11th *Gaia* Science Alert workshop
20/01/2021

Variable objects processing in the *Gaia* consortium

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& M. Audard, L. Eyer, B. Holl, G. Jevardat de Fombelle, I. Lecœur-Taïbi, L. Rimoldini, K. Nienartowicz (CU7/DPCG Geneva team), P. Garcia-Lario, P. Gavras, + international CU7 team, + Gaia Data Processing and Analysis Consortium (DPAC)

- Introduction
- **Variable objects processing** within the *Gaia* consortium
- **Variability studies** using the *Gaia* archive
- Conclusions

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

Introduction

SN 185 : **“guest star”** (Chinese records)

→ SN 386

→ SN 393

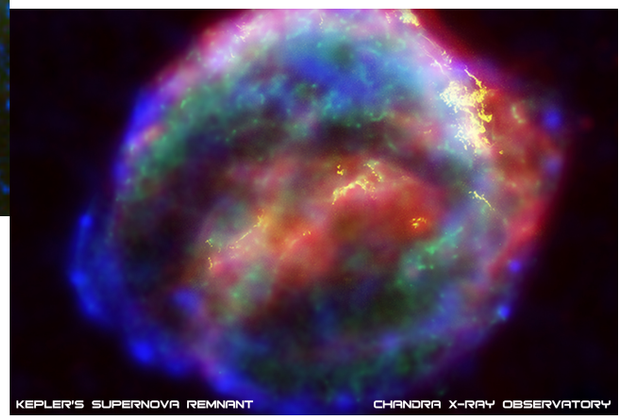
SN 1572 : Tycho **supernovae**

→ SN 1604 : Kepler supernovae (Europe+Korea+China)

http://wise.ssl.berkeley.edu/gallery_Tycho_SNR.html

SN1572

SN1604



http://chandra.harvard.edu/photo/printgallery/2004/

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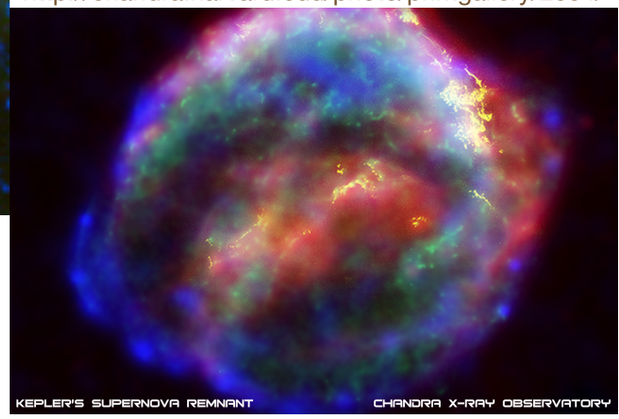
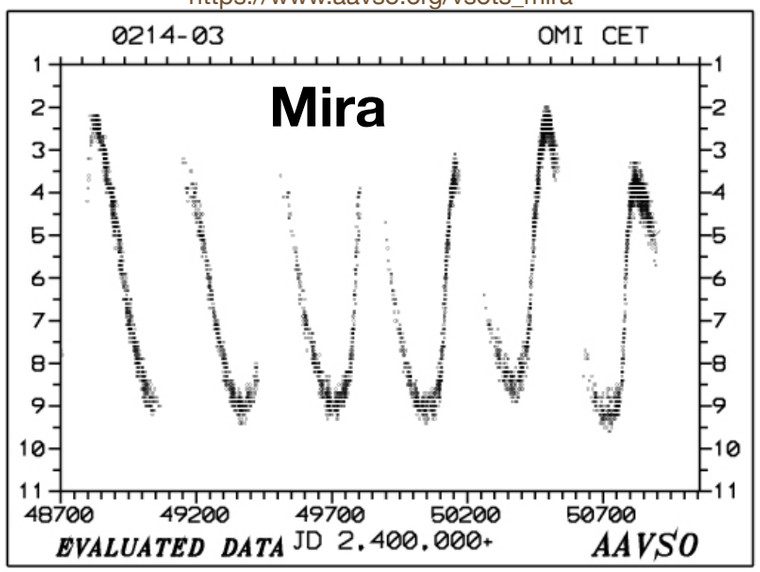


https://www.aavso.org/vsots_mira



7 mag

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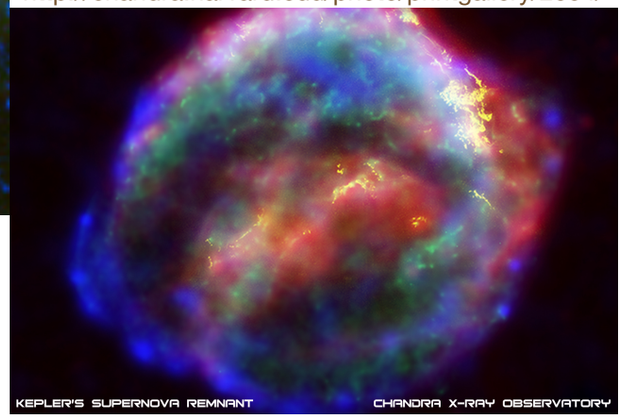

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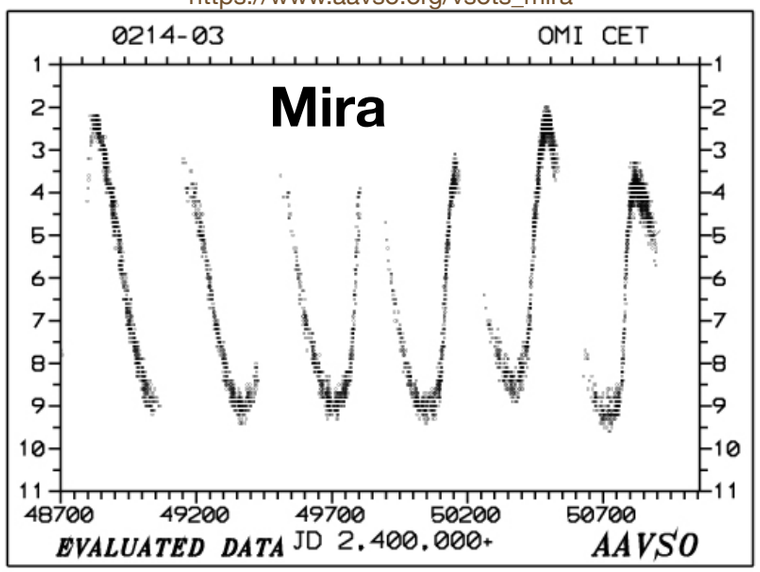

