The Hubble Catalogue of Variables

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The HCV project 2015-2018

A Catalogue of Variables based on Hubble Space Telescope data

Motivation

- ✓25 yr timeline of HST data
- ✓Multi-epoch observations for several fields (~140 observed > x3)
- ✓Multi-wavelength information (UV to IR)
- ✓Faint magnitude limits (in cases ~30mag)
- ✓Largely unexplored

Objectives of the Hubble Catalogue of Variables

- ✓Rapid access to HST data in order to identify candidate variables on a massive scale
- ✓Development of a system that, in a **highly automated** way, will
  - ✓**extract information from the HSC**
  - ✓**process that information to detect candidate variables**
  - ✓**perform validation to confirm the candidates as valid variables**
- ✓These variables will be collected in a catalogue that will be made avail users from the astronomical community via a **web-based interfac**
- ✓The HCV system will consist of three elements:
  - ✓**a processing pipeline to generate the HCV**
  - ✓**the HCV itself**
  - ✓**a web-based user interface allowing users to access the contents of the HCV**
- ✓**Catalogue will be reconstructed for new versions of the HSC**

PUBLIC RELEASE DATE MARCH 2018

The HCV will be part of the MAST portal

MAST: Mikulski Archive for Space Telescopes

Welcome to the Hubble Legacy Archive

The Hubble Legacy Archive (HLA) is designed to optimize science from the Hubble Space Telescope by providing online, enhanced Hubble products and advanced browsing capabilities. The HLA is a joint project of the Space Telescope Science Institute (STScI), the Space Telescope European Coordinating Facility (ST-ECF), and the Canadian Astronomy Data Centre (CADC).

Enter Site here.

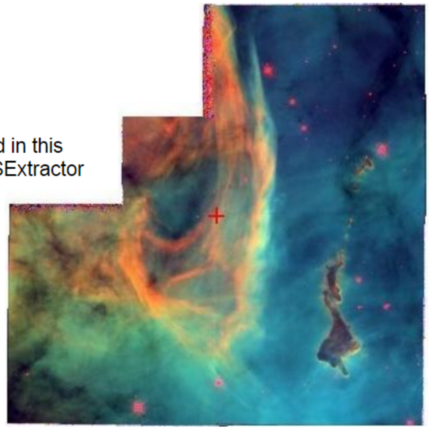
DR9.1 Release (2016 September 29)

NEW DATA PRODUCTS

- Newly processed ACS and WFC3 source lists. Almost all old source lists have been replaced in this catalog. The new source lists have higher quality astrometry and photometry, especially for SExtractor catalogs in crowded fields. These new source lists were used in the construction of version 2 of the **Hubble Source Catalog**, which is being released simultaneously with HLA DR9.1.

USER INTERFACE ENHANCEMENTS

- The interactive display's advanced HSC controls can be used to show either the current HSCv2 catalog or the previous HSCv1 catalog.
- The **Gaia DR1** catalog is available for overlay in the display.
- New controls can change the catalog overlay region to load sources from only a small part of the image. This greatly improves performance in large images and crowded regions.
- See the **display help** for more information on the new display features.



See the **release notes** for more details on this and past releases.

- ✓ Hubble Legacy Archive
  (25 years imaging IR-UV and spectroscopy)
- ✓ Hubble Source Catalog (v2.1)
- ✓ Hubble Catalog of variables

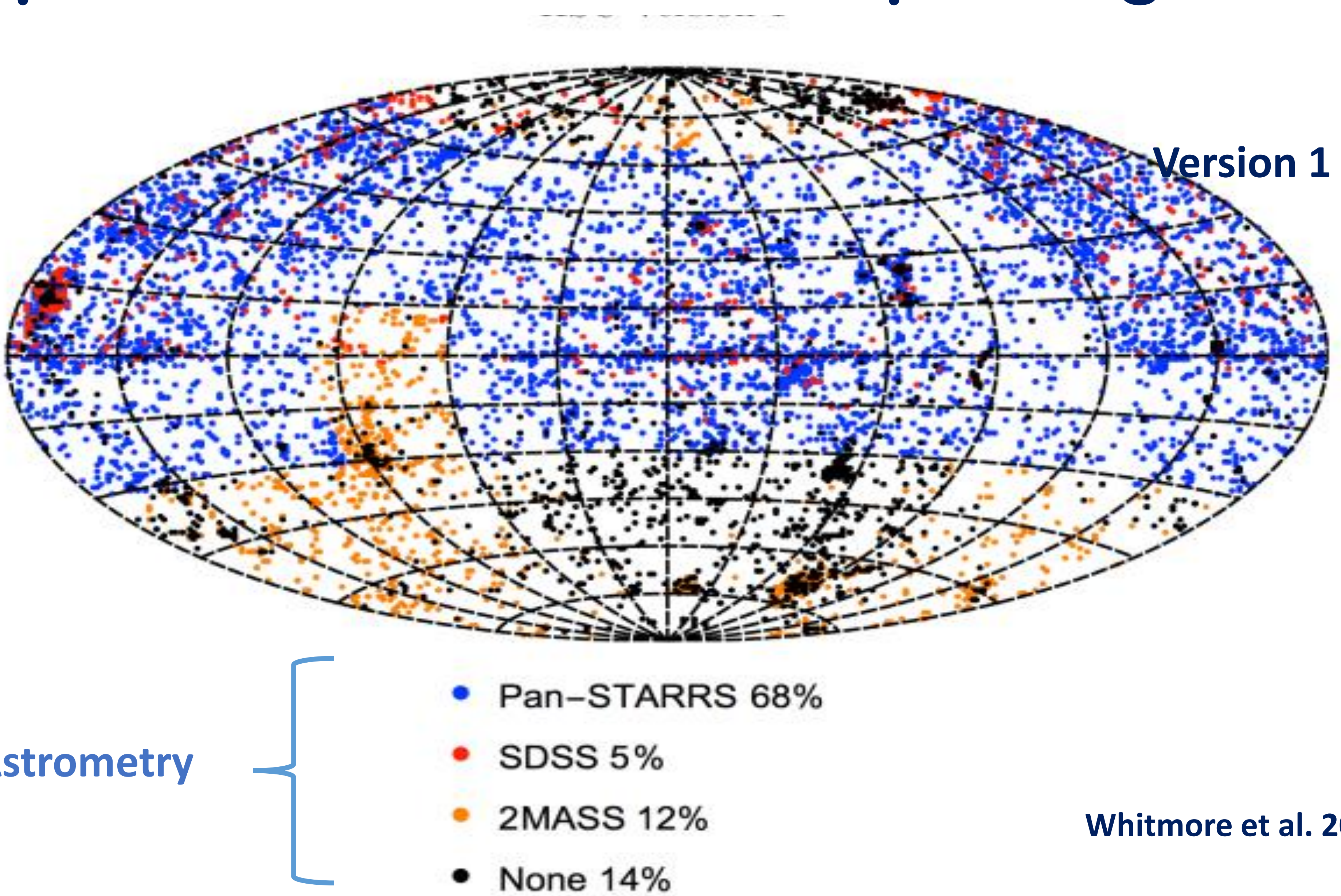
Web interface - MAST portal

The input data: The Hubble Source Catalogue (HSC-version 2.1 released Jan 2017)

- ✓Number of sources: ~10^8 objects (~3x 10^8 detections)
- ✓Spatial coverage: 0.1% of the sky
- ✓ Instruments currently included: WFPC2, ACS/WFC, WFC3/UVIS and WFC3/IR
- ✓ Photometry:
  - ✓Aperture photometry (SExtractor)
  - ✓Visit based
  - ✓Accurate at a **few % level** (but systematic offsets up to 0.1mag)
- ✓ Astrometry
  - ✓ absolute astrometry from matching with the PanSTARRS, SDSS, or, 2MASS reference systems
  - ✓absolute astrometry accuracy better than **0.1”**
  - ✓**9%** of areas NOT matched with ref. systems- poorer absolute astrometry
  - ✓ relative astrometry accuracy **2.3mas** (mode)

