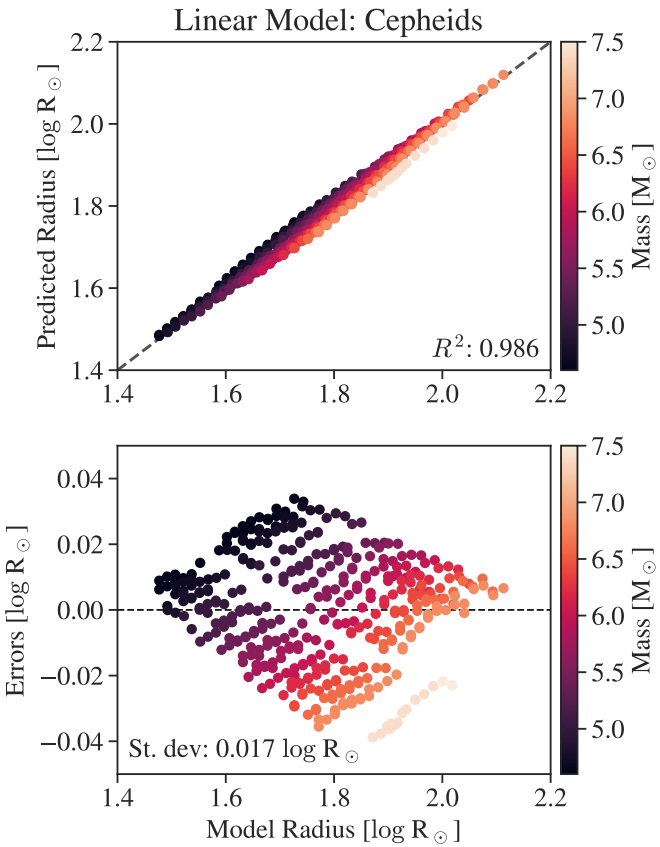
$$R^2 = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \bar{y})^2}$$