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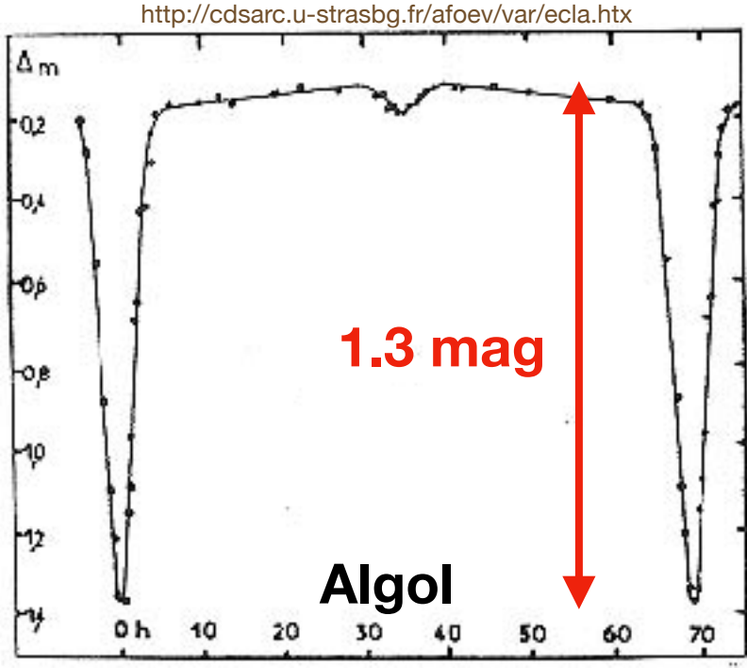

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1784: **delta Cephei** (John Goodricke)

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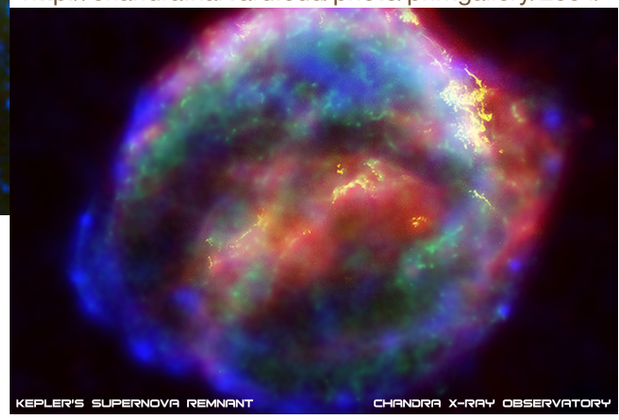

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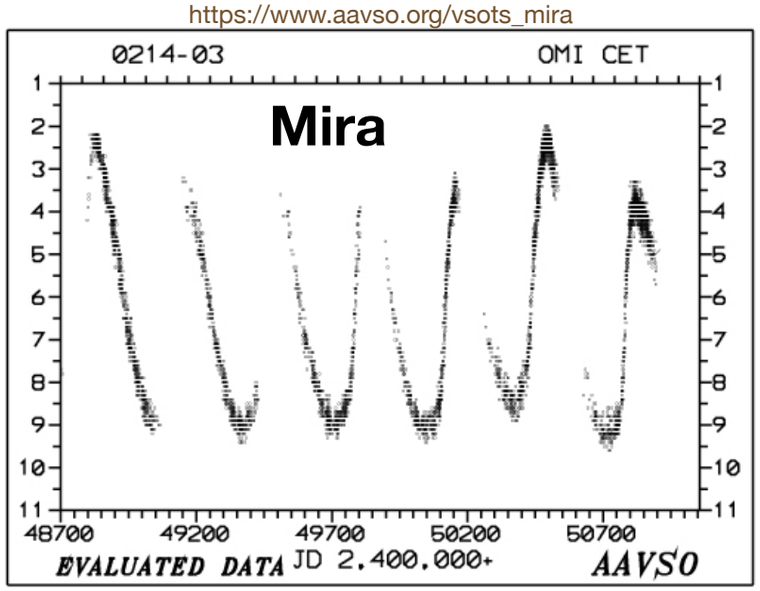

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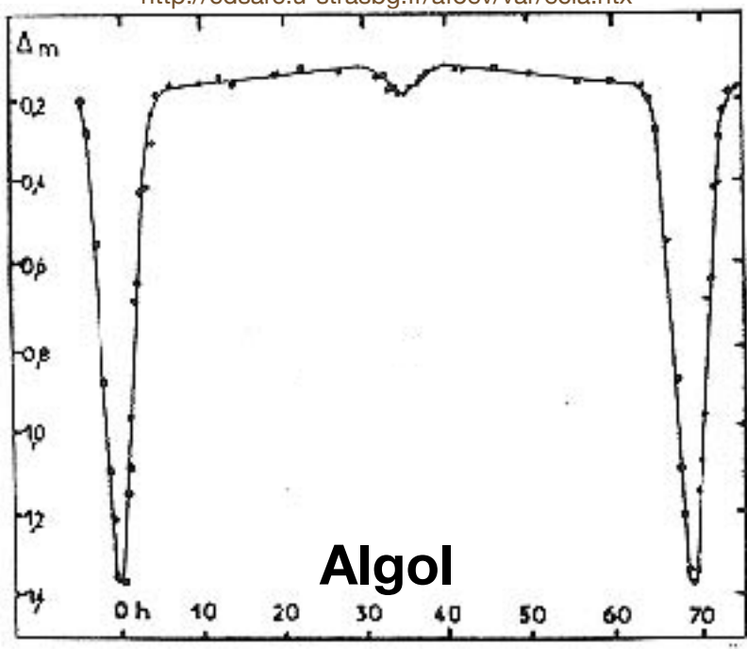
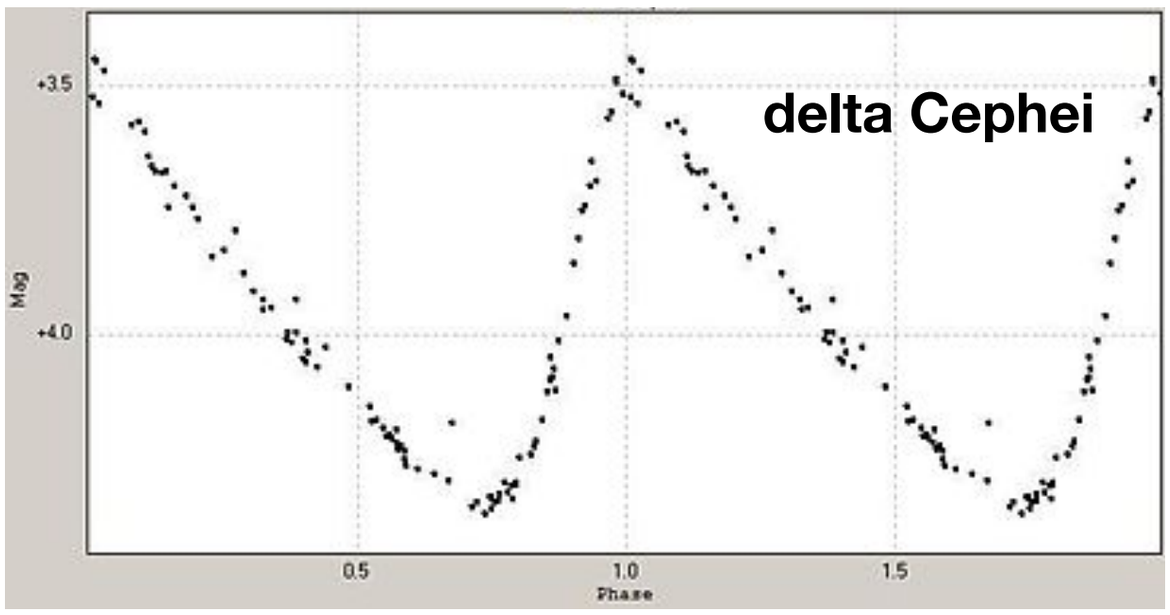