HSC v1: Whitmore et al., 2016, AJ, 151, 134

Spatial distribution of HSC pointings

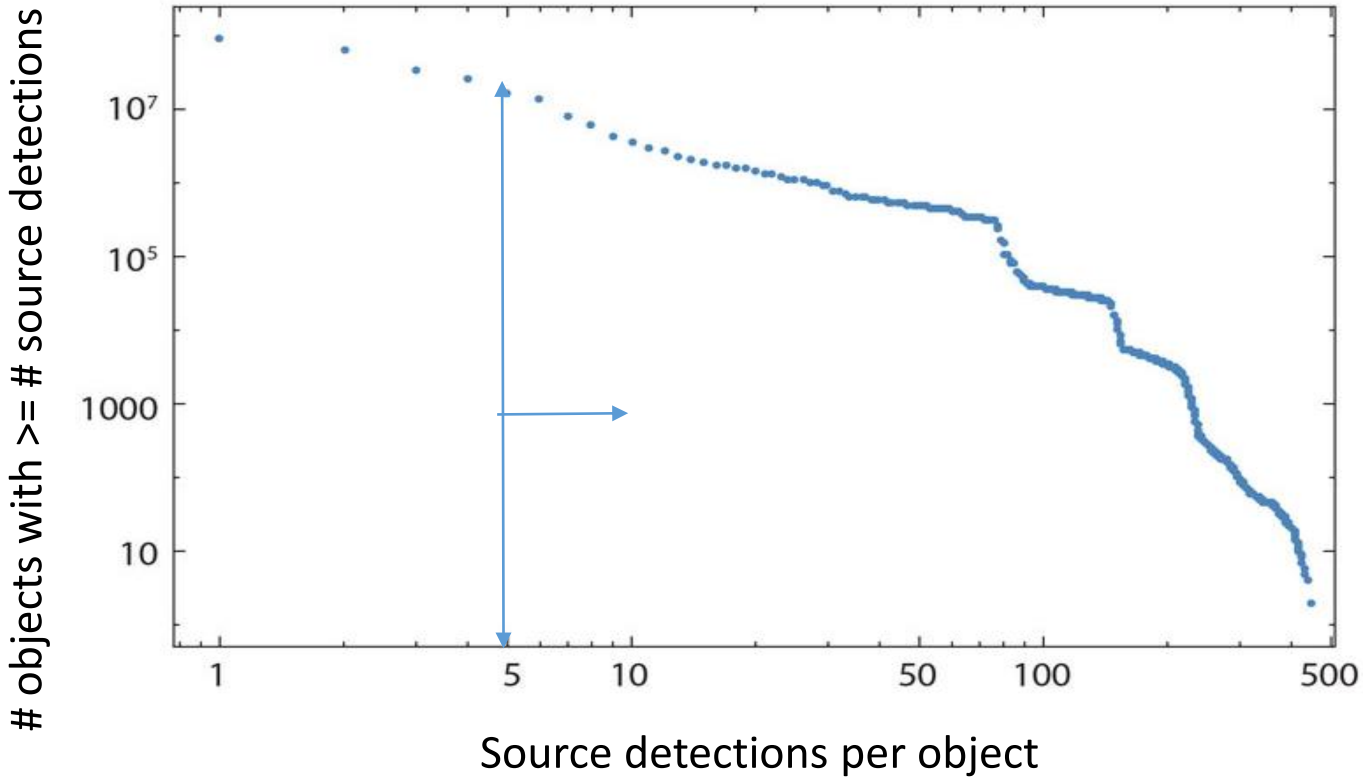


Version 1

Astrometry

Whitmore et al. 2016

The number of objects (matches) in the HSC catalog as a function of the number of visits in each match



- >10 million objects have time coverage of more than 1 year.

  (so expect a few 10^5 variables)

- >1 million objects are detected more than 25 times

- >1 million objects are detected in 5 or more filters.

✓ **Peaks in the distribution are partially due to repeat observations of: the Galactic bulge (~25 visits), M31 Halo (~60 visits), and M4 (~120 visits)**

Whitmore et al. 2016

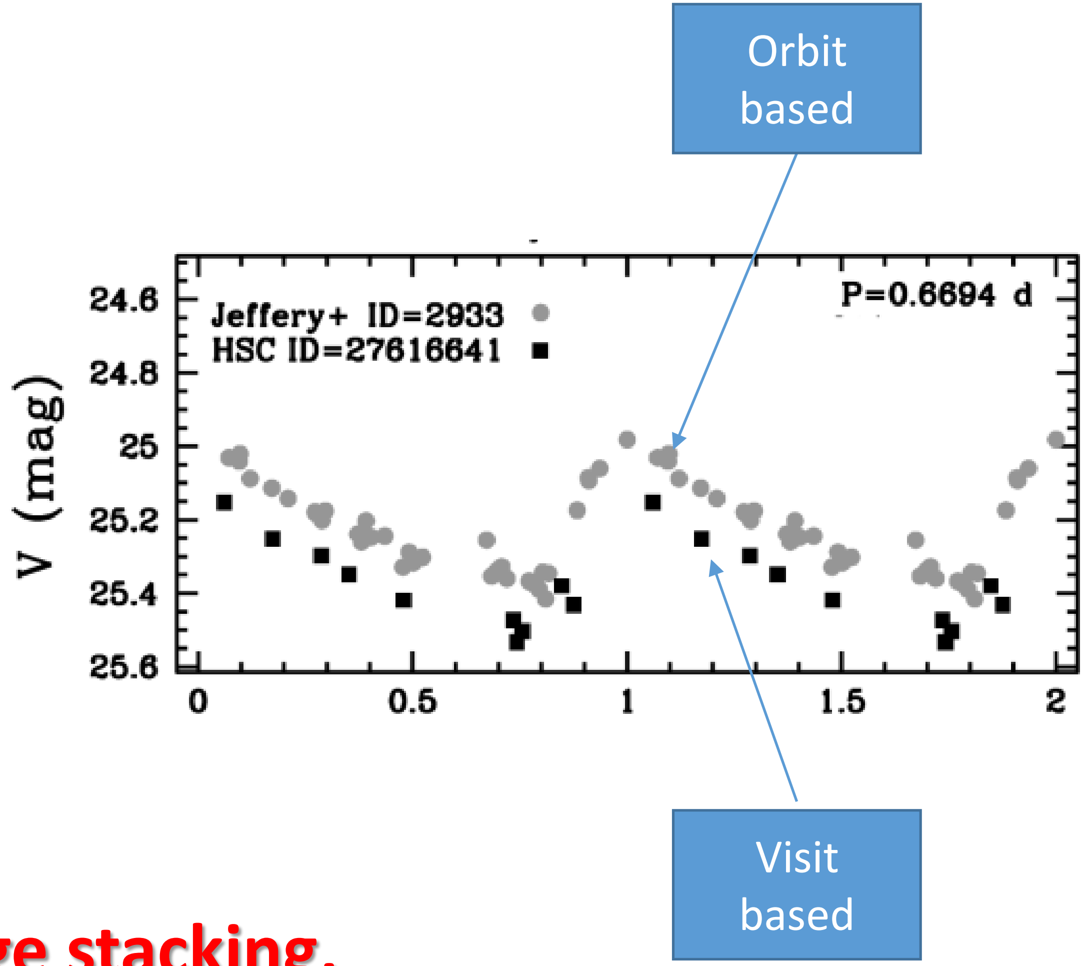
HCV Challenges

✓ **Data inhomogeneity**

- ✓ Great variety in observing cadence
- ✓ 112 instrument+filter combinations

✓ **Data quality**

- ✓ Visit-combined measurements
- ✓ Aperture rather than psf photometry
- ✓ Small number of epochs in most cases
- ✓ Systematics affecting photometry (**blending**, **residual CR**, **imperfect image stacking, diffraction spikes, saturation**)



HCV Variability Detection Algorithm

Light-curve Data Collection

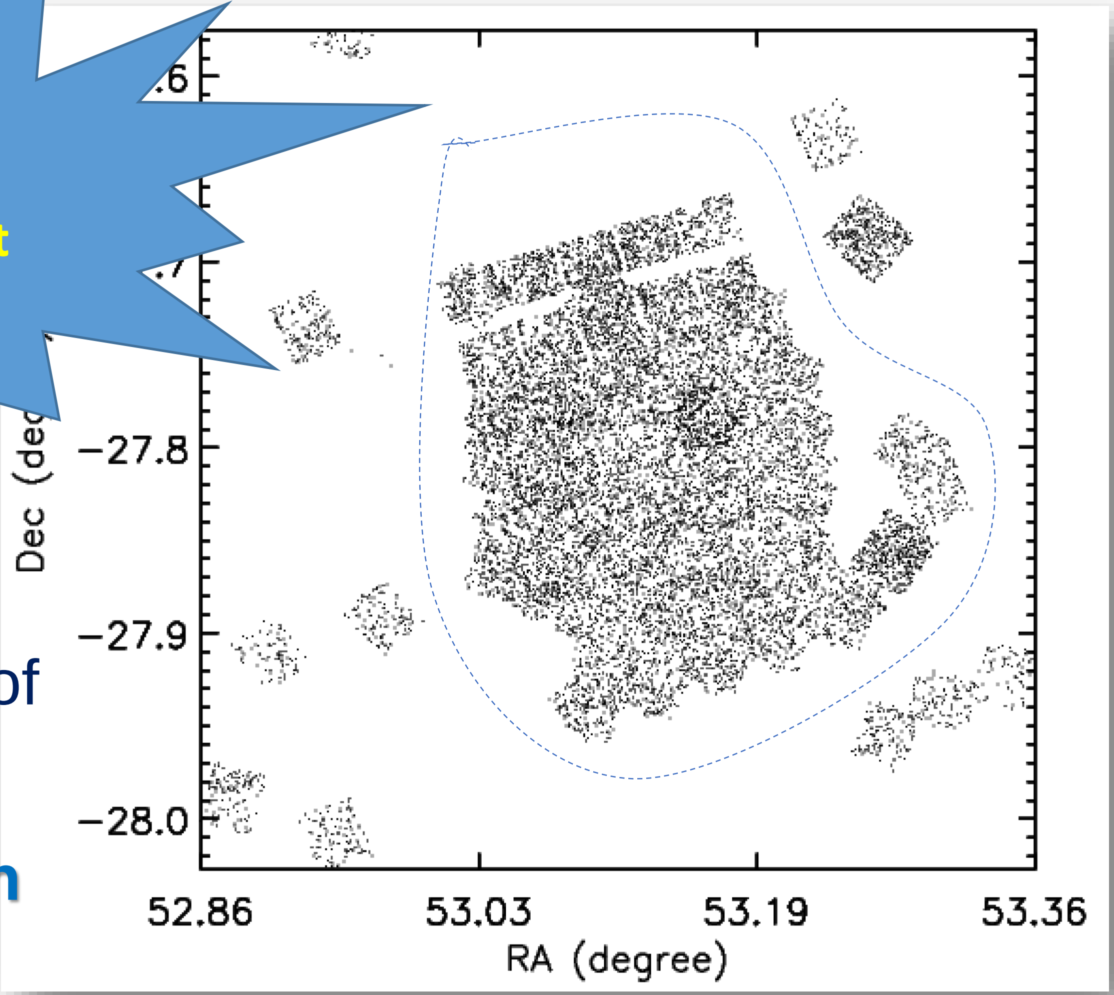
Group-based (a group consists of overlapping white-light images)