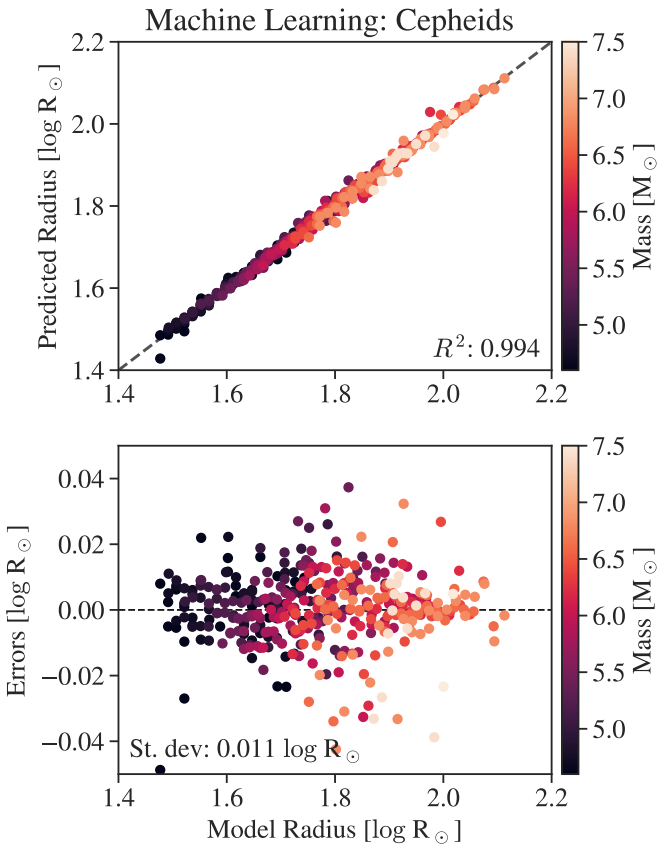
Predicted fundamental parameters

IUCAA

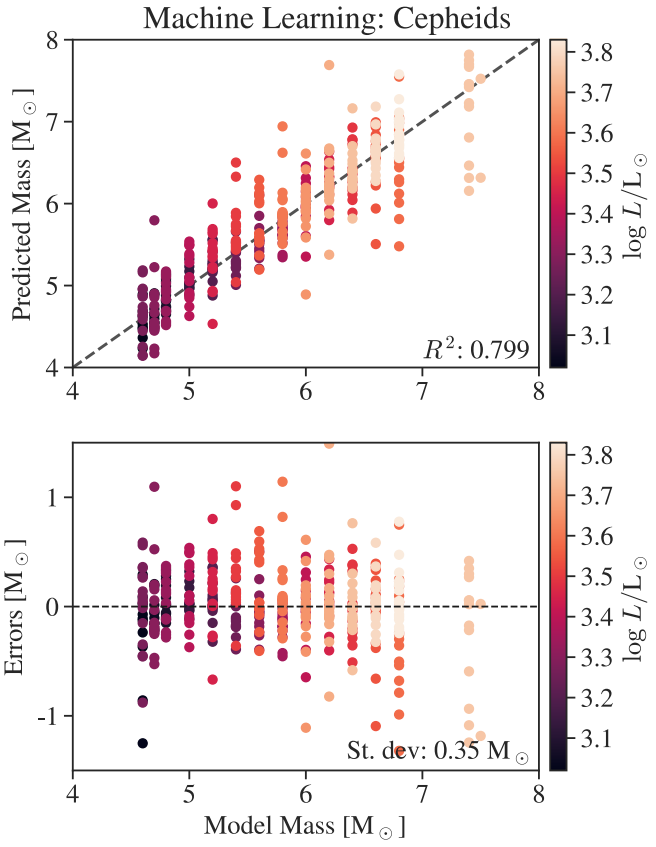
Ensemble based analyses

Radius





Mass

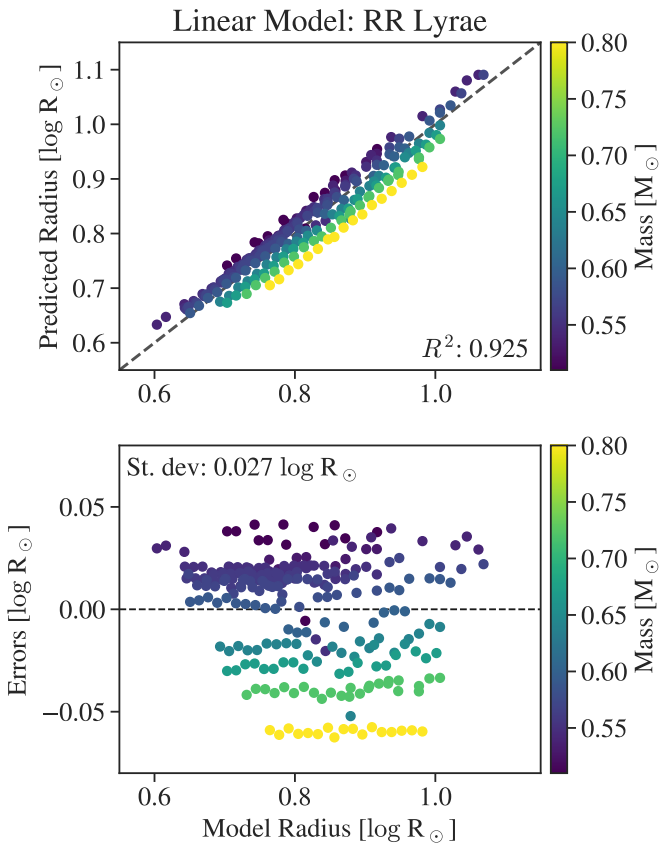


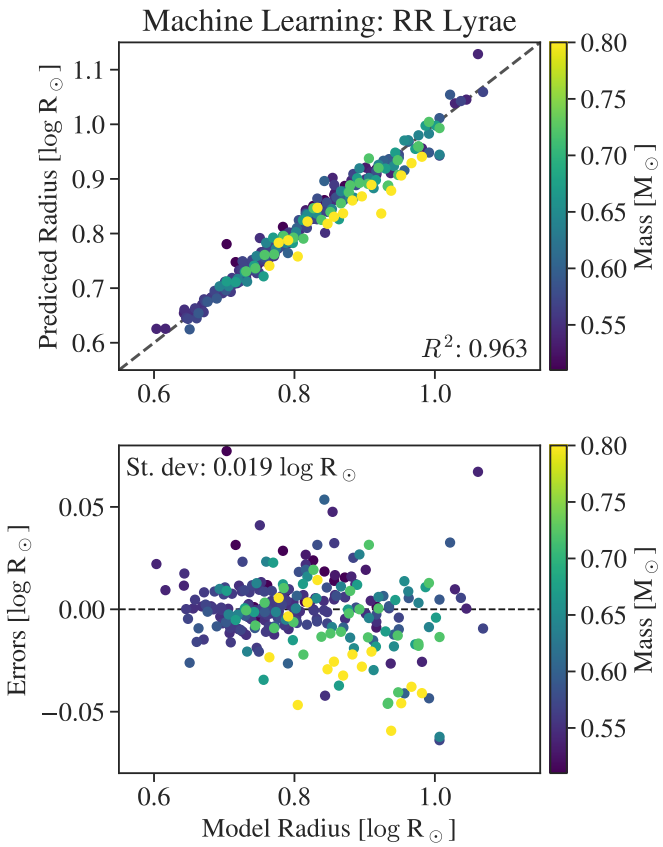
Predicted fundamental parameters

IUCAA

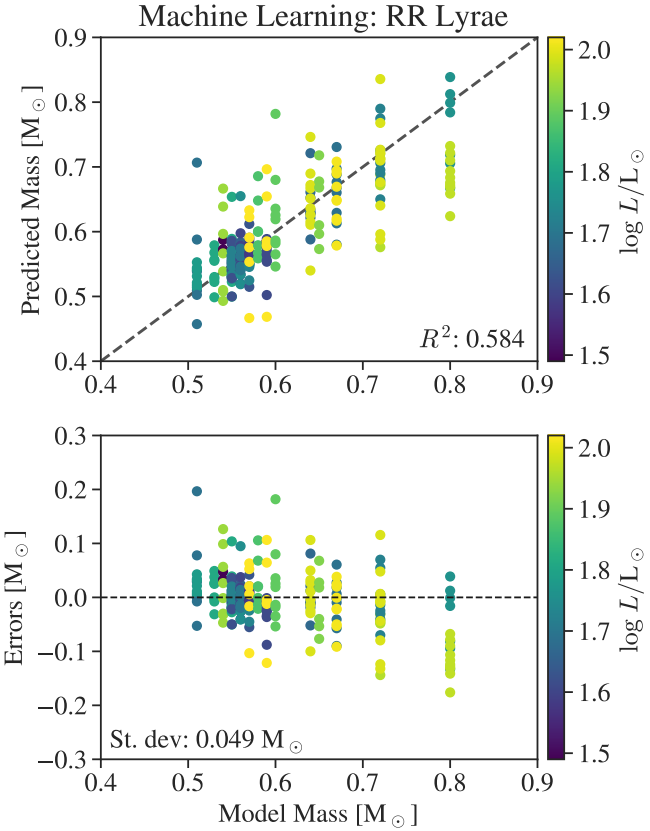
Ensemble based analyses

Radius





Mass

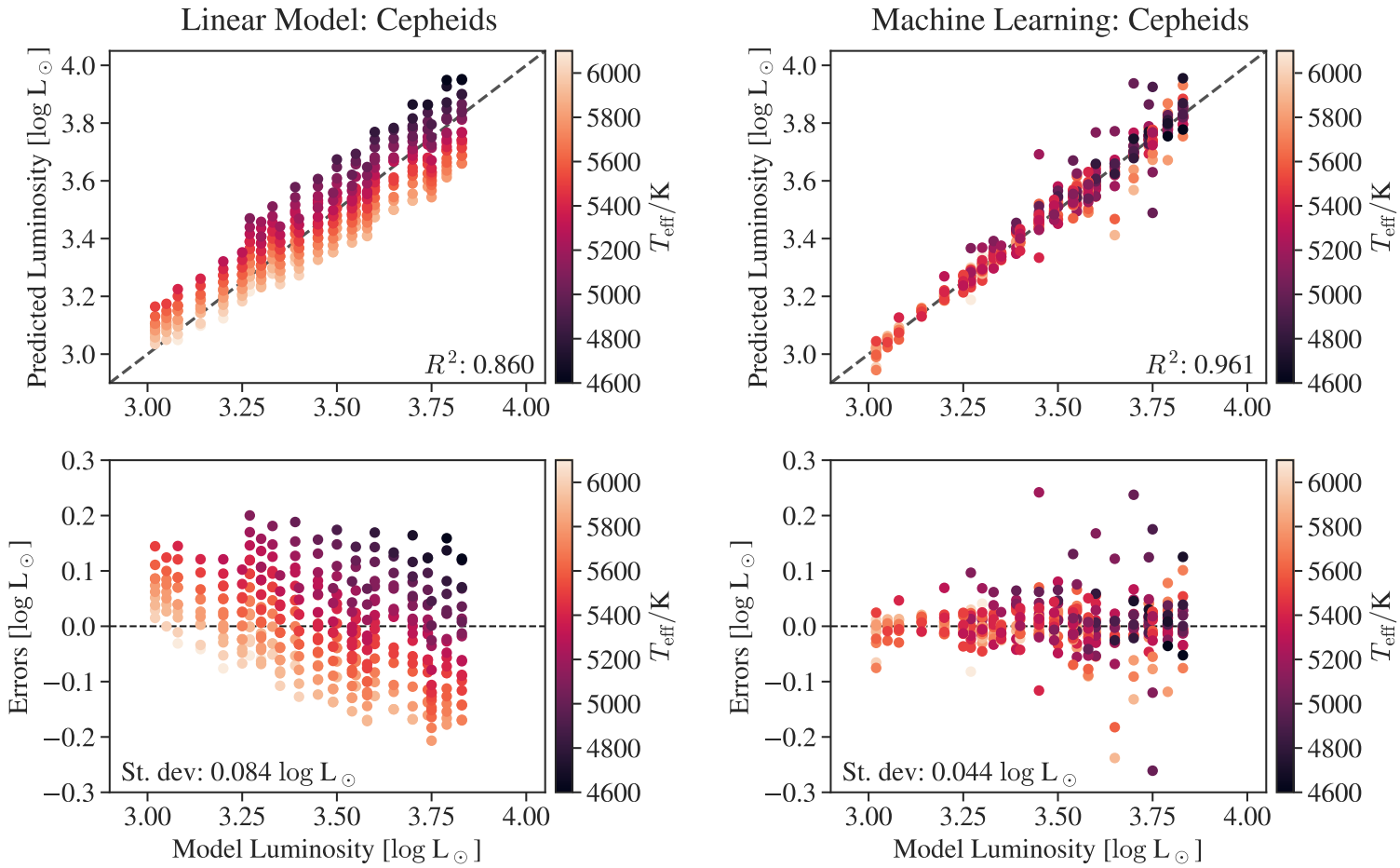


Predicted fundamental parameters

IUCAA

Ensemble based analyses

Predicted luminosities of Cepheid and RR Lyrae stars

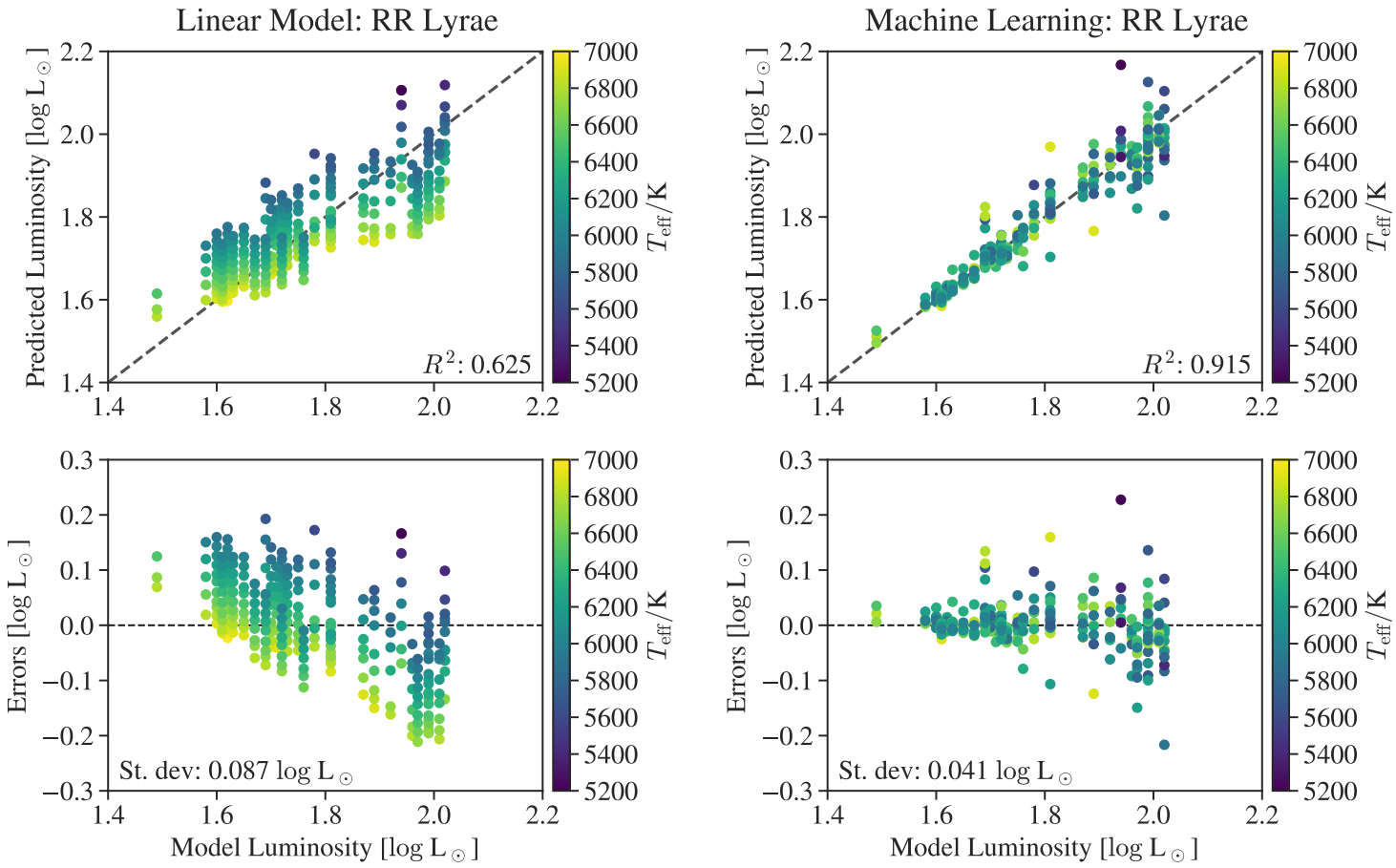