0.9 mag

By 1786: 10 variable stars …

https://en.wikipedia.org/wiki/Delta_Cephei

… already 3 distinct classes of variable objects

Eclipse

EA

Eclipsing binary
(Algol type)

Cataclysmic

SN

Supernovae

Pulsation

M

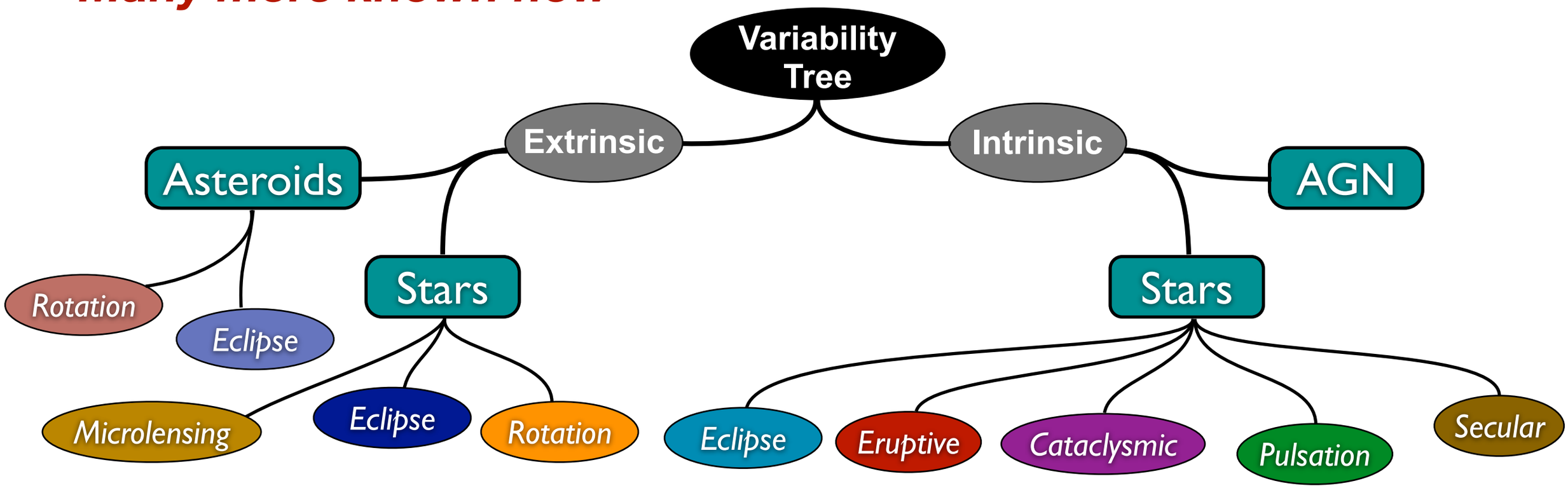
Miras

CEP

δ Cepheids

Introduction

Many more known now



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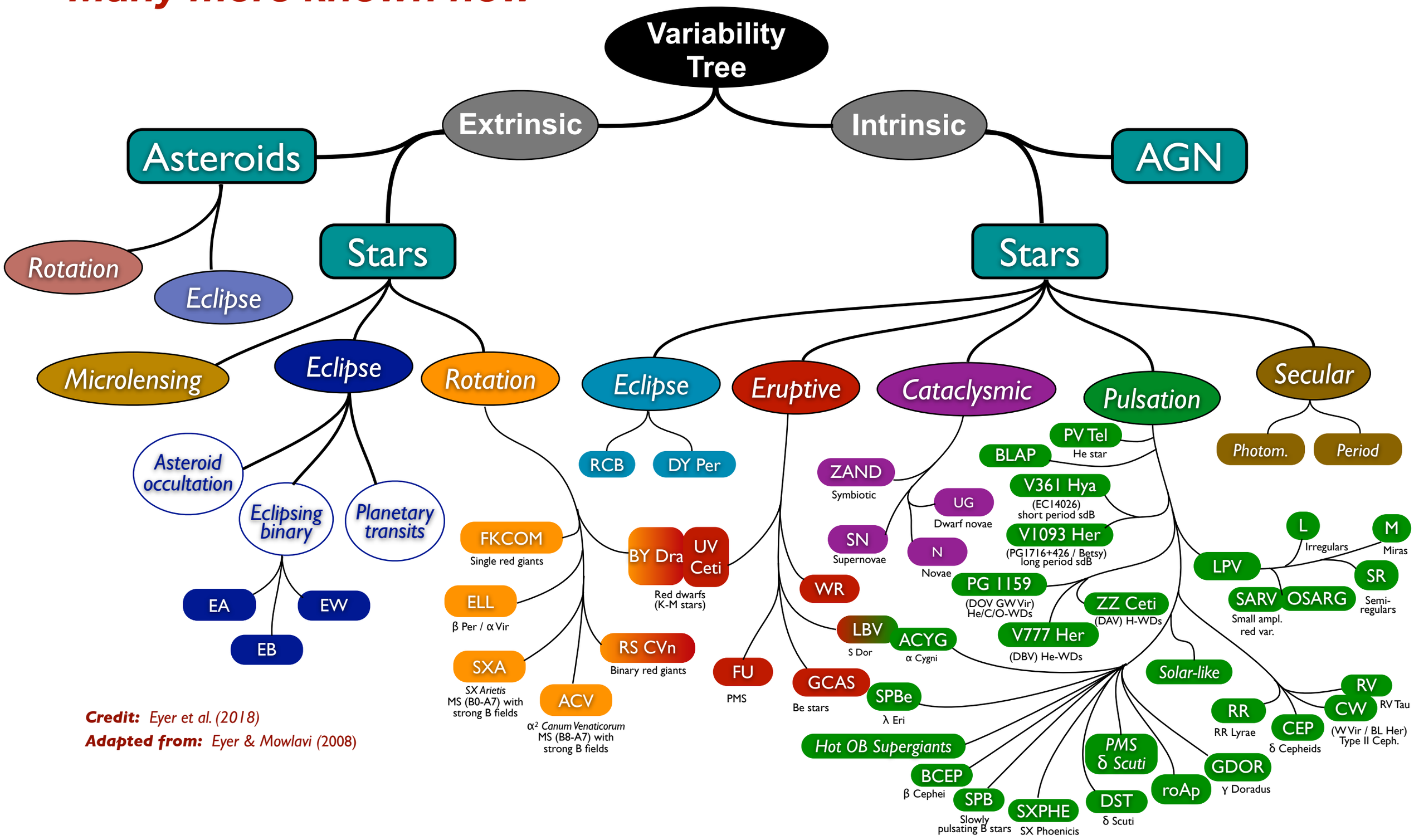
Introduction