Pre-processing: Filte… out:

- saturated sources
- sources affecte…
(blending)
- sources affec…
individual images

Challenge: “fix” photometric systematics without affecting transient detectability

GOODS-South WFC3/F160W

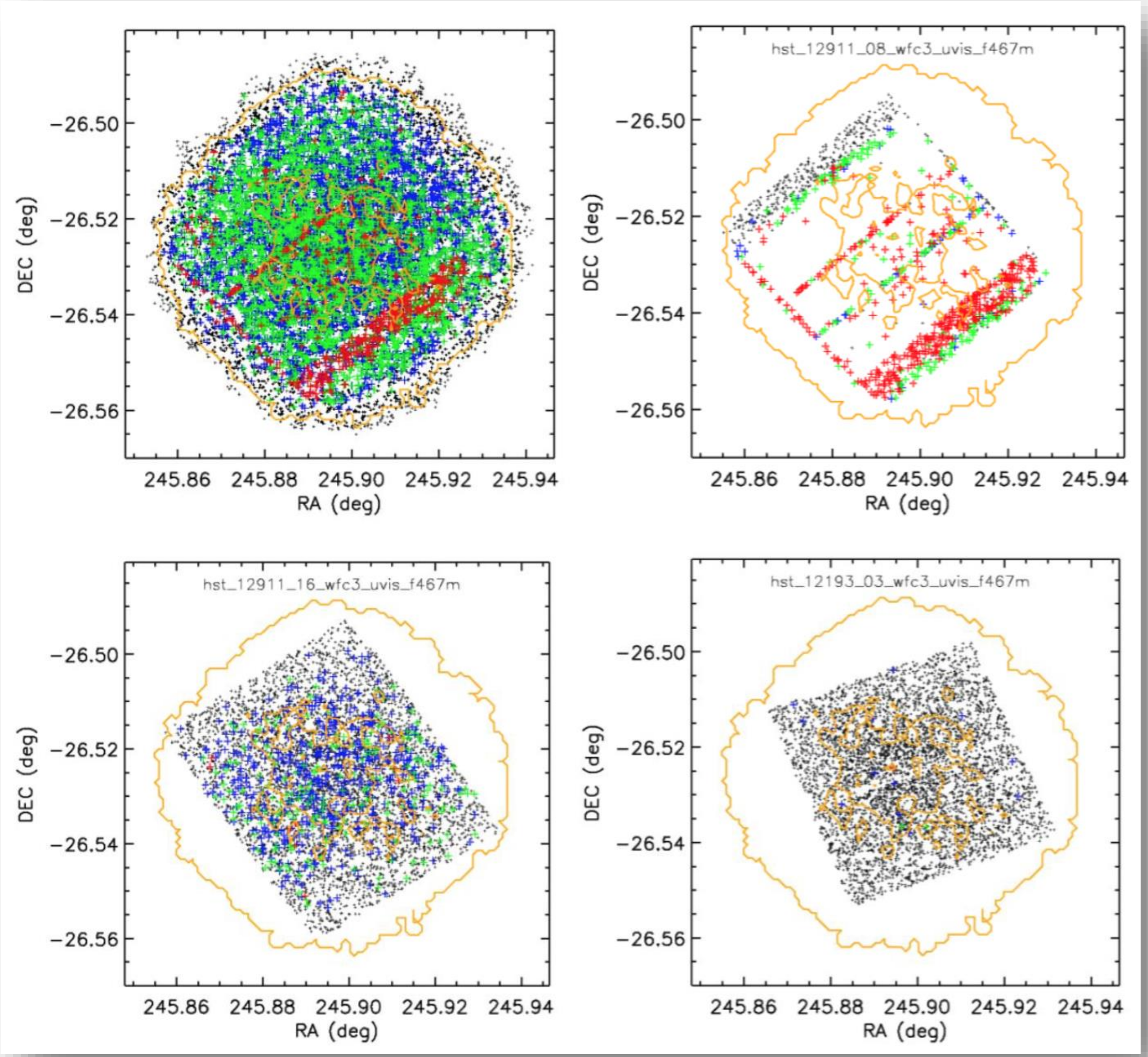


Variability Detection:

based on statistical characterization of the light-curve using different types of variability indexes

Variability Validation and Verification

Error statistics – bad image identification



Blue: 1σ
Green: 2σ
Red: 3σ

- ✓ Baseline re-calculation IF there are "bad" images (excluding them)

this way one avoids removing outliers that might be due to transient phenomena

Variability Detection

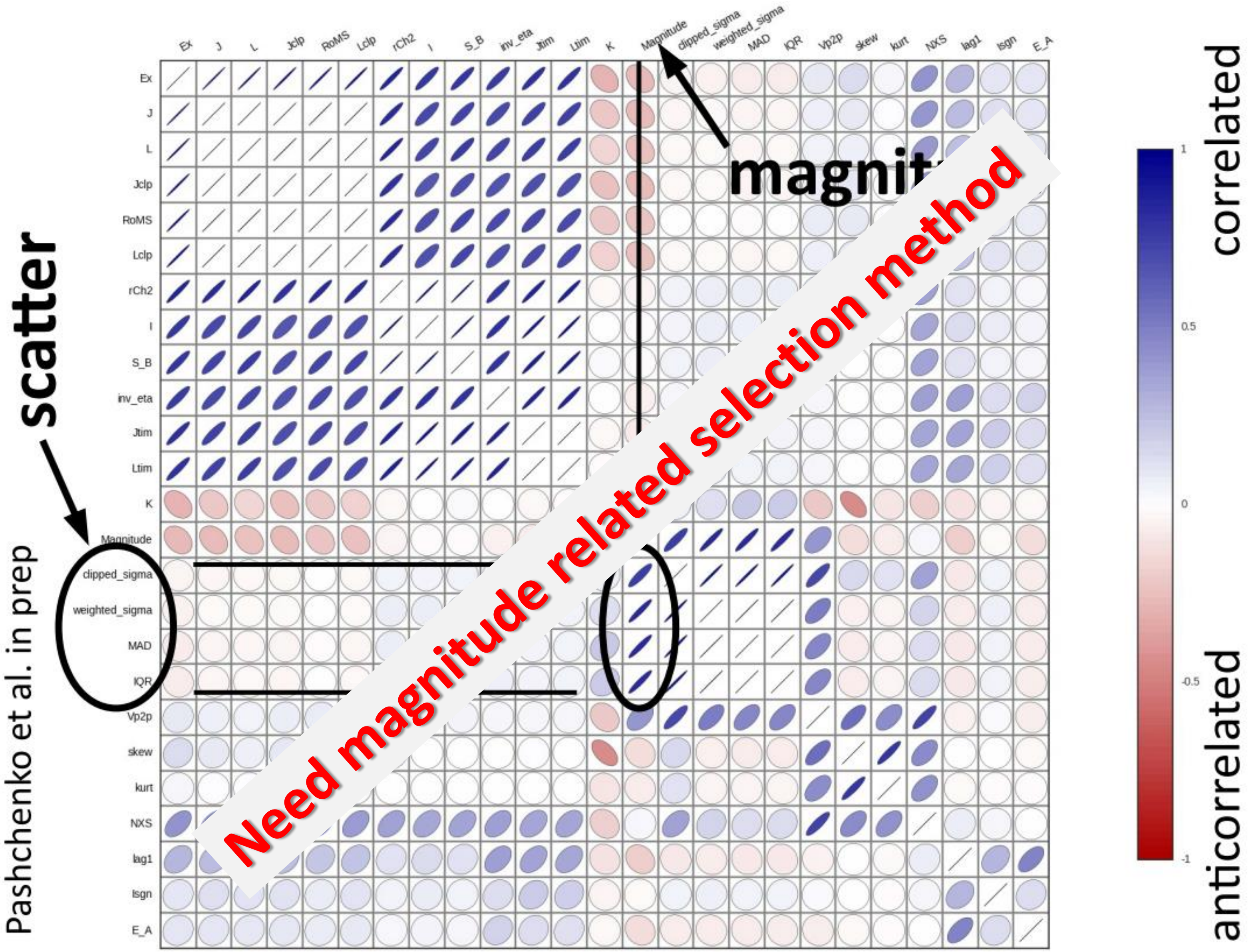
Statistical characterization of LC: Variability Indices (VI's)

- ✓VI's are numerical parameters characterizing the degree of variability of an object
- ✓Different VI's are sensitive to different types of variability
- ✓One expects a variable object to have a significantly different value in some VI than non-variables (variable objects < few %)
- ✓ Types of Variability Indexes
  - ✓ Scatter-based
  - ✓ Correlation-based
  - ✓ Evaluated using simulated and real HST LCs and PCA