Predicted fundamental parameters

IUCAA

Ensemble based analyses

Predicted luminosities of Cepheid and RR Lyrae stars

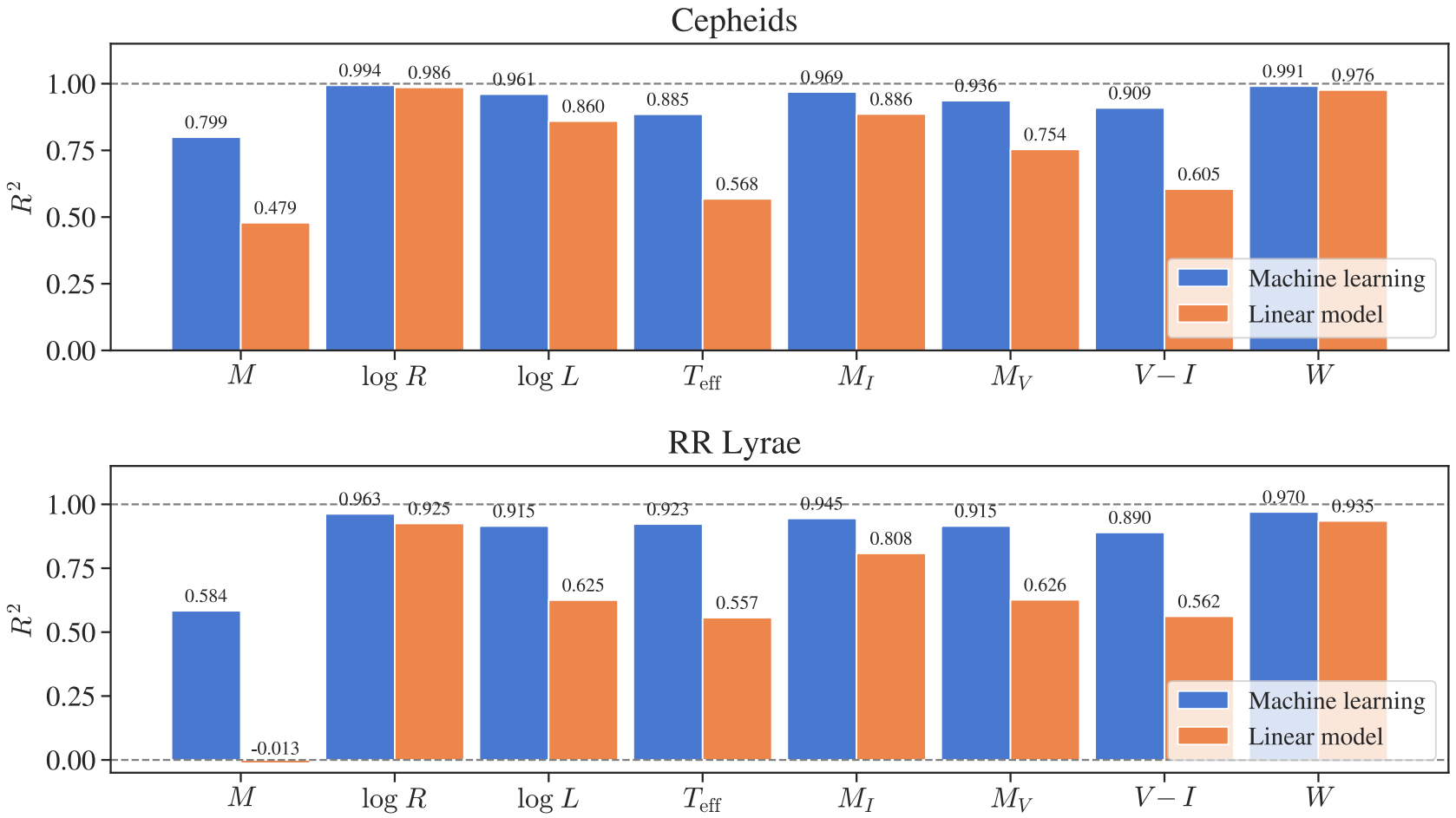


Predicted fundamental parameters

IUCAA

Ensemble based analyses

Light Curve Structure Importances

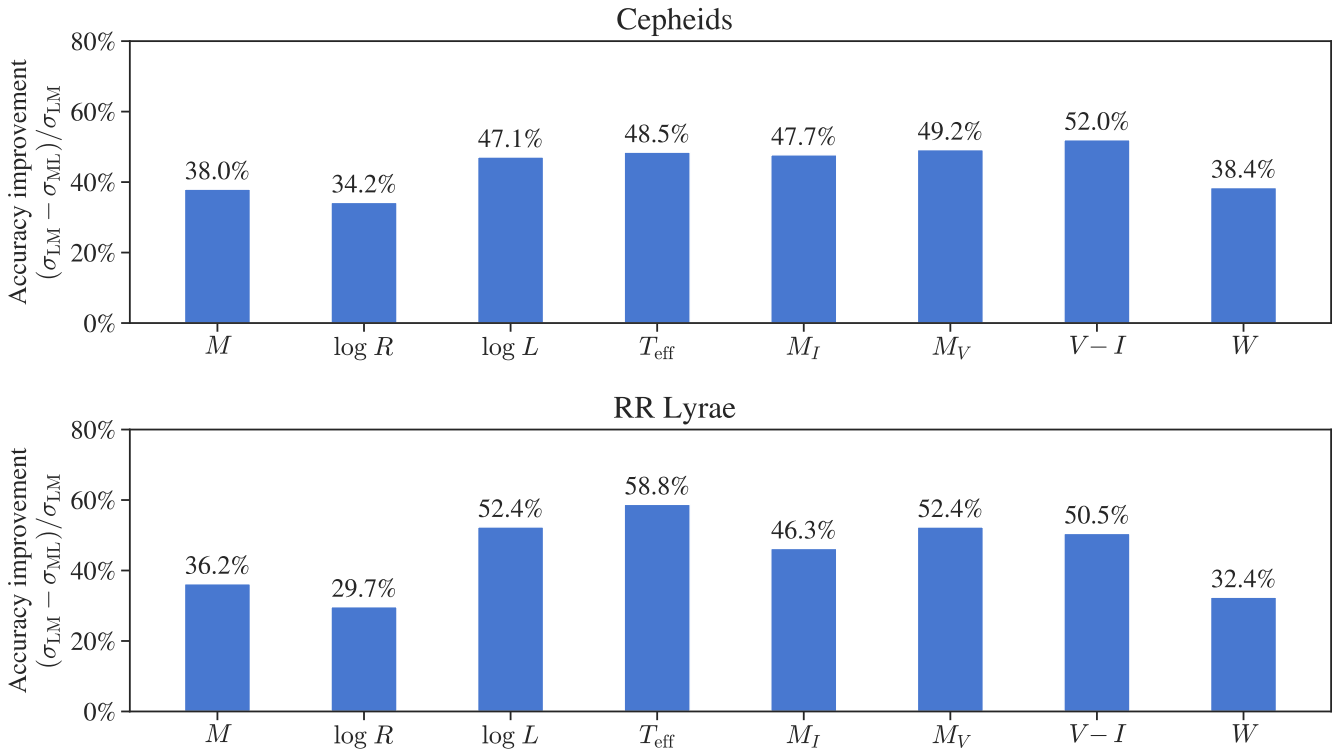


Predicted fundamental parameters

IUCAA

Ensemble based analyses

Light Curve Structure Importances



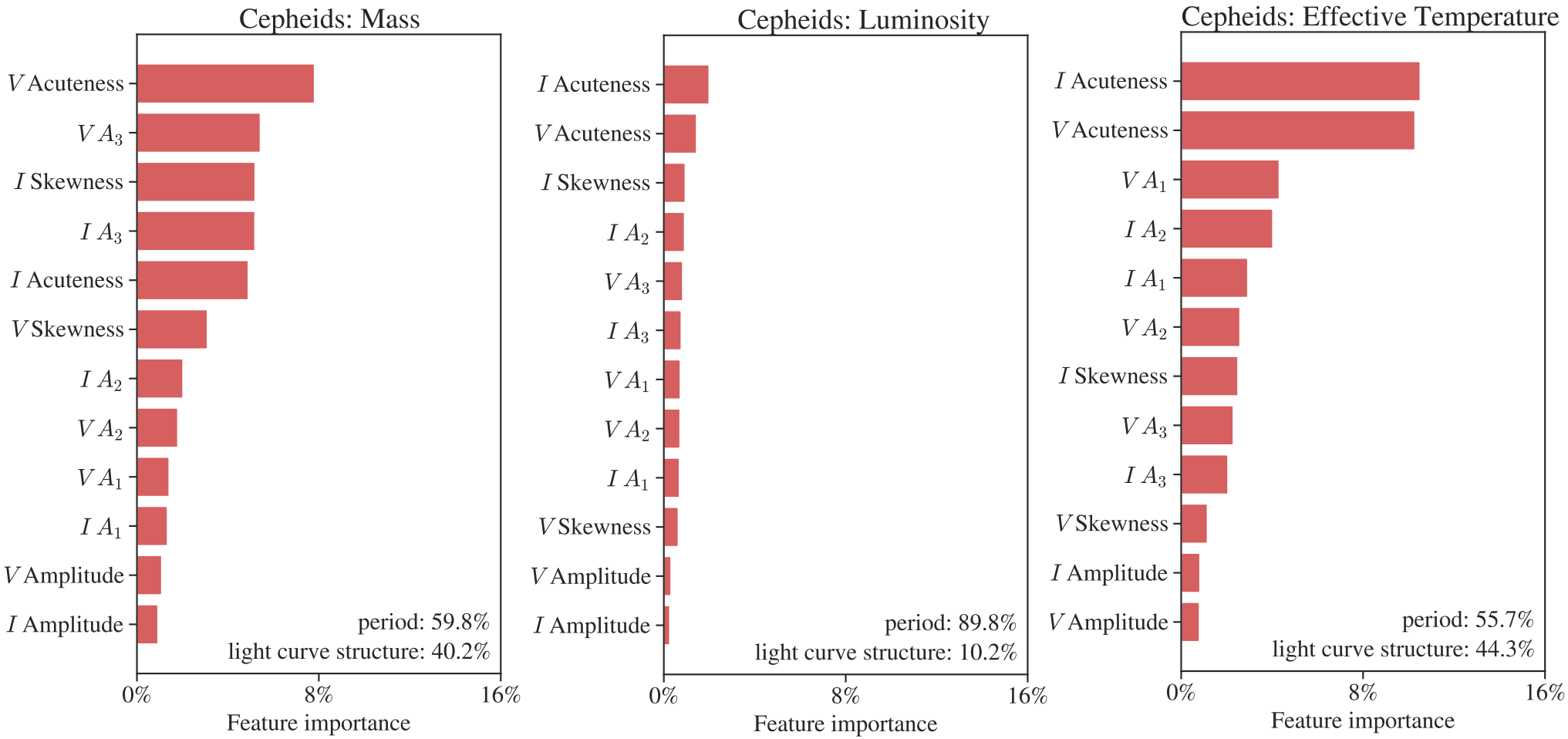
	LM		ANN	
Variable	CEP	RRL	CEP	RRL
$M/\mathrm{M}_\odot$	0.56	0.077	0.35	0.049