Many more known now



Credit: *Eyer et al. (2018)*

Adapted from: *Eyer & Mowlavi (2008)*

Introduction

Pioneering photometric large-scale surveys

EROS	**1990** - 2003	(Palanque-Delabrouille et al. 1998)
MACHO	**1992** - 1997	(Alcock et al. 1993, 1997)
OGLE	**1992** - present	(Udalski et al. 1992, 1997)

Number of variables in *recent* years

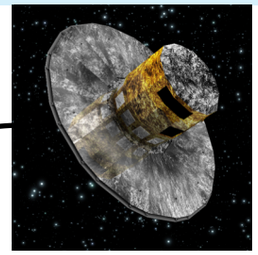
NOT EXHAUSTIVE !

Catalina	:	~110 000	(Drake et al. **2017**)
Pan-STARRS	:	~240 000	(Sesar et al. **2017**)
ATLAS	:	~430 000	(Heinze et al. **2018**)
ASAS-SN	:	~426 000	(Jayasinghe et al. **2021**)
OGLE-IV	:	~1 000 000	(http://ogledb.astrouw.edu.pl/~ogle/OCVS/)
AAVSO	:	~1 500 000	(https://www.aavso.org, as of June **2020**)
ZTF DR1 (variables)	:	~10 000 000	(variables in DR1; Ofek et al. **2020**)
DR2 (periodics)	:	~600 000	(periodics in DR2; Chen et al. **2020**)
Gaia *(now)* DR1 in var. catalogs	:	~3 000	(Clementini et al. **2016**)
DR2 in var. catalogs	:	~500 000	(Holl et al. **2018**)
Large-amplitudes	:	~20 000 000	(Mowlavi et al. **2020**; from full DR2 archive)
Gaia *(future)* DR3 in var. catalogs	:	7 000 000 **?**	(expected 2022)
DR4	:	>100 000 000 **?**	

Future surveys: Vera Rubin Observatory (LSST), …

Explosion of the number of variables due to large scale surveys !

Variable source processing within the consortium



CU3
Core processing

Initial Data Treatment
Source list creation
Astrometric Global Iterative Solution

Cambridge
Near-real time processing
(CU5 + GSA)

Gaia Science Alerts

Scientific community

ESA
Gaia
archive

CU4
Object processing

Non-single stars
Solar-system objects
Extended objects

CU5
Photometric processing

G photometry
BP&RP spectrophotometry

CU7
Variability processing

+ Data Processing Center in Geneva (DPCG)

CU6
Spectroscopic reduction

RVS spectroscopy,
Radial Velocities

CU8
Astrophysical parameters

e.g. stellar parameterization,
interstellar extinction

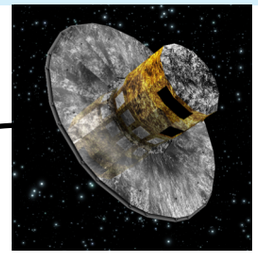
CU9
Catalogue access

Gaia archive
design & implementation

CU = Coordination Unit
within the *Gaia Data Processing and Analysis Consortium*

Variable source processing within the consortium

DR2 data flow for **CU7**



CU3
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(CU5 + GSA)

Gaia Science Alerts

Scientific community

ESA
Gaia
archive

CU4
Object processing

CU5
Photometric processing

astrometry

calibrated
G, G_{BP}, G_{RP}

CU7
Variability processing

+ Data Processing Center in Geneva (DPCG)

CU9
Catalogue access

Variability tables

- Cepheids
- RR Lyrae
- Long-period variables
- Rotation-modulation variables
- delta Scuti & SX Phoenicis
- Short time scale variables

CU6
Spectroscopic reduction

CU8
Astrophysical parameters

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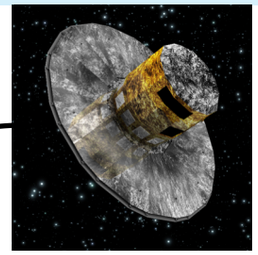
Variable source processing within the consortium

DR2 data flow for **CU7**

DR3 additional flow for **CU7**

DR4 additional flow for **CU7**



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archive

CU4
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CU5
Photometric processing

astrometry

calibrated G, G_{BP}, G_{RP}

BP, RP spectra

Eclipsing binaries

CU7
Variability processing

+ Data Processing Center in Geneva (DPCG)

CU9
Catalogue access

CU6
Spectroscopic reduction

RV, RVS spectra?