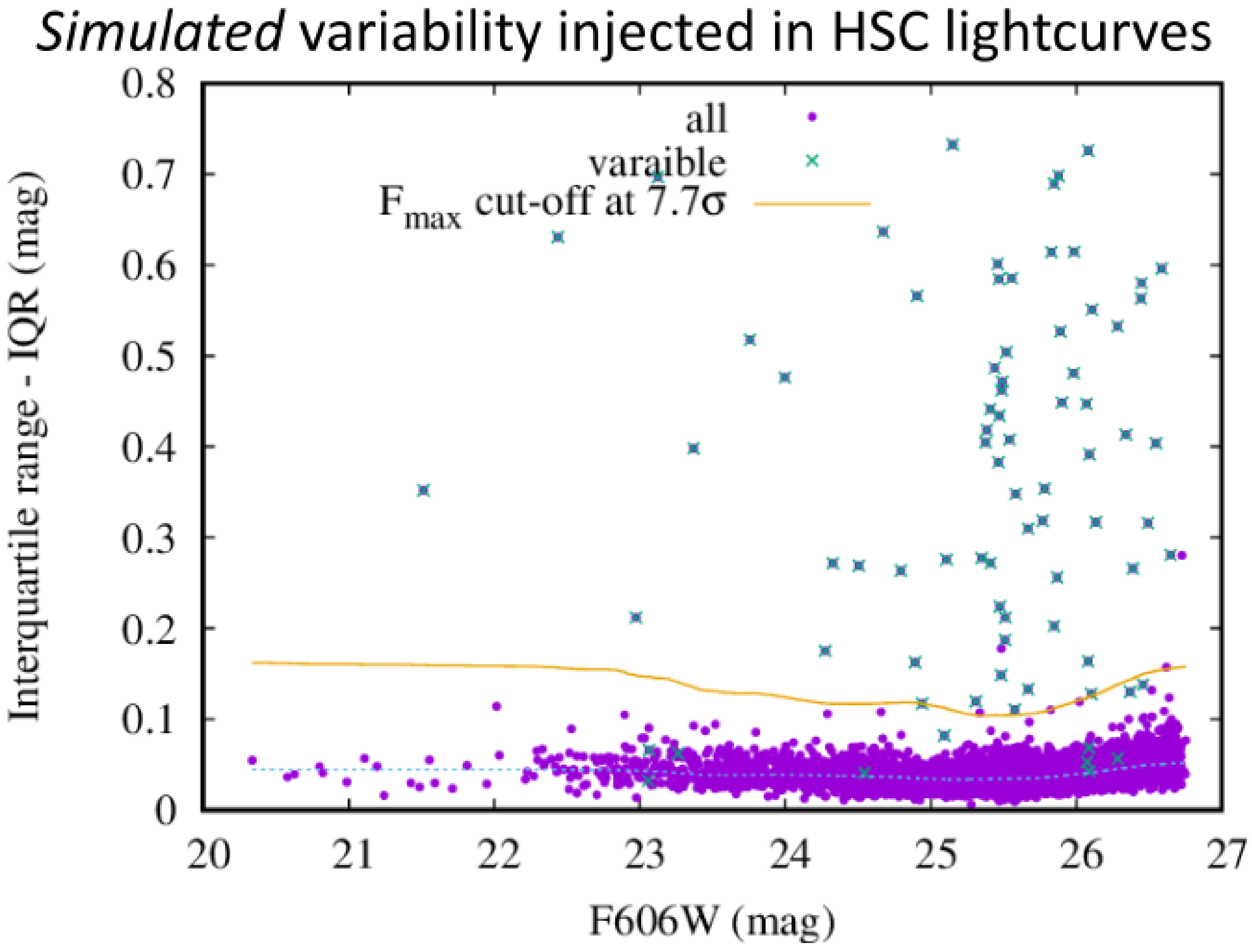
Different Variability Indices Explored

Index	Errors	Order	Time	Reference
		Scatter-based indices		
weighted standard deviation – σ	✓			Kolesnikova et al. (2008)
clipped σ – σ_{clip}				Kolesnikova et al. (2008)
median abs. deviation – MAD				Zhang et al. (2016)
interquartile range – IQR				Sokolovsky et al. (2017)
reduced χ^2 statistic – χ^2_{red}	✓			de Diego (2010)
robust median statistic – RoMS	✓			Rose & Hintz (2007)
norm. excess variance – σ^2_{NXS}	✓			Nandra et al. (1997)
norm. peak-to-peak amp. – v	✓			Sokolovsky et al. (2009)
		Correlation-based indices		
autocorrelation – l_1		✓		Kim et al. (2011)
inv. von Neumann ratio – $1/\eta$		✓		Shin, Sekora & Byun (2009)
Welch-Stetson index – I_{WS}	✓	✓	✓	Welch & Stetson (1993)
flux-independent index – I_{fi}	✓	✓	✓	Ferreira Lopes et al. (2015)
Stetson's J index	✓	✓	✓	Stetson (1996)
time-weighted Stetson's J_{time}	✓	✓	✓	Fruth et al. (2012)
clipped Stetson's J_{clip}	✓	✓	✓	Sokolovsky et al. (2017)
Stetson's L index	✓	✓	✓	Stetson (1996)
time-weighted Stetson's L_{time}	✓	✓	✓	Fruth et al. (2012)
clipped Stetson's L_{clip}	✓	✓	✓	Sokolovsky et al. (2017)
S_B statistic	✓	✓		Figuera Jaimes et al. (2013)
excursions – E_x	✓	✓	✓	Parks et al. (2014)
excess Abbe value – $\mathcal{E}_{\mathcal{A}}$		✓	✓	Mowlavi (2014)
		Shape indices		
Stetson's K index	✓			Stetson (1996)
kurtosis				Friedrich, Koenig & Wicenec (1997)
skewness				Friedrich, Koenig & Wicenec (1997)

VI covariance matrix



Magnitude related selection method



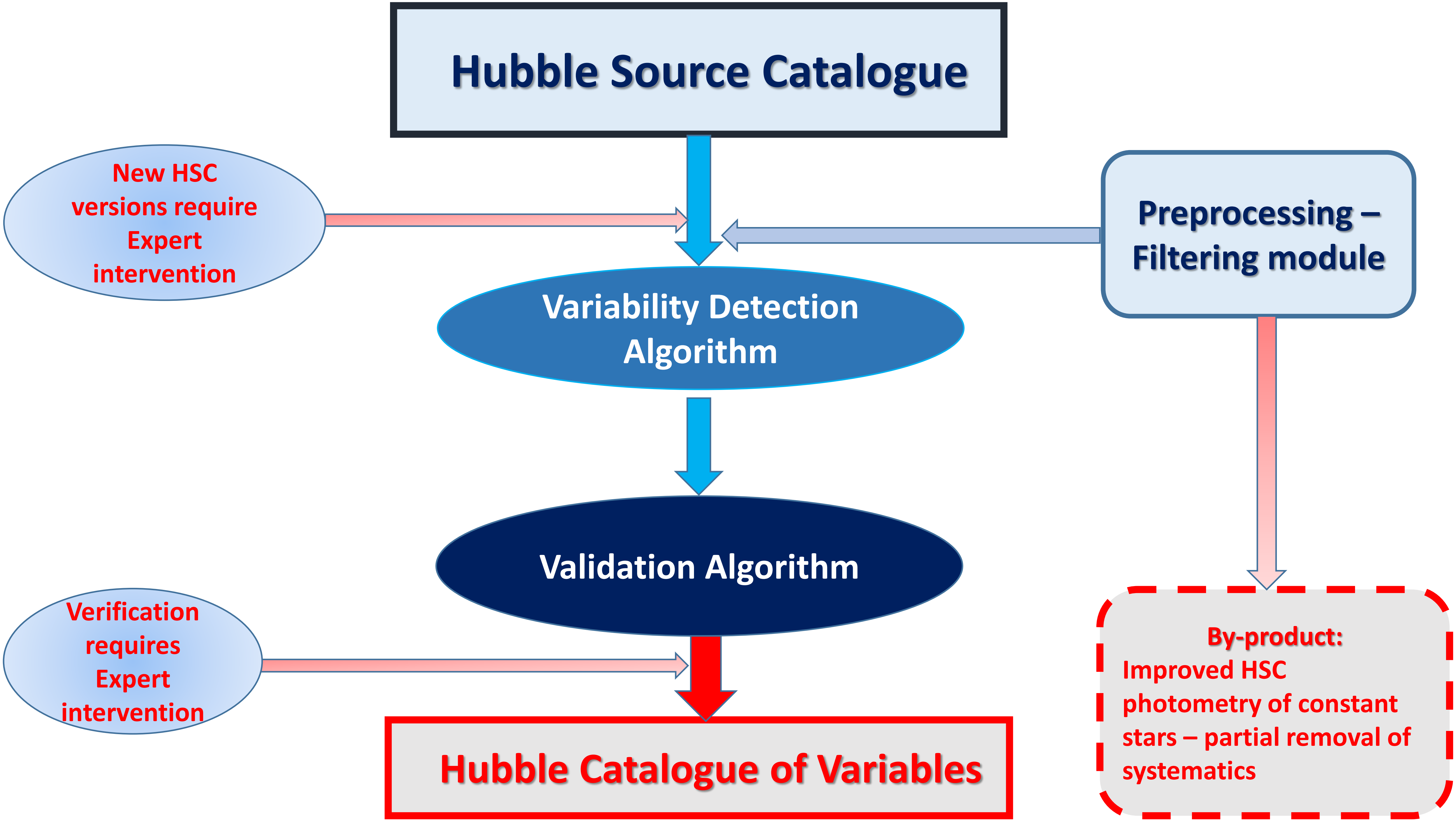
Variability Validation Algorithm

- ✓ **validation algorithm** for the candidate variables detected by the variability detection algorithm (VDA)

- ✓ Applies **criteria** to classify a candidate variable as
  - ✓ multi-filter variable
  - ✓ single-filter variable

+ quality flags

- ✓ **the Control Sample Database**
  - ✓ Well studied fields used to test the results of the pipeline
  - ✓ Automation of **verification procedure**


Hubble Source Catalogue
New HSC versions require Expert intervention
Preprocessing – Filtering module
Variability Detection Algorithm
Validation Algorithm
Verification requires Expert intervention
By-product:
Improved HSC photometry of constant stars – partial removal of systematics
Hubble Catalogue of Variables

ASSESSMENT OF VDA & VA PERFORMANCE
Utilisation of a Control Sample and simulated light curves

- **The Control Sample:**
  - HST fields with published variables
    - different numbers of visits
    - different source number densities
    - different numbers and types of known variables
    - different camera and filter combinations
    - different objects (star clusters, resolved galaxies, unresolved galaxies)

>1000 variables

  - Recovery of a high percentage of known variables (with a low level of artifacts) in these fields is an obvious pre-requisite for the acceptance, at an initial level, of both algorithms (VDA and VA).