$\log R/\mathrm{R}_\odot$	0.017	0.027	0.011	0.019
$\log L/\mathrm{L}_\odot$	0.084	0.087	0.044	0.041
$T_{\rm eff}/\mathrm{K}$	209	240	108	98
M_I	0.19	0.16	0.10	0.086
M_V	0.26	0.21	0.13	0.098
$V-I$	0.070	0.056	0.033	0.028
W	0.11	0.11	0.065	0.076

Predicted fundamental parameters

IUCAA

Ensemble based analyses

Which light curve structure parameters are the most important?

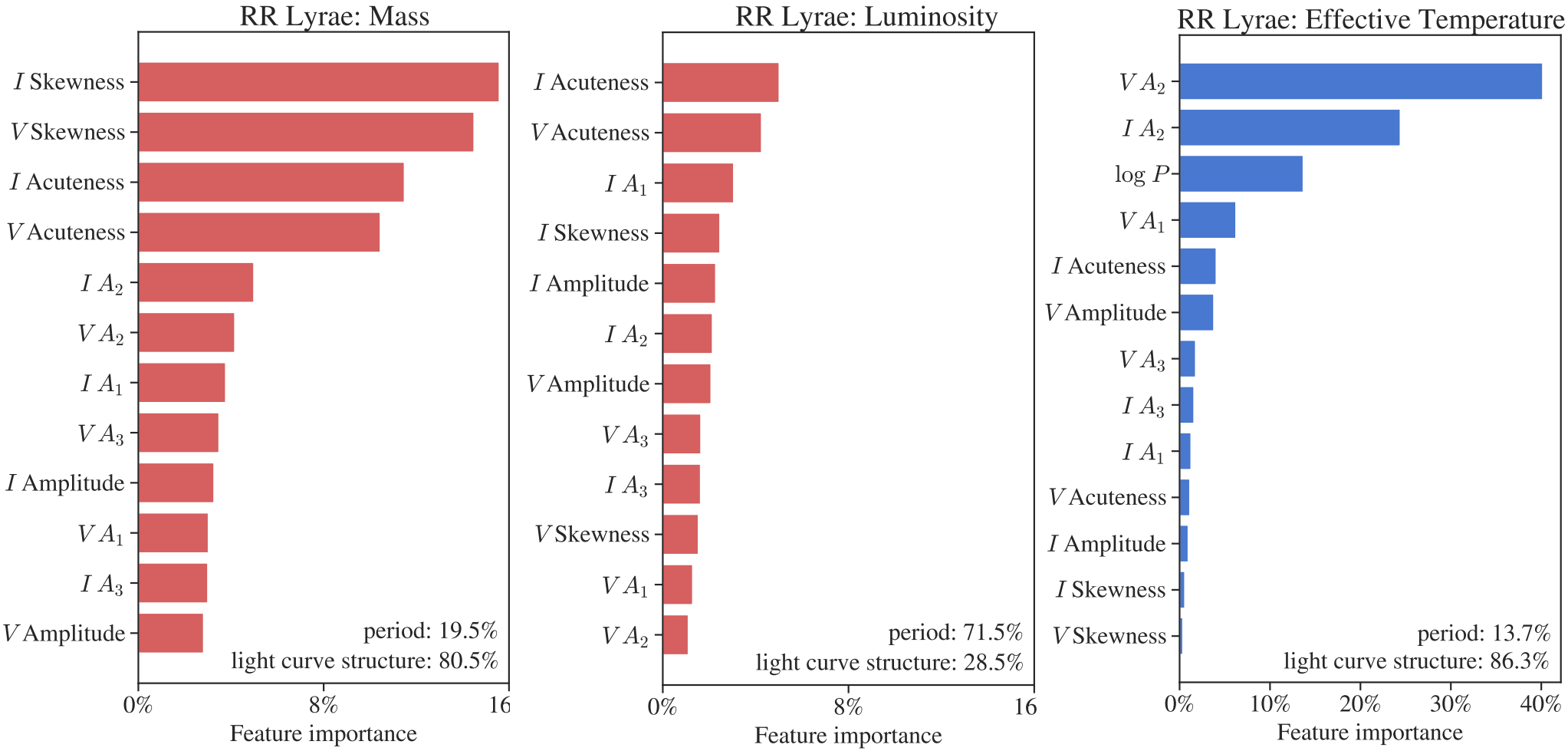


Predicted fundamental parameters

IUCAA

Ensemble based analyses

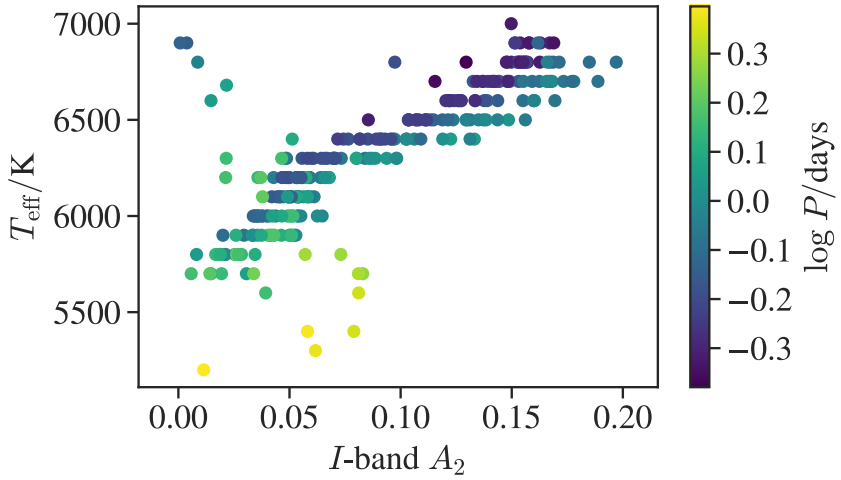
Which light curve structure parameters are the most important?