APs

CU8
Astrophysical parameters

Variability tables

- Cepheids
- RR Lyrae
- Long-period variables
- Rotation-modulation variables
- delta Scuti & SX Phoenicis
- Short time scale variables

+ many more types …

+ even more types …

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Variable source processing within CU7

DR2 data flow for **CU7**

DR3 additional flow for **CU7**

CU5

Calibrated G, G_{BP}, G_{RP} RP spectra

CU6

Radial velocities

Pre-processing

Cleaned time-series

Statistics

General Variability Detection

Special Variability Detection

Variable candidates

Characterization

Period search

Classification

Variability types

Specific Object Studies (SOS)

ESAC
Gaia DPAC
Main DataBase

Purity versus Completeness

→ 2 types of variability catalogues published in Gaia Data Releases

*Classification catalogue (**completeness**-oriented)*

Validation

Validation

*Variability catalogues (**purity**-oriented)*

= uses machine-learning techniques

Variable source processing within CU7

DR2 variables (see Holl et al. 2018)

	# Total	# Classif	# SOS	Reference
RR Lyrae	**228’904**	195’780	140’784	Rimoldini et al. (2019) [Classif] Clementini et al. (2019) [SOS]
Long-Period Variables	**151’761**	151’761	89’617	Mowlavi et al. (2018) [Classif+SOS]
Rotation-modulation	**147’535**	—	147’535	Lanzafame et al. (2018)
Cepheids	**11’438**	8’550	9’575	Rimoldini et al. (2019) [Classif] Clementini et al. (2019) [SOS]
delta Scuti & SX Phoenicis	**8’882**	8’882	—	Rimoldini et al. (2019)
Short-time scale	**3’018**	—	3’018	Roelens et al. (2018)

Completeness & Contamination for SOS tables:

(Table 3 in Holl et al. 2018)

SOS Type	Catalog (and region)	Completeness	Contamination
Cepheids	OGLE-IV (LMC, limited region)	74%	~ 5%[a]
RR Lyrae stars	OGLE-IV (LMC, limited region)	64%	~ 9%[a]
LPV	OGLE-III[b] (SMC+LMC)	~ 30%	< few%
Short Timescale	OGLE-II, III, IV (MCs)	0.05%	10–20%
Rotational Modulation	The Pleiades (Hartman et al. 2010)	0.7 – 5.0%	< 50%[c]

Variable source processing within CU7

DR3 variables (planned for 2022) : expected **~7-10 million variables** for **~20 variability types/subtypes**

Example of new variability types in DR3:

Young Stellar Objects
Main Sequence variables
Eclipsing Binaries
Ellipsoidals
Flaring/eruptive
White Dwarfs
Microlensing events
Exo-planets
(Super)novae
AGNs/QSOs/Blazars

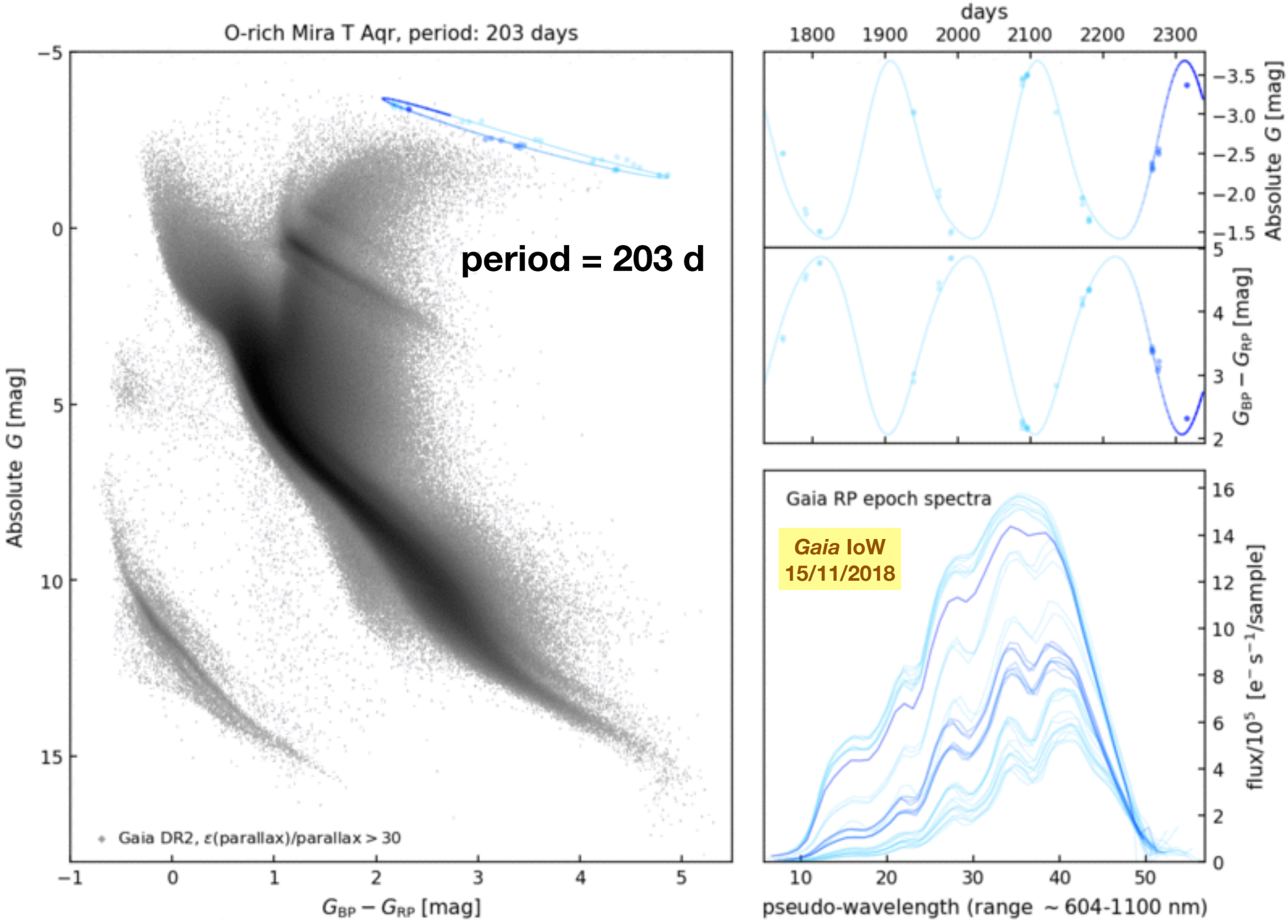
+ *Gaia* Andromeda Photometric Survey (GAPS):
*photometric time series for **all** sources in 5.5° radius around Andromeda*

Motion of variable stars in the HR diagram based on a Gaia DR2 sample

See also: Gaia Collaboration, Eyer, Rimoldini et al. (2018)