- **Simulated lightcurves** have also be employed in order to assess the performance of the VDA and VA for parts of the parameter space not covered by the Control Sample.
- **PCA** has been applied to several CS fields to explore te behavior and interdependencied of the different VIs

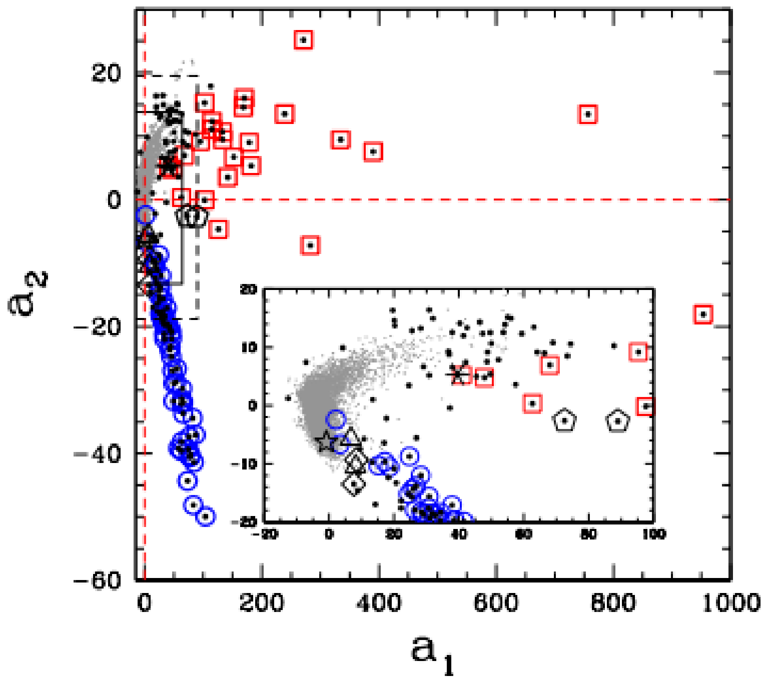
First results

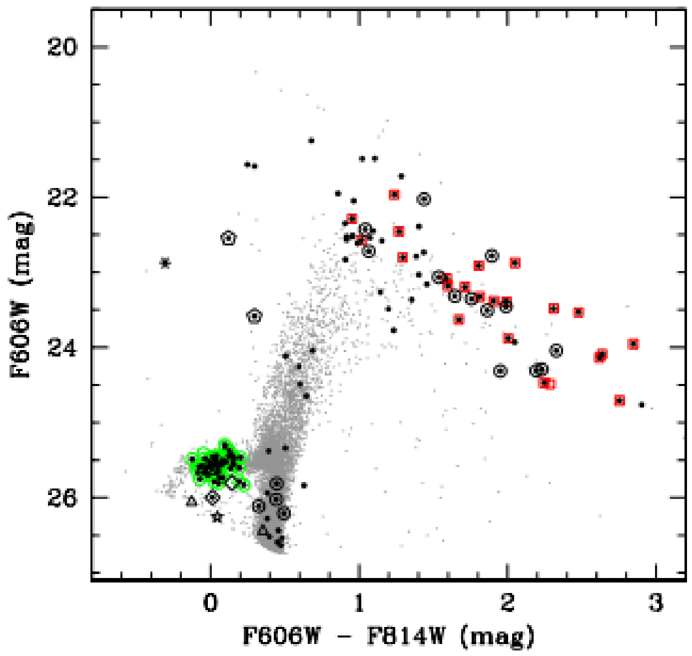
- ✓Pre-Processing leads to improvement of HSC
- ✓HCV tests led to the identification of problems that also improved the HSC
- ✓First results on variables are very promising:
  - ✓high recovery rate of known variables in control sample fields
- ✓Even in very well studied fields (e.g. M31 halo11) we discovered several new bona-fide variables
- ✓Total number of variables in the HCV based on the current version of the HSC is of the order of 10^5
- ✓ BUT systematic errors remain in some cases

Results on Control Sample Fields: The example of M31 (halo11, stream and disk fields)

One of the “best” CS fields

Field Name	# known variables	# recovered var.	# tot new cand.	# true var.	#possible var.	# artifacts	# cand.
Halo11	88	78 (89%)	65	10	6	9	40
Stream	22	21 (95%)	56	2	15	1	38
Disk	21	21 (100%)	171	7	11	27	126





PCA seems to be able to provide a crude classification of variables

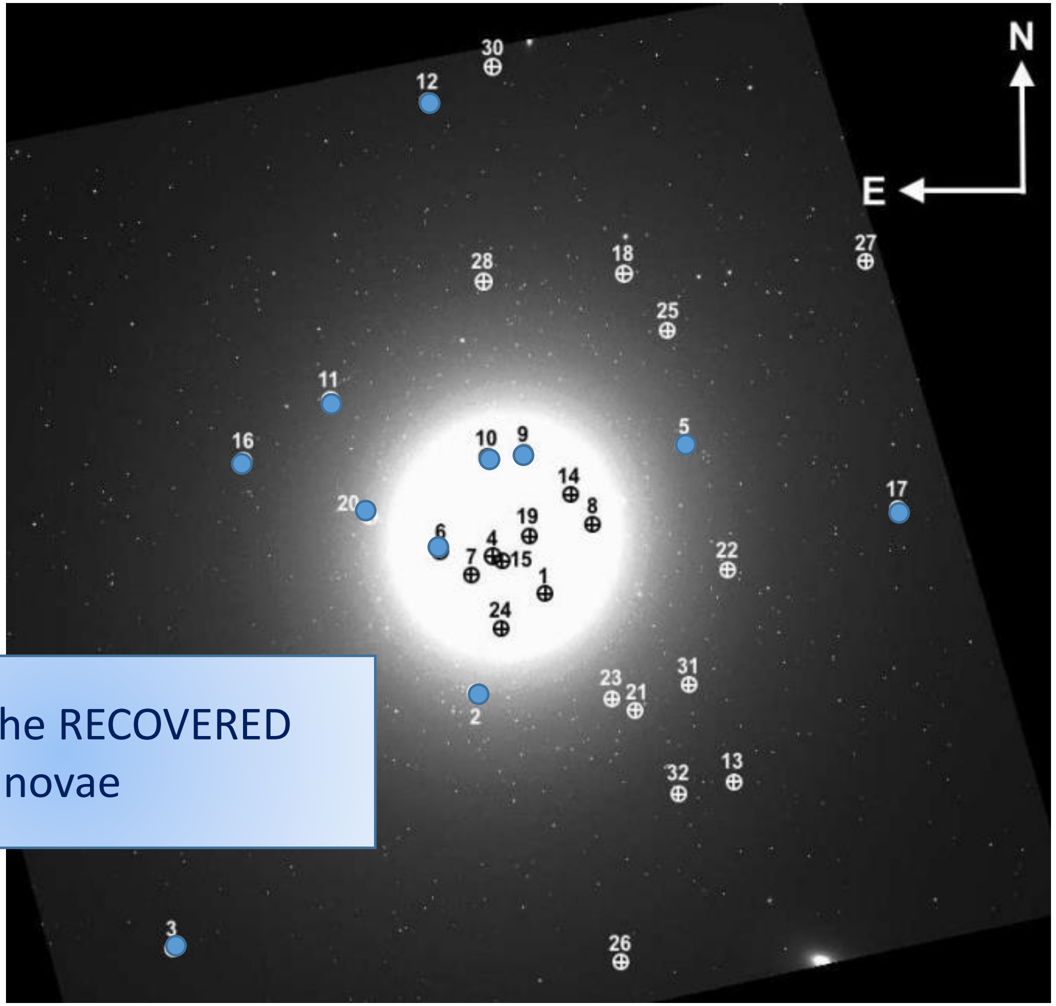
Moretti, et al. 2017, MNRAS, in preparation

HST survey for Novae in M87

One of the "worse" CS fields (very high and variable background)

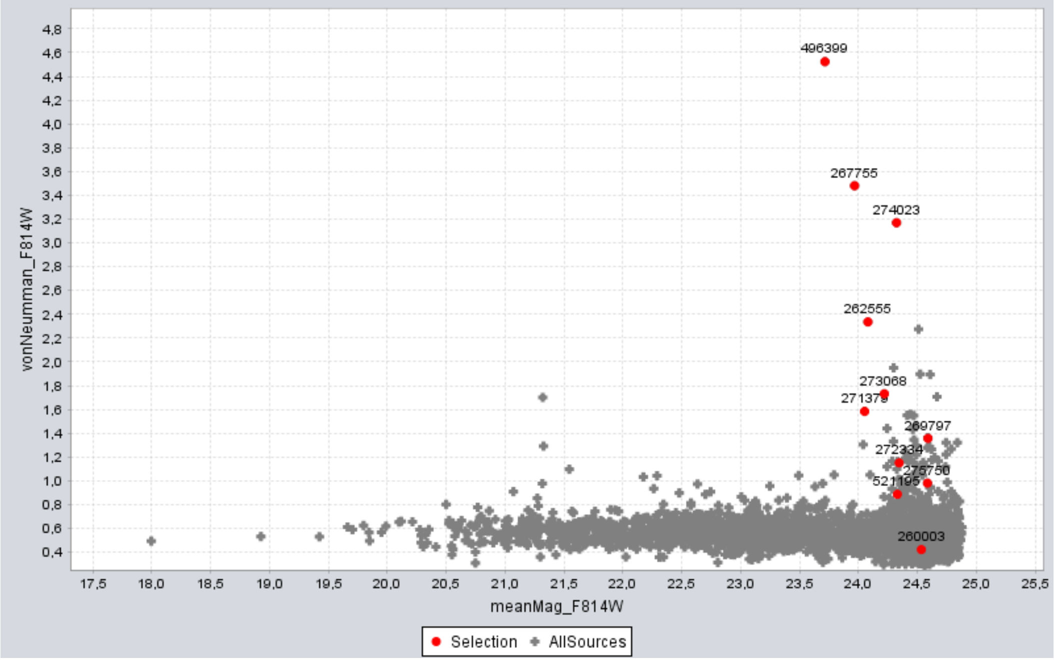
- 32 classical novae
- ACS F814W 61 visits (4x360s)
  + F606W (1x500s)
  to get colours
- Over period of 72 days
  + older observations to rule out LPVs