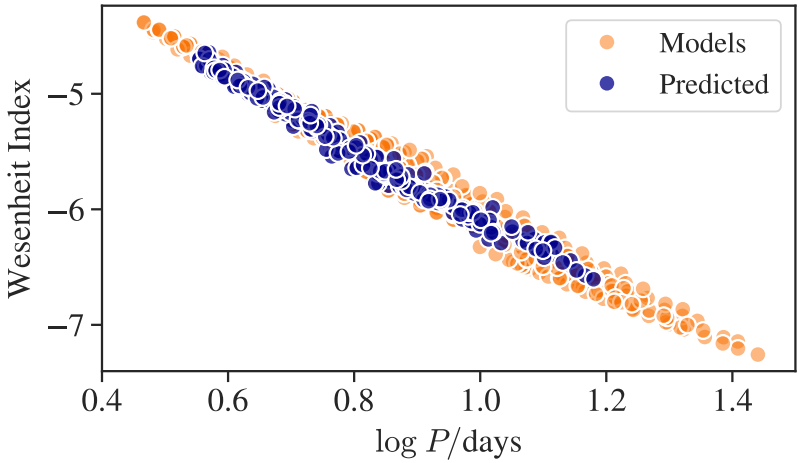


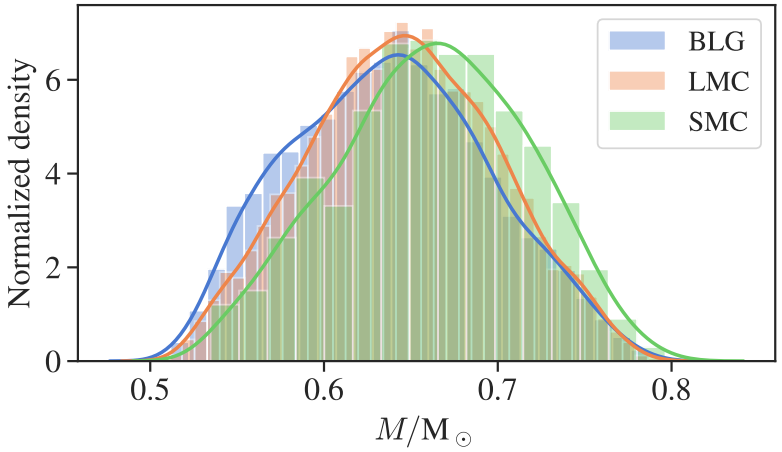
Predicted fundamental parameters

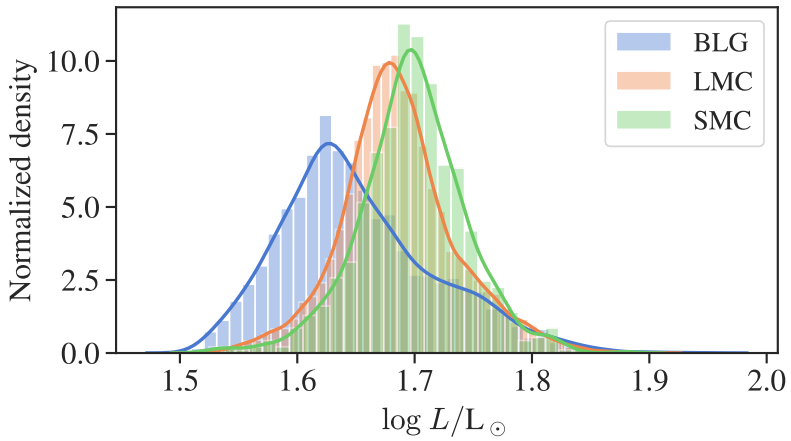
IUCAA

Model fitting approach to ensemble based analyses



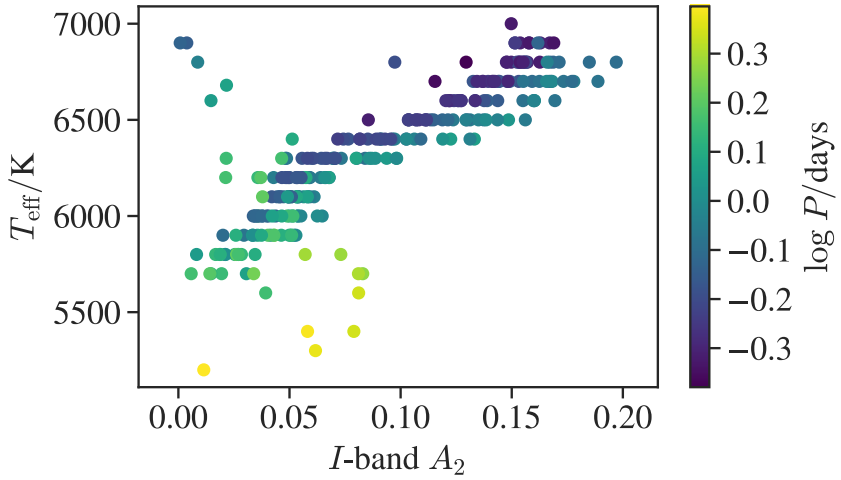


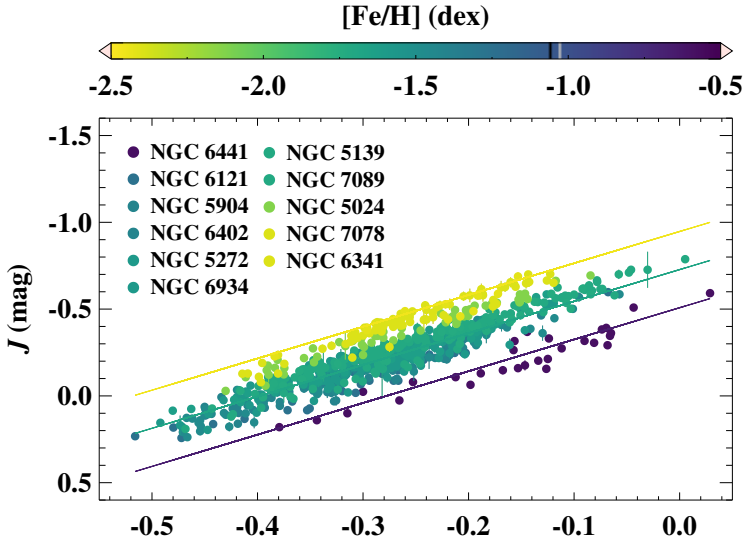


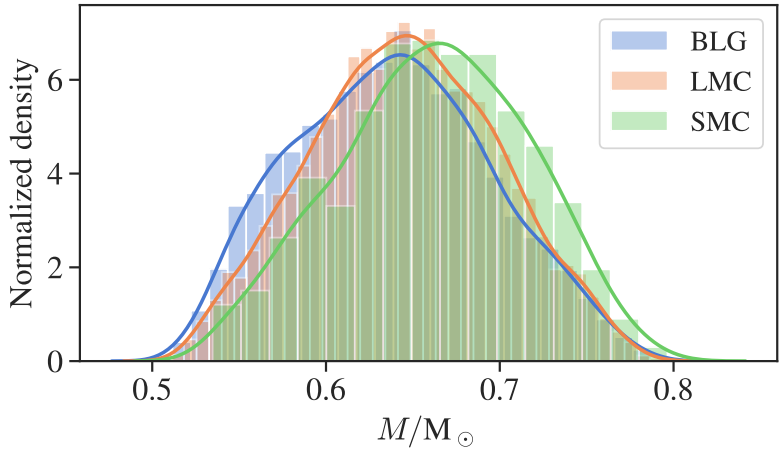


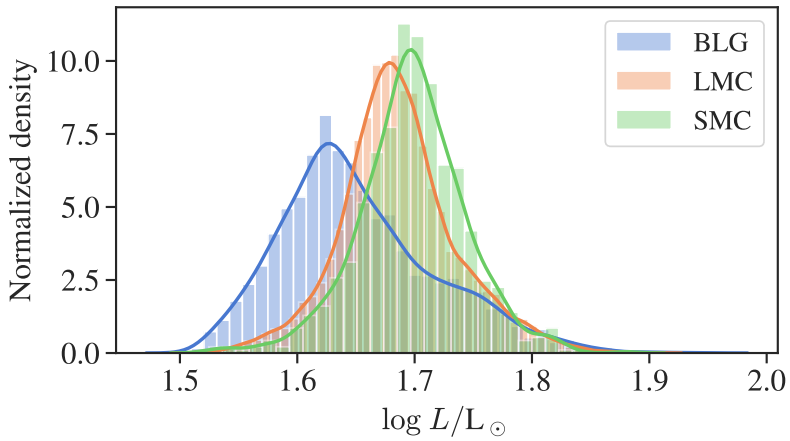
Predicted fundamental parameters

Model fitting approach to ensemble based analyses



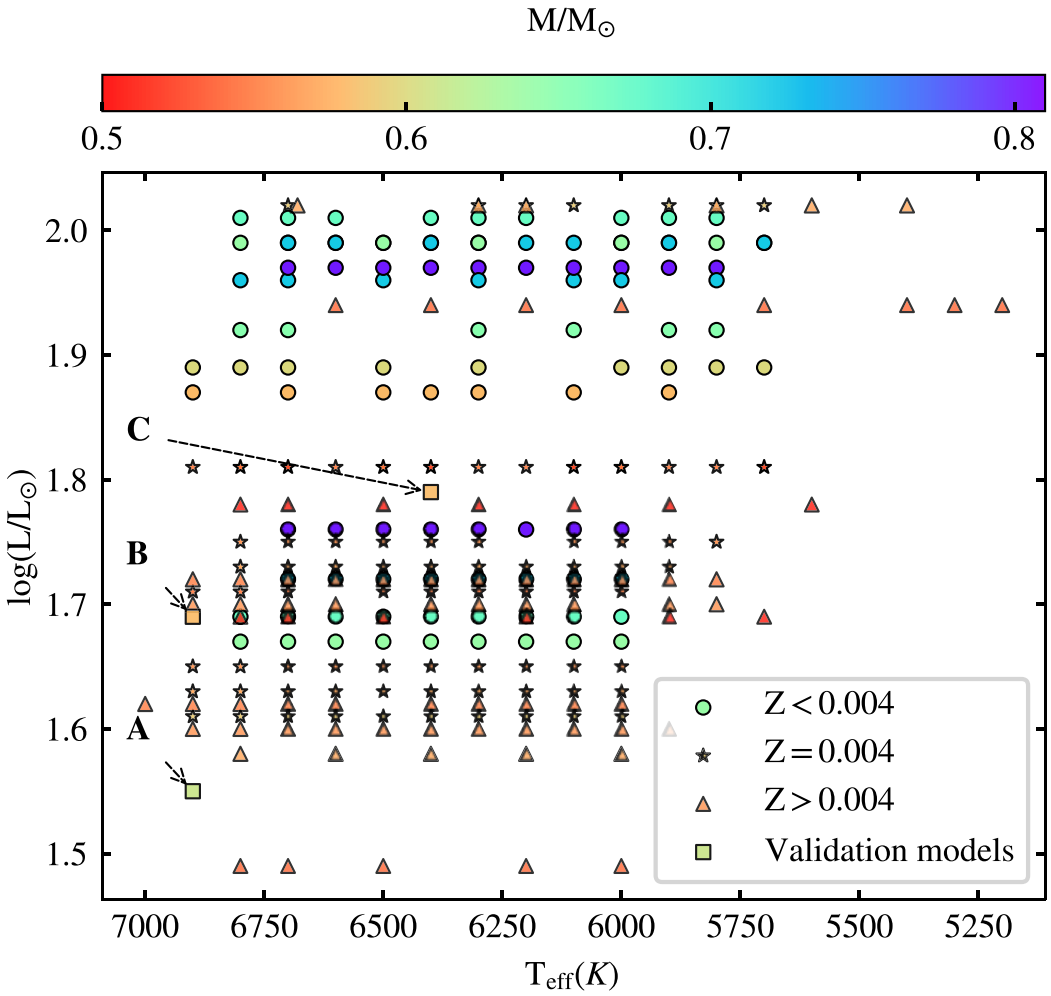






ANN light curve interpolator