Variable source processing within CU7

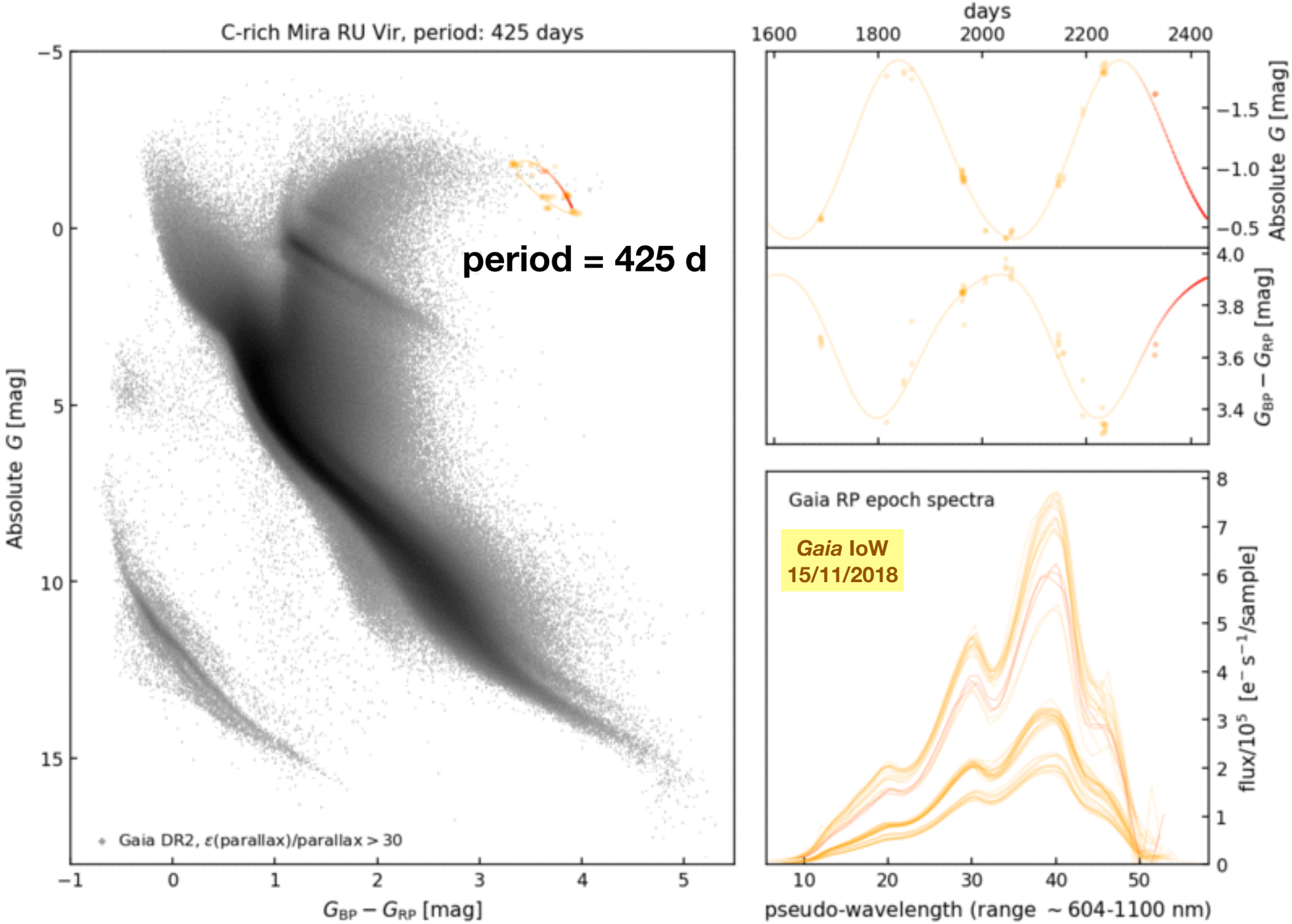
Variability of a O-rich long-period variable