Shara et al. 2016



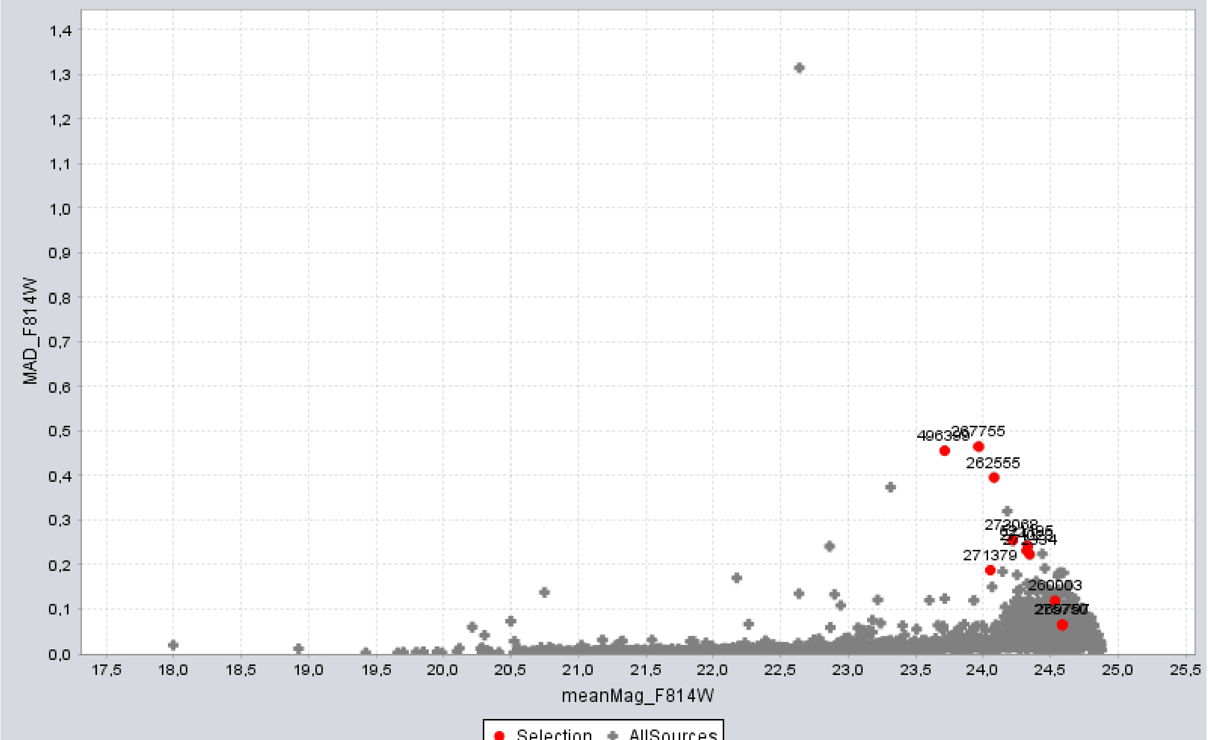
In cyan the RECOVERED novae

Location of identified novae in VI vs mean-mag diagrams



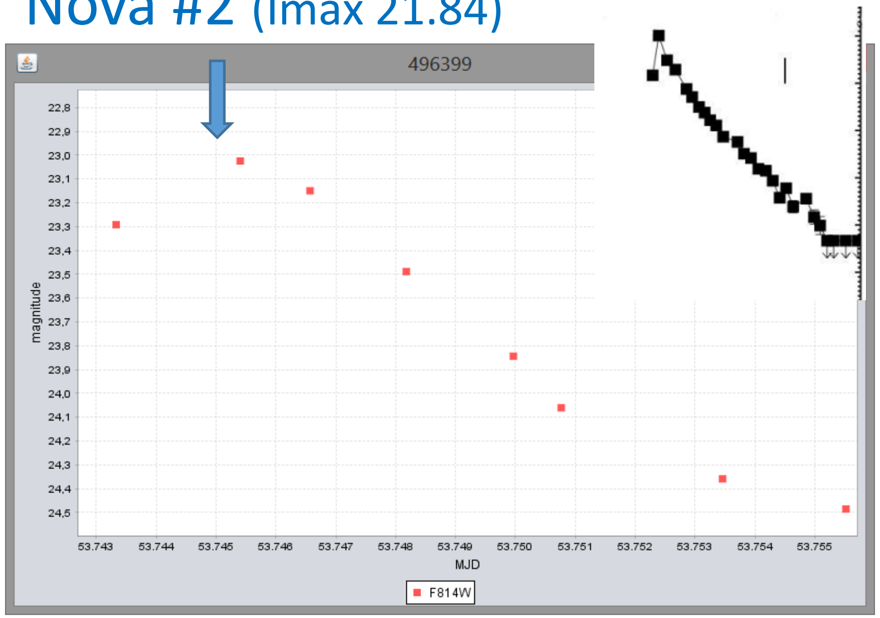
1/η correlation based VI

MAD scatter based VI

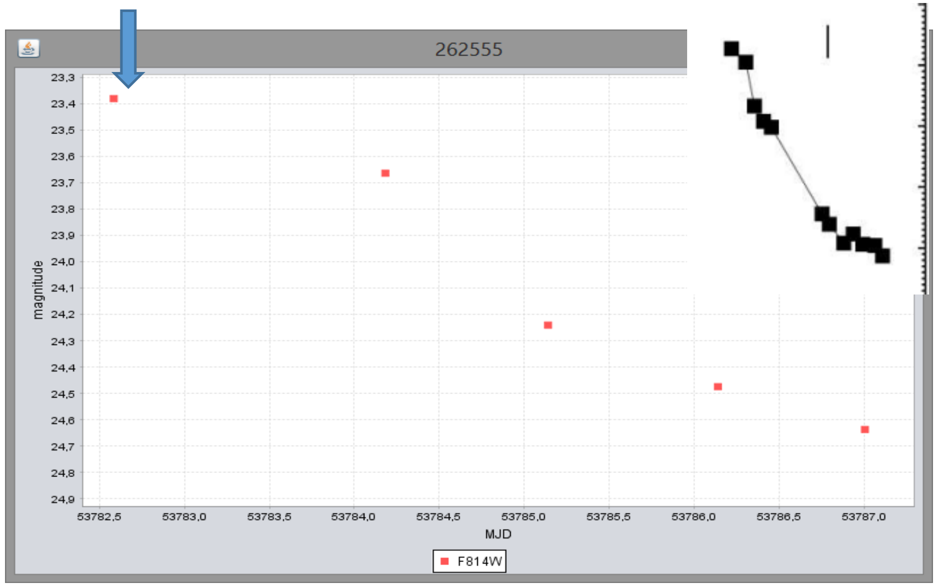


Examples of HCV selected novae

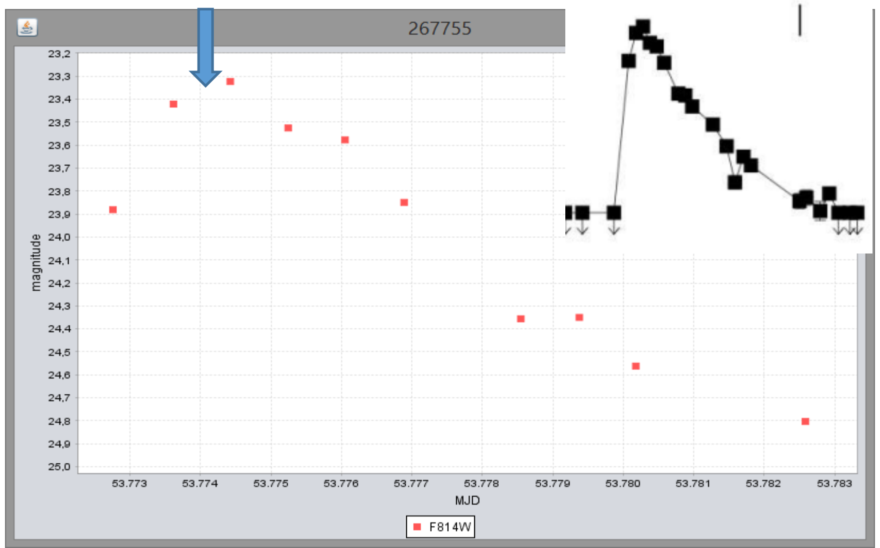
Nova #2 (Imax 21.84)