Interpolating the theoretical grid of pulsation models



$$\boldsymbol{x} \equiv \left[\frac{M}{\mathrm{M}_\odot},\ \log\left(\frac{L}{\mathrm{L}_\odot}\right),\ T_{\mathrm{eff}},\ X,\ Z,\ \log(P)\right],$$

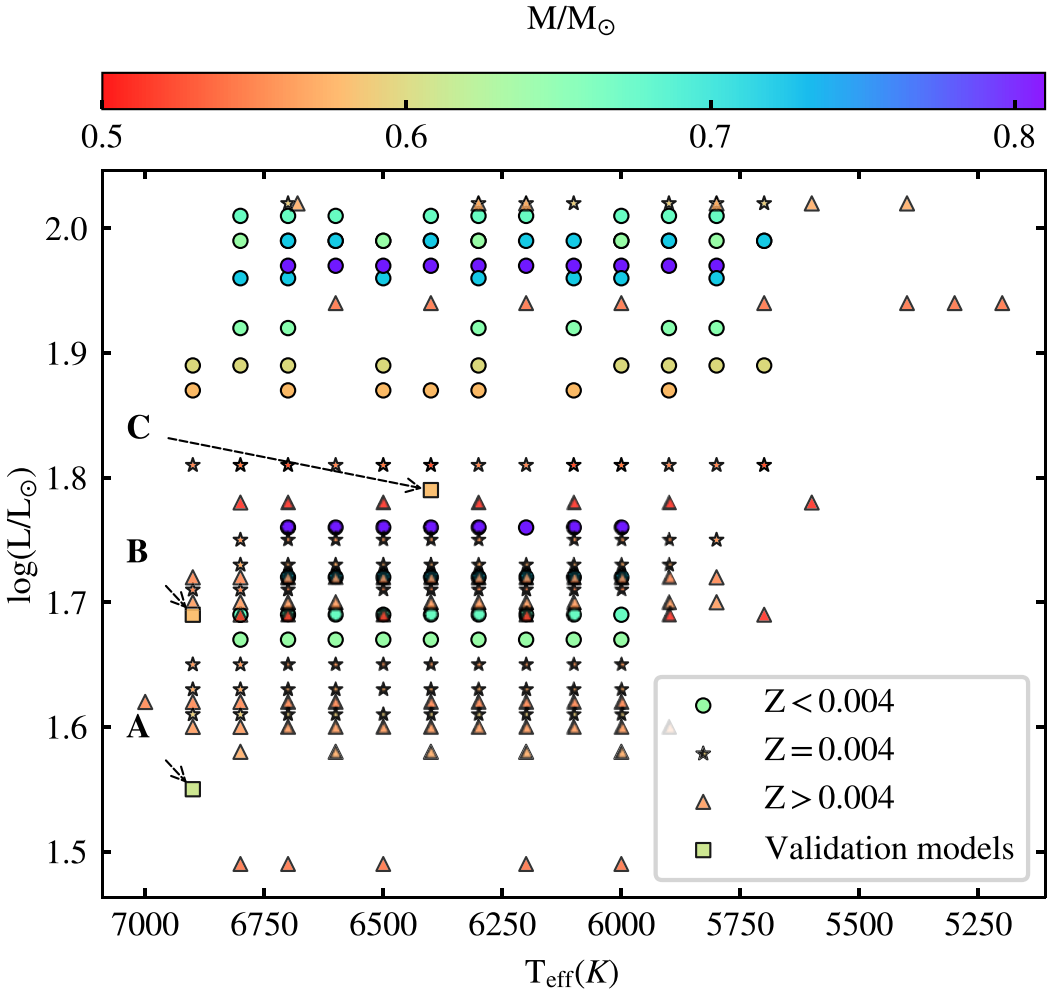
S. no.	Name of hyperparameter	Possible values
1	No. of hidden layers	[1, 2, 3]
2	No of neurons in one hidden layer	[16, 32, 64, 128]
3	Optimizer	‘ adam’ (Kingma & Ba 2014)
4	Learning rate	$[10^{-2} - 10^{-4}]$(log sampling)
5	Activation function	[‘ relu’, ‘ tanh’]
6	Weights initialization	‘ GlorotUniform’