Mowlavi, Trabucchi, Lebzelter (2019)
Movie credit: M. Trabucchi

Variable source processing within CU7

Variability of a C-rich long-period variable



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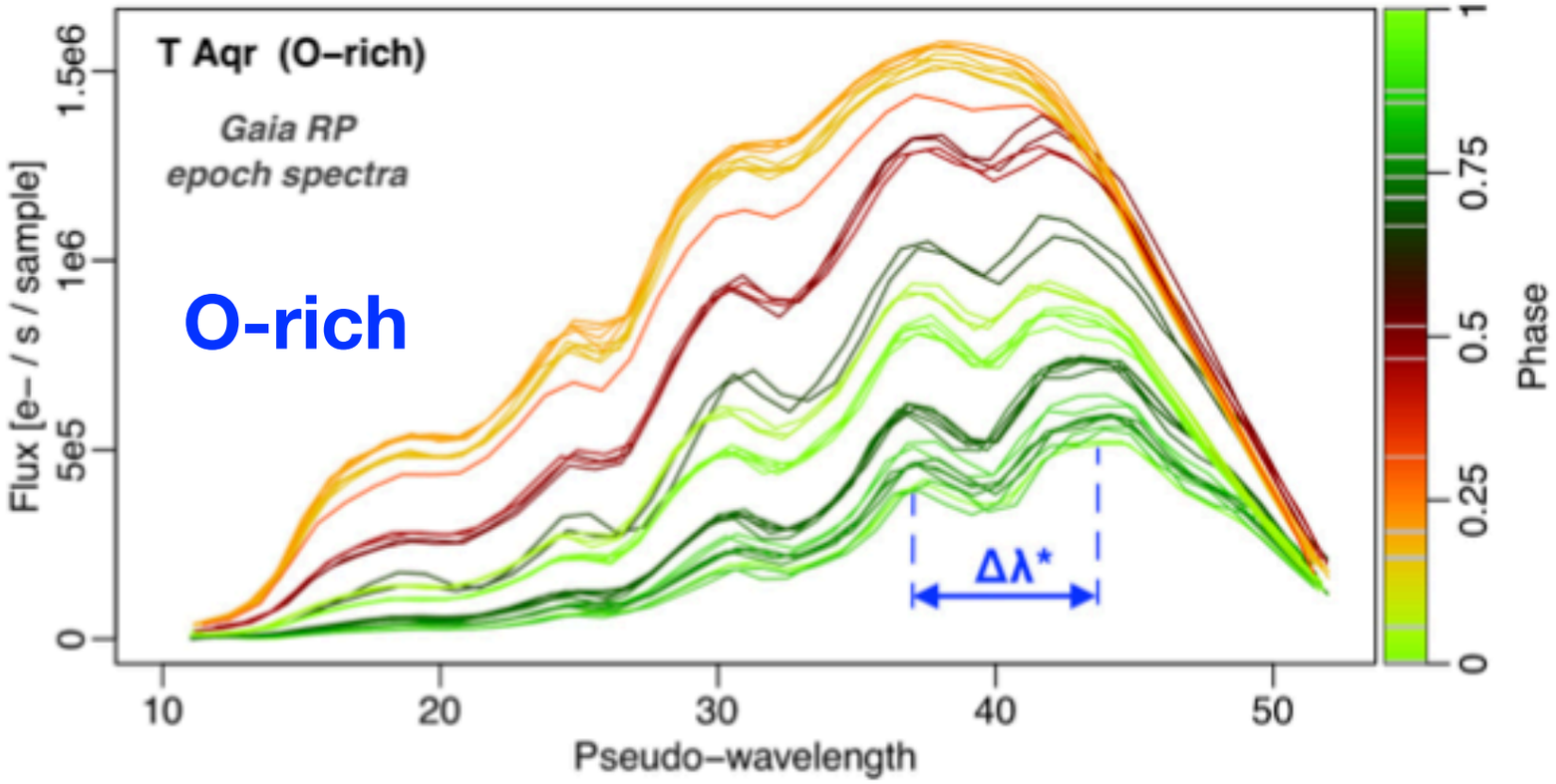
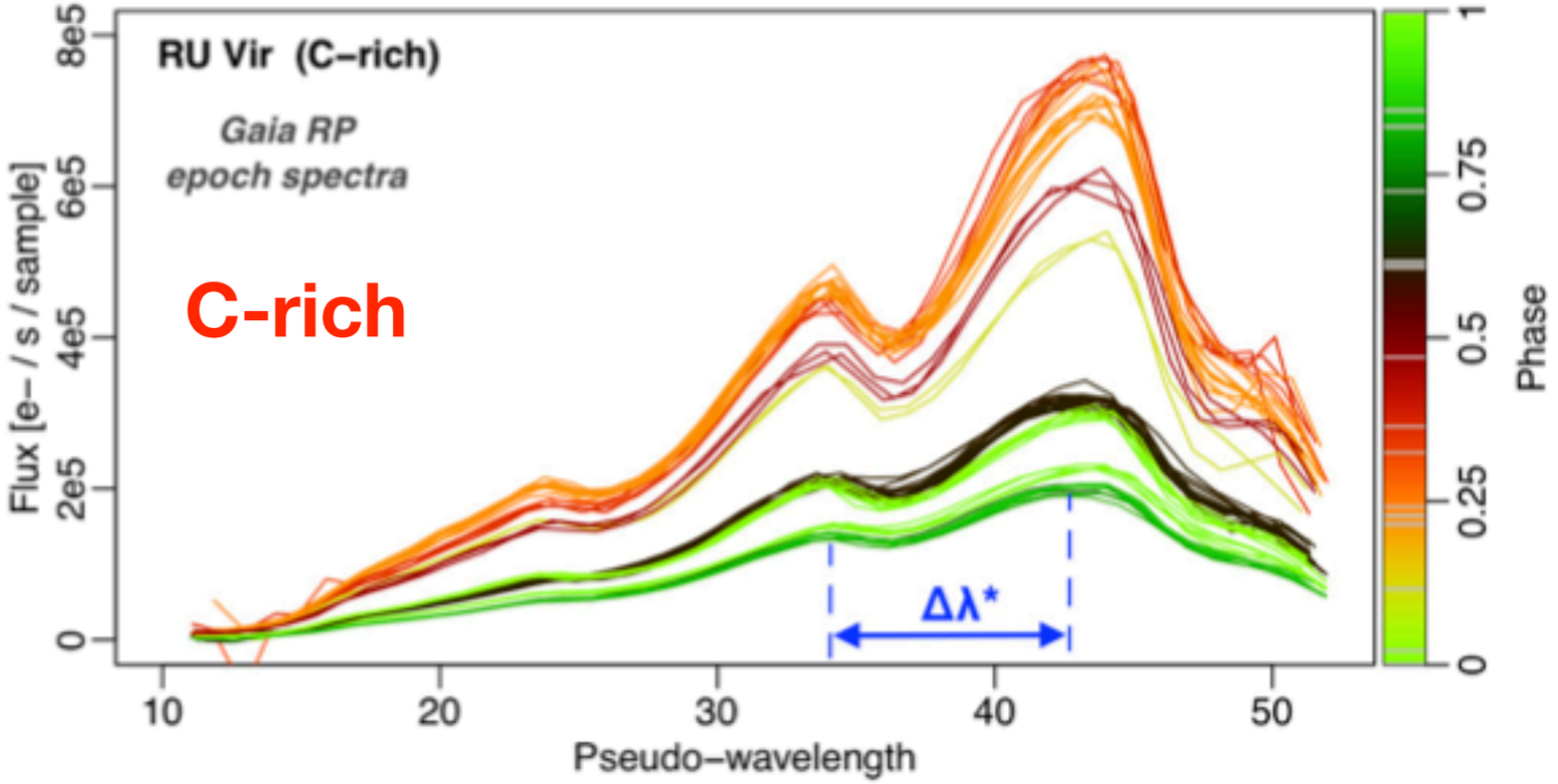