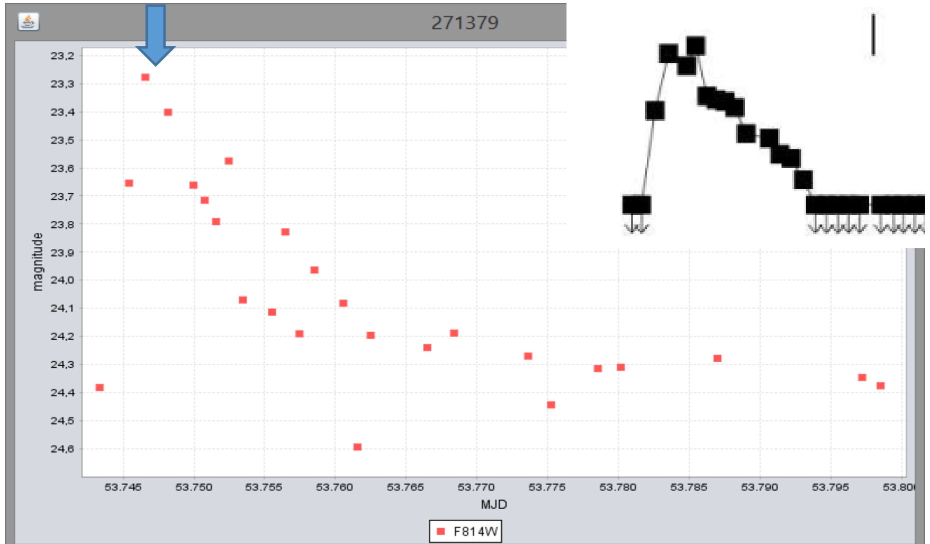
Nova #3



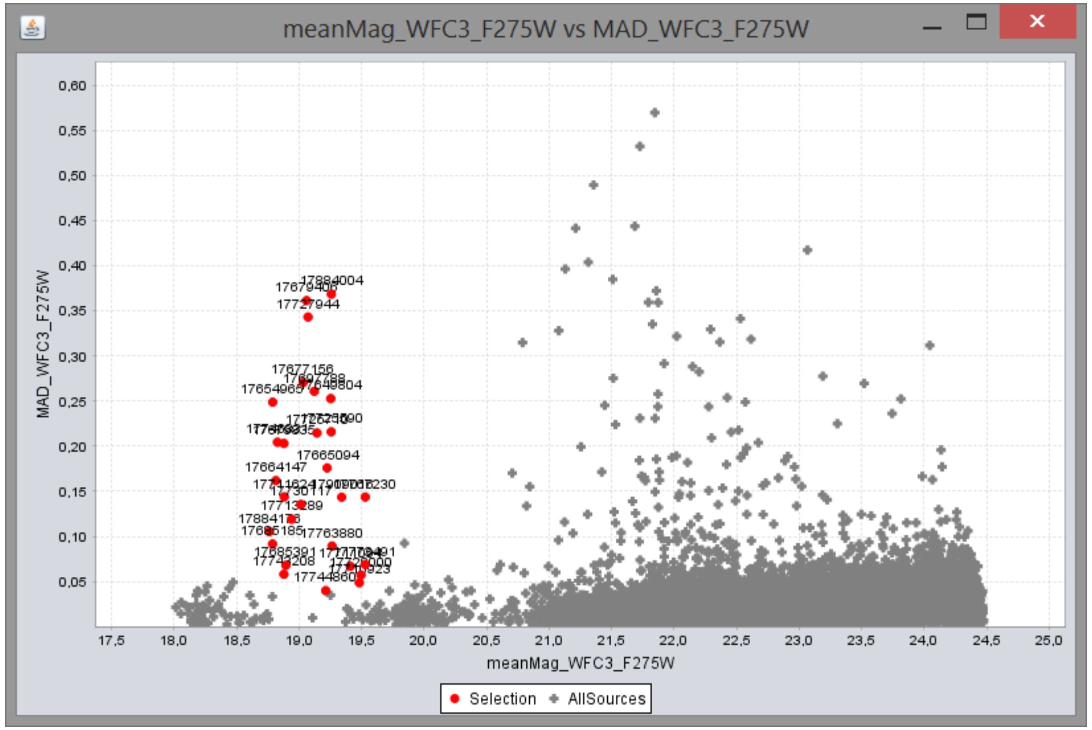
Nova #5

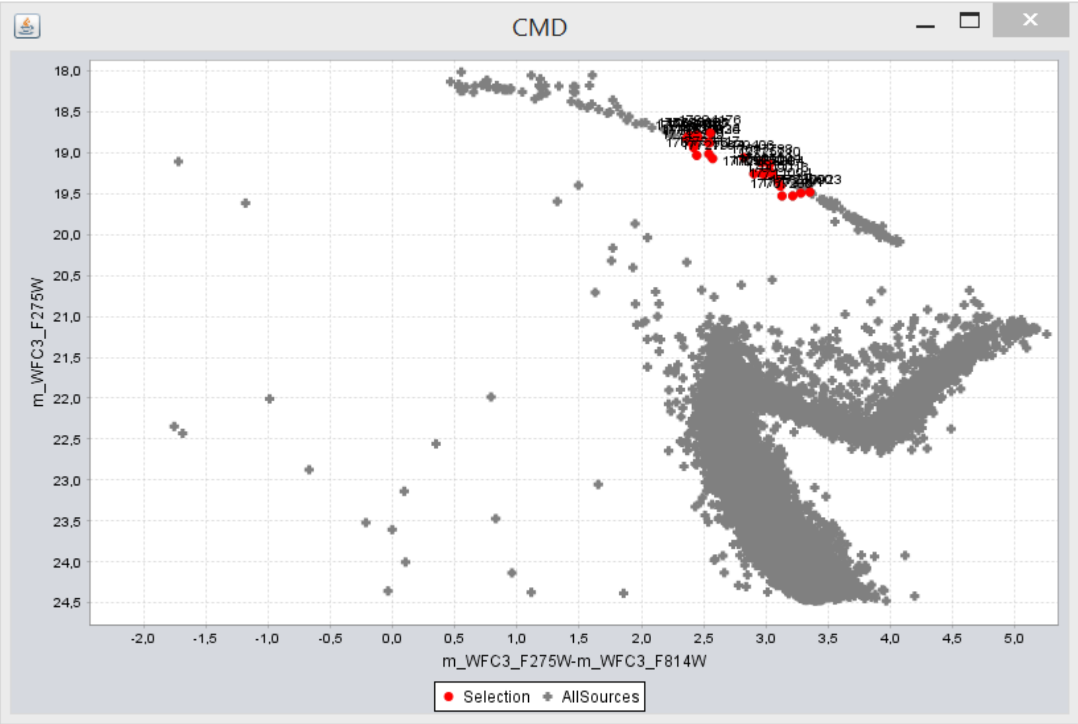


Nova #6



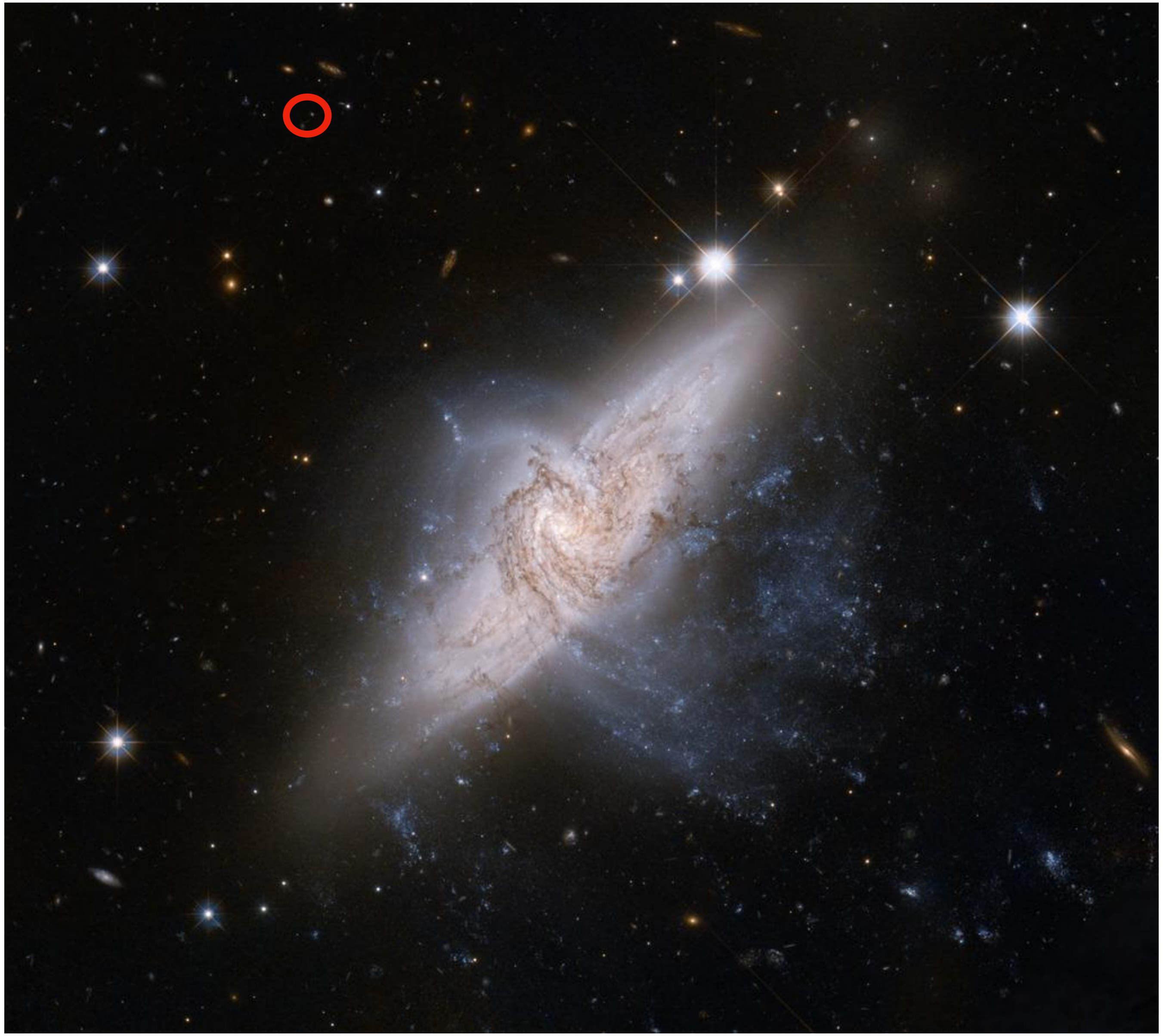
HCV V1 “Random field 1” NGC 1851

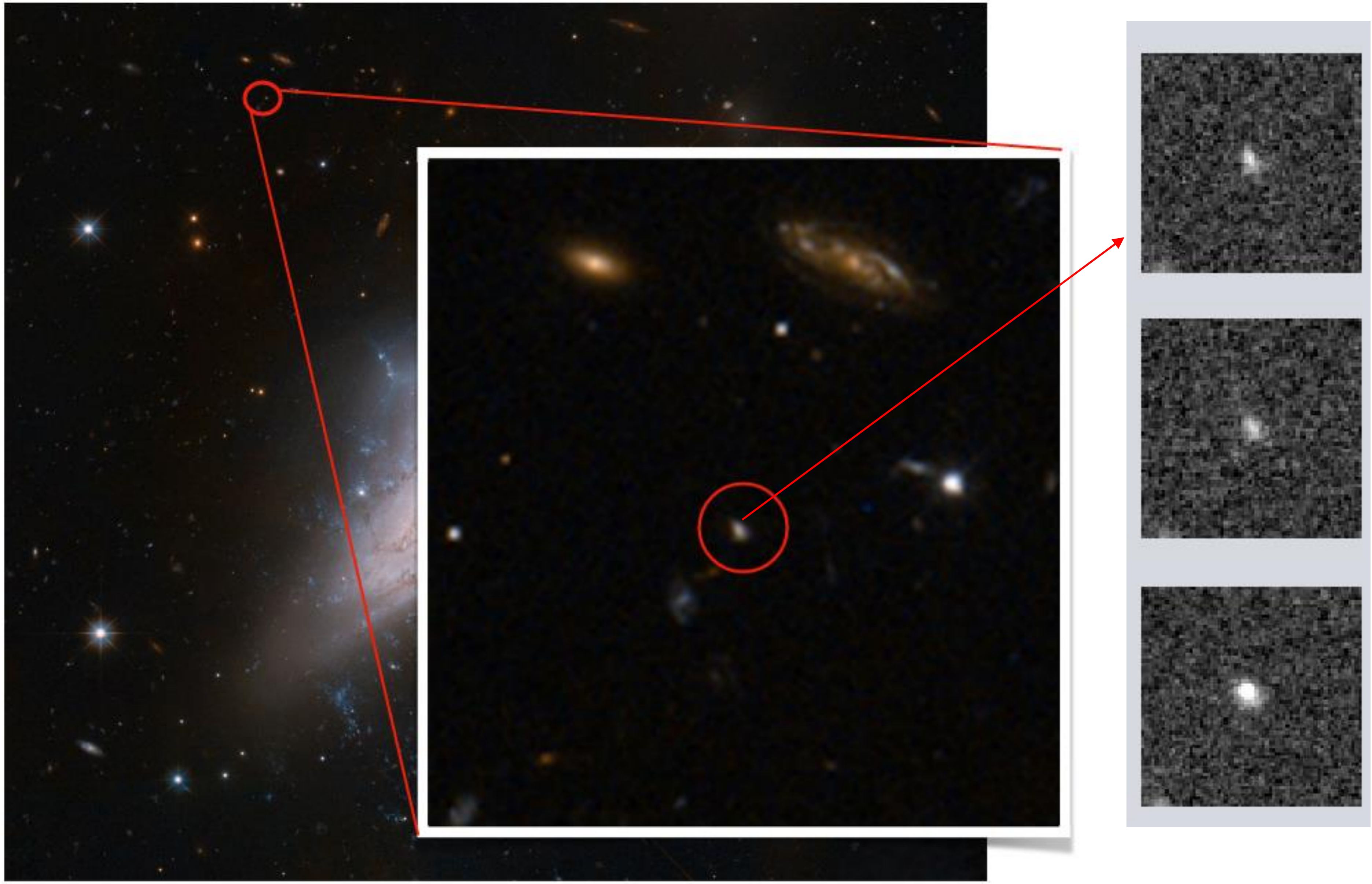