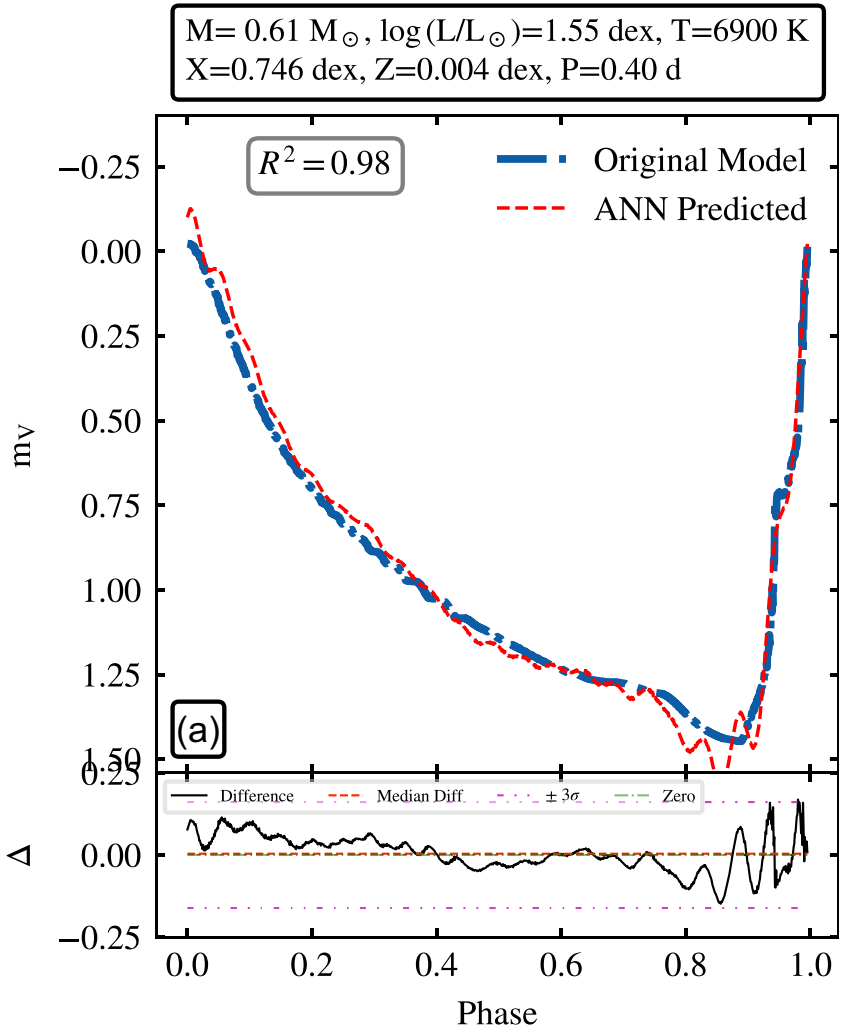
Kumar, Bhardwaj+2023

ANN light curve interpolator

IUCAA

Interpolating the theoretical grid of pulsation models





ANN light curve interpolator

IUCAA

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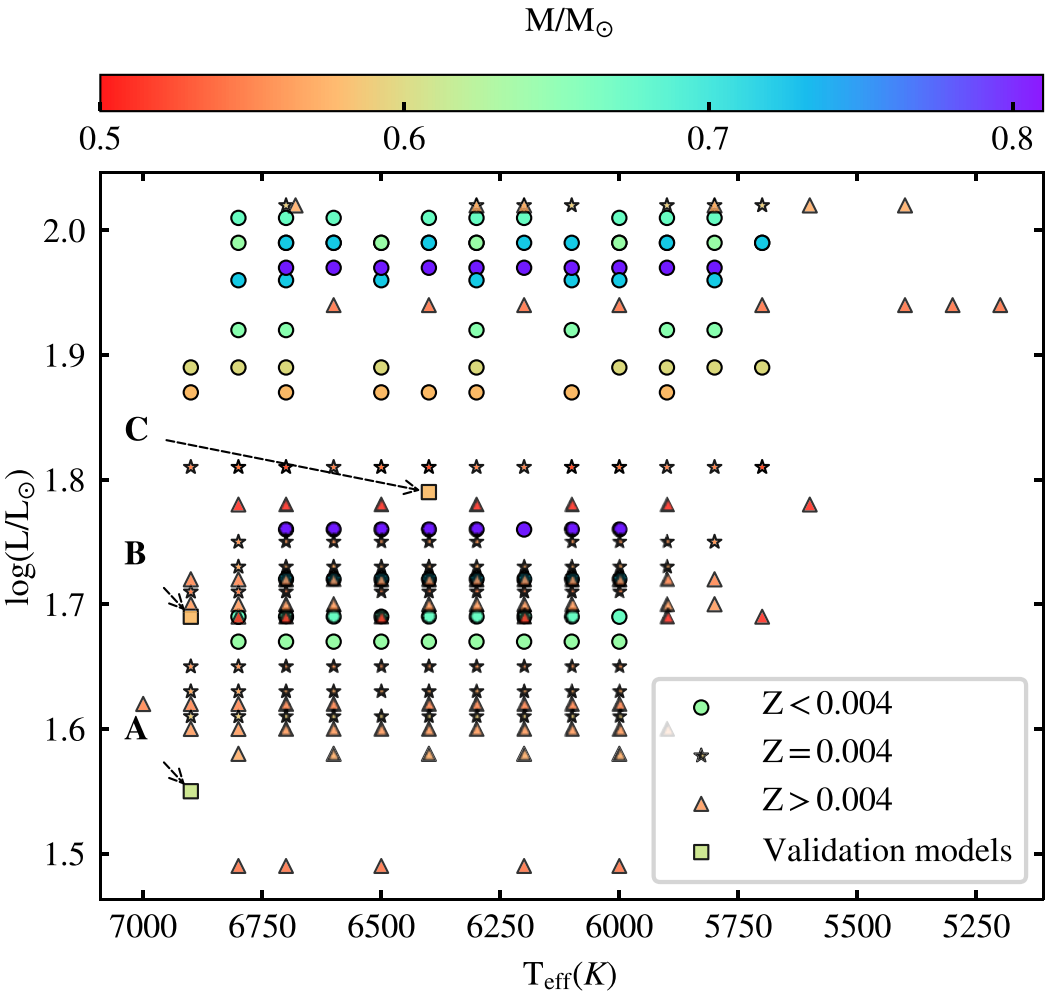
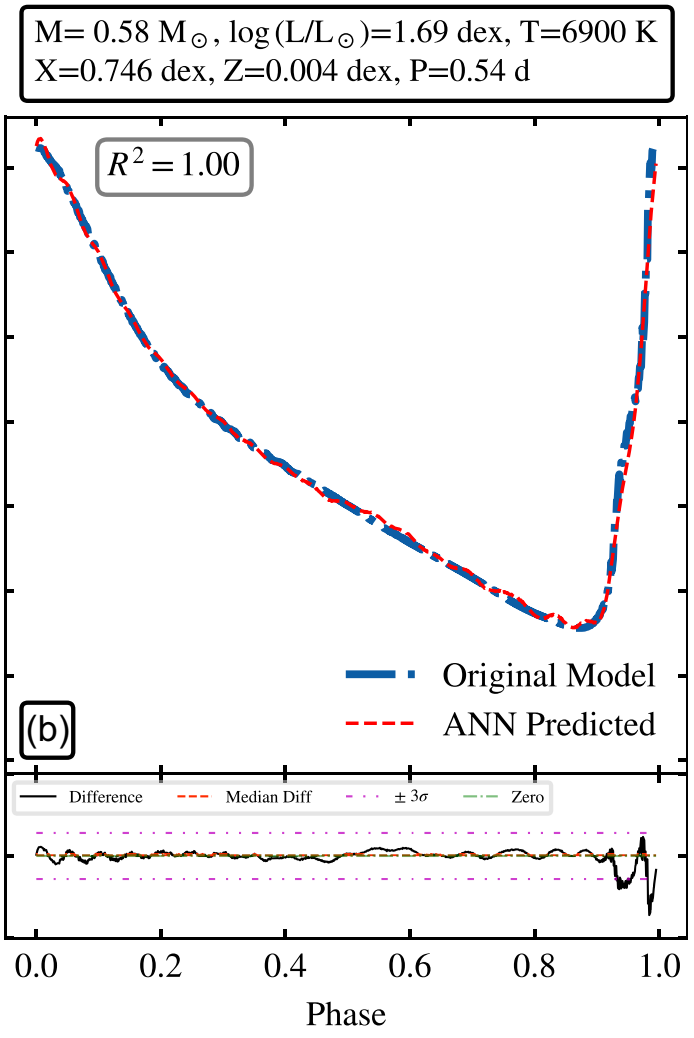
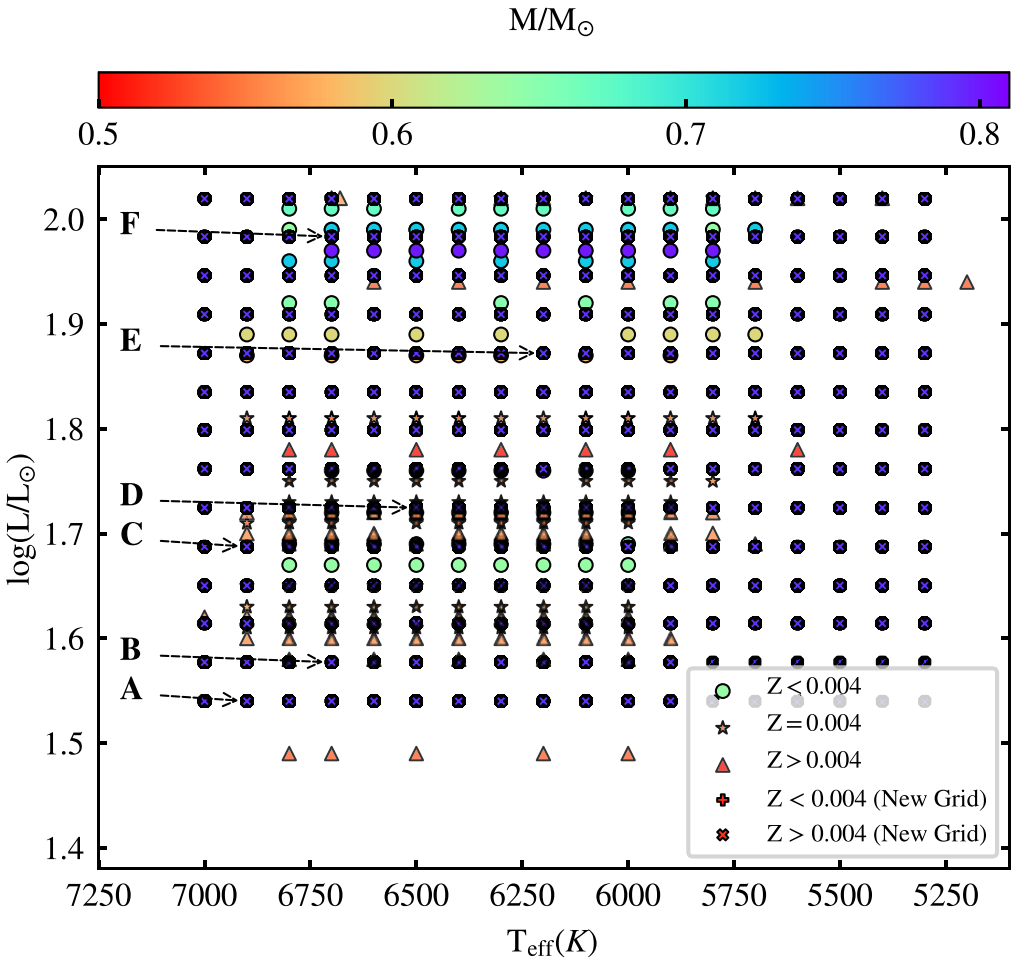