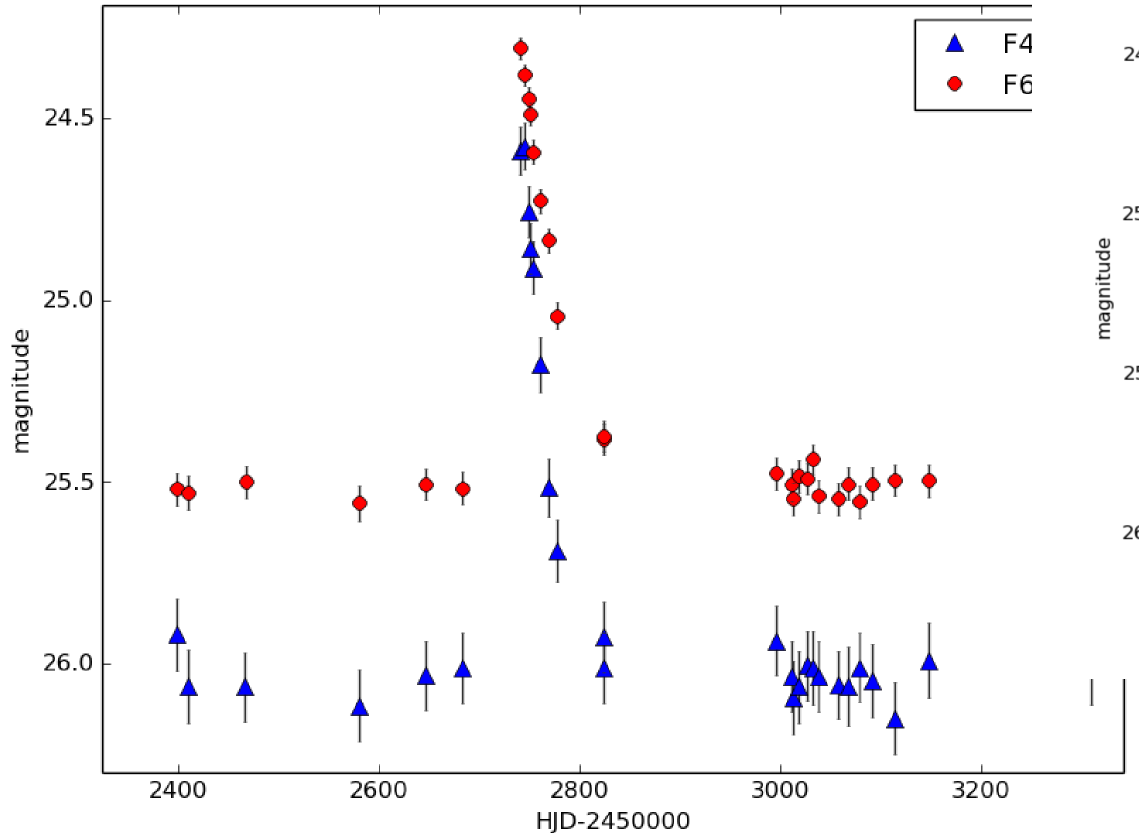
RR-Lyrae in NGC 1851

Transient object in the field of NGC 3314

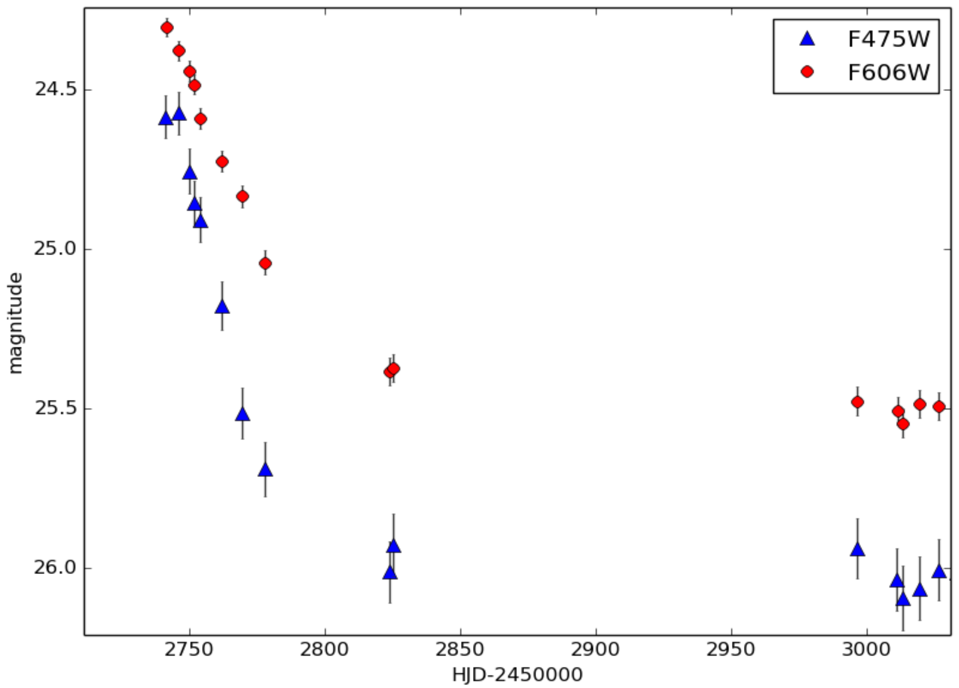




Light-curve of transient source



Spetsieri et al., in prep



1.5 mag drop in F475W

1 mag drop in F606W

Interval: 120 days