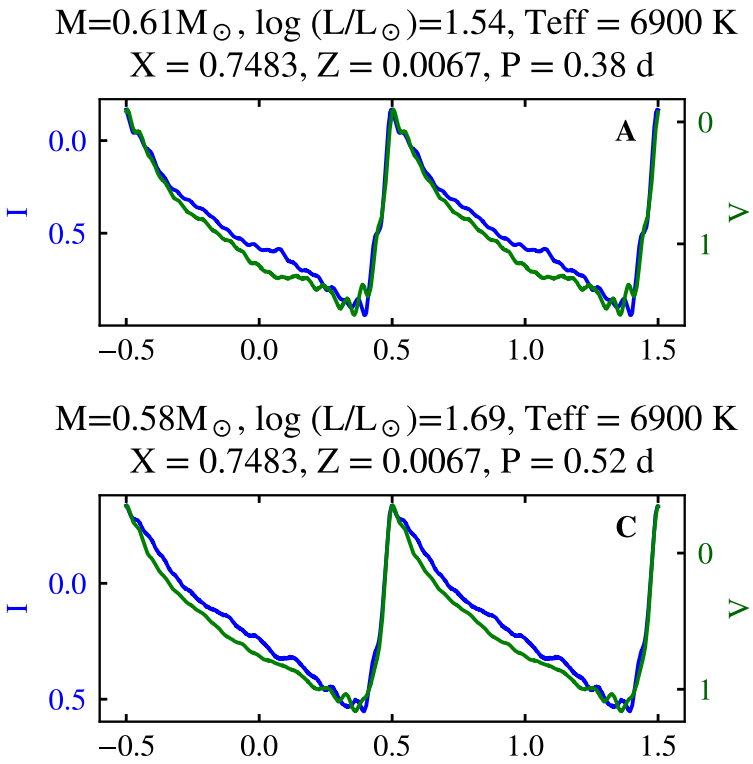


ANN light curve interpolator

IUCAA

Interpolating the theoretical grid of pulsation models

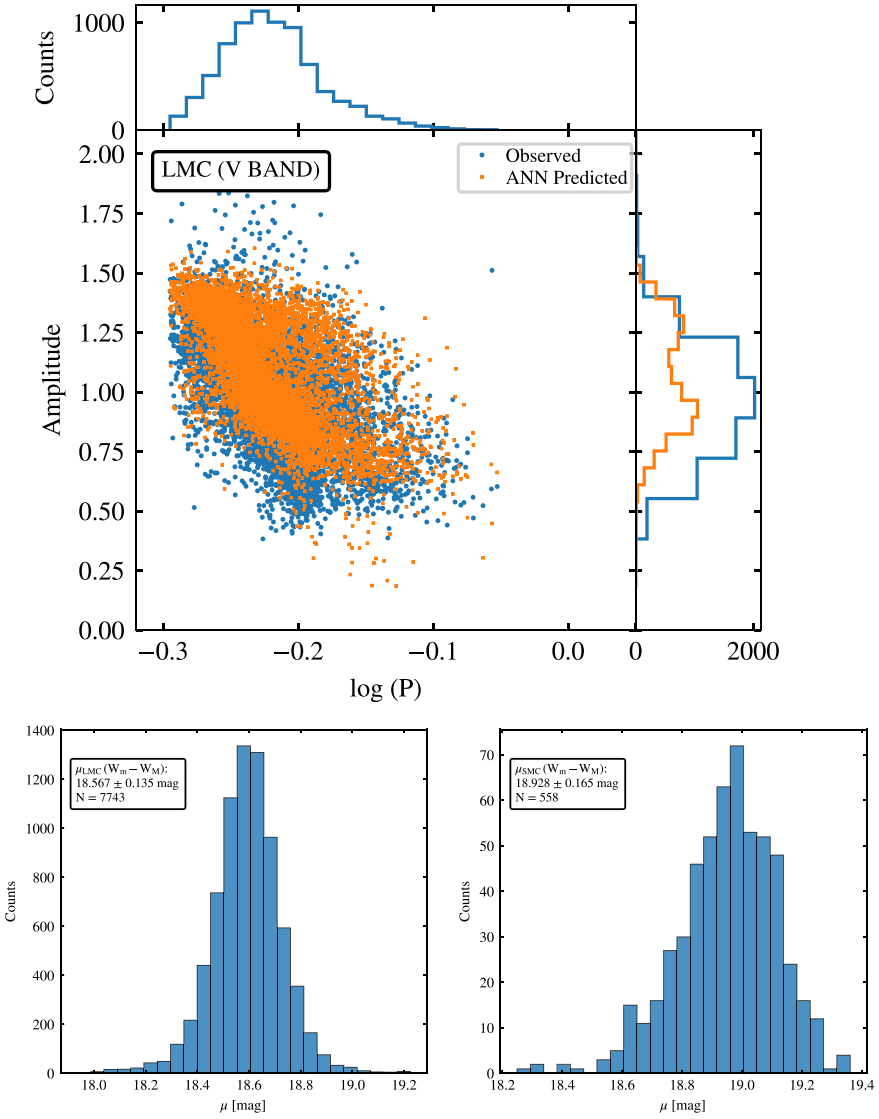


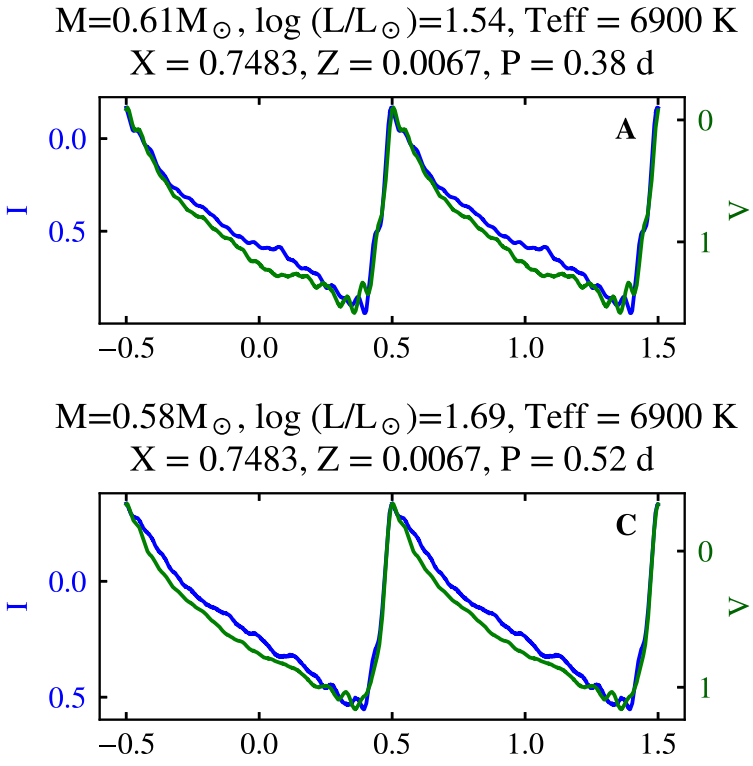


ANN light curve interpolator

IUCAA

Interpolating the theoretical grid of pulsation models





ANN light curve interpolator

IUCAA

Generate the V band light curves of RRab stars

Please input the values of mass, luminosity, temperature, chemical composition (X,Z) and period in the specified format
It should be noted that the ANN model is an interpolator and can only predict the light curves of RRab stars with parameters within the original grid of models.
The respective range of parameters are provided against the input boxes

M :	0,61	$M_\odot$ [0.5 - 0.8 $M_\odot$]
L :	1,54	dex [1.49 - 2.02 dex]
T :	6900	K [5200 - 7200 K]
X :	0,74832	dex [0.71 - 0.7549 dex]
Z :	0,00668	dex [0.0001 - 0.02 dex]
P :	0,3771	day [0.1 - 2.0 day]

Predict

Reset

**** Please Reset the form before submitting the next set of parameters. ****
User may change the value of the period to get the light curve of the star with the desired period.

https://ann-interpolator.web.app/vband.html