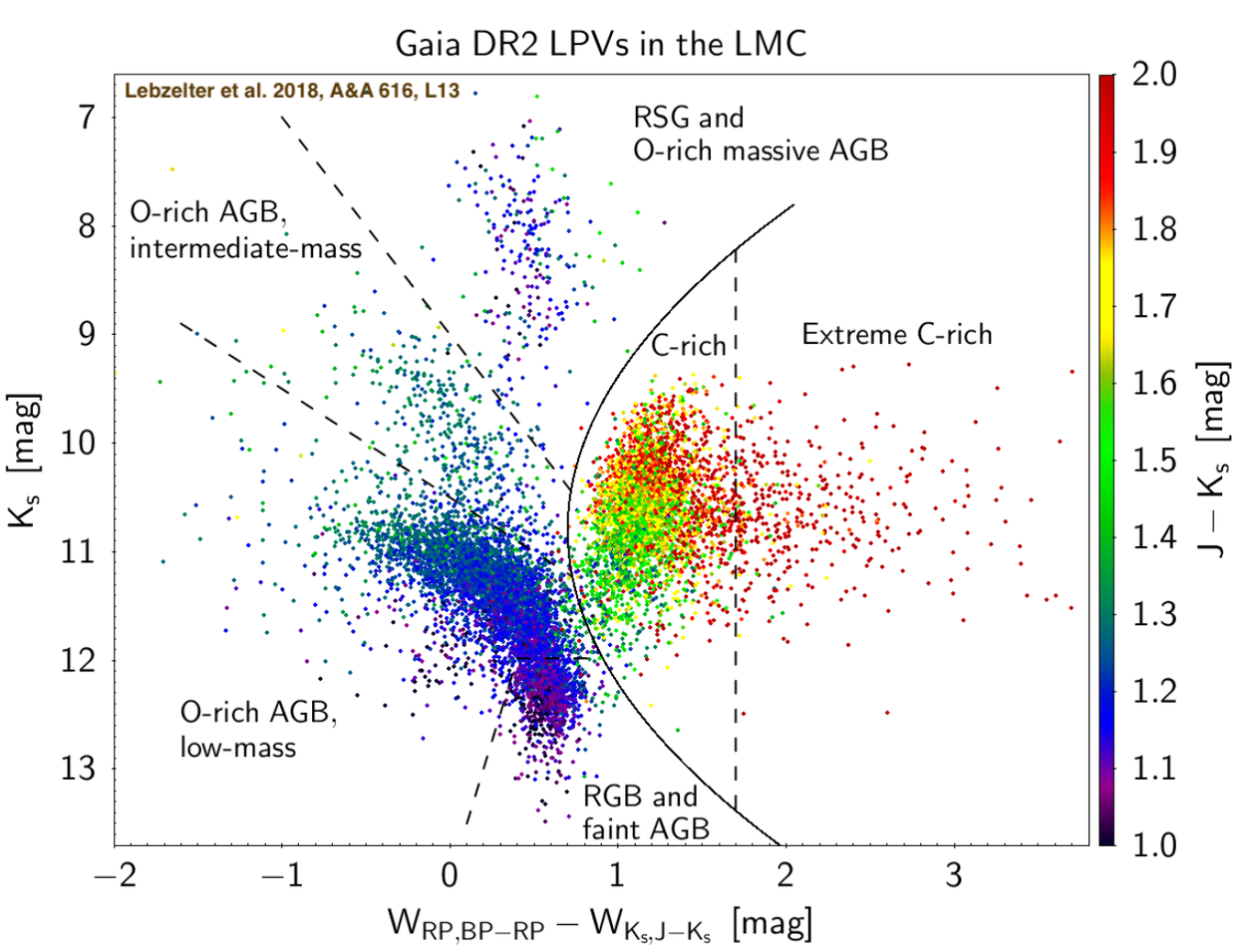
→ ***Use RP spectra in DR3*** *to discriminate between* ***O-rich*** *and* ***C-rich*** *red giants*

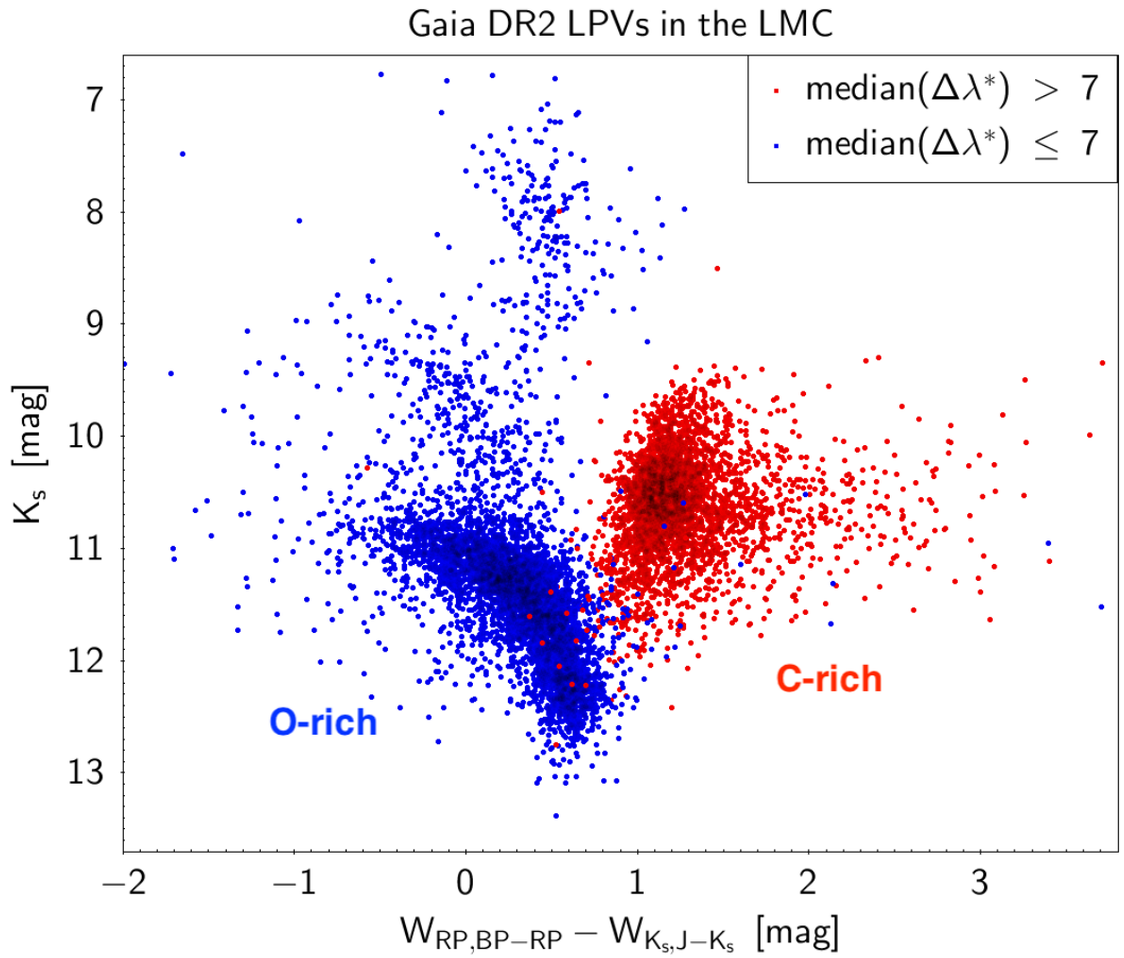
Gaia Image of the week (15/11/2018)

Credits: ESA/Gaia/DPAC, N. Mowlavi, et al.

Variable source processing within CU7

DR3: Using RP spectra *to discriminate between O-rich and C-rich red giants*





Note: spectra will not published in DR3

Gaia Image of the week (15/11/2018)

Credits: ESA/Gaia/DPAC, N. Mowlavi, et al.

Variability amplitude proxy for all sources in the Gaia archive

$$A_{\mathrm{proxy,G}} = \sqrt{N_{\mathrm{G}}}\,\frac{\varepsilon(I_G)}{I_G}$$

`phot_g_mean_flux_error`

`phot_g_mean_flux`

`phot_g_n_obs`

Includes scatter due to:

*- **noise** in the data*

*- **stellar variability***

$$\mathrm{range}(G) \simeq 3.3\, A_{\mathrm{proxy,BP}}$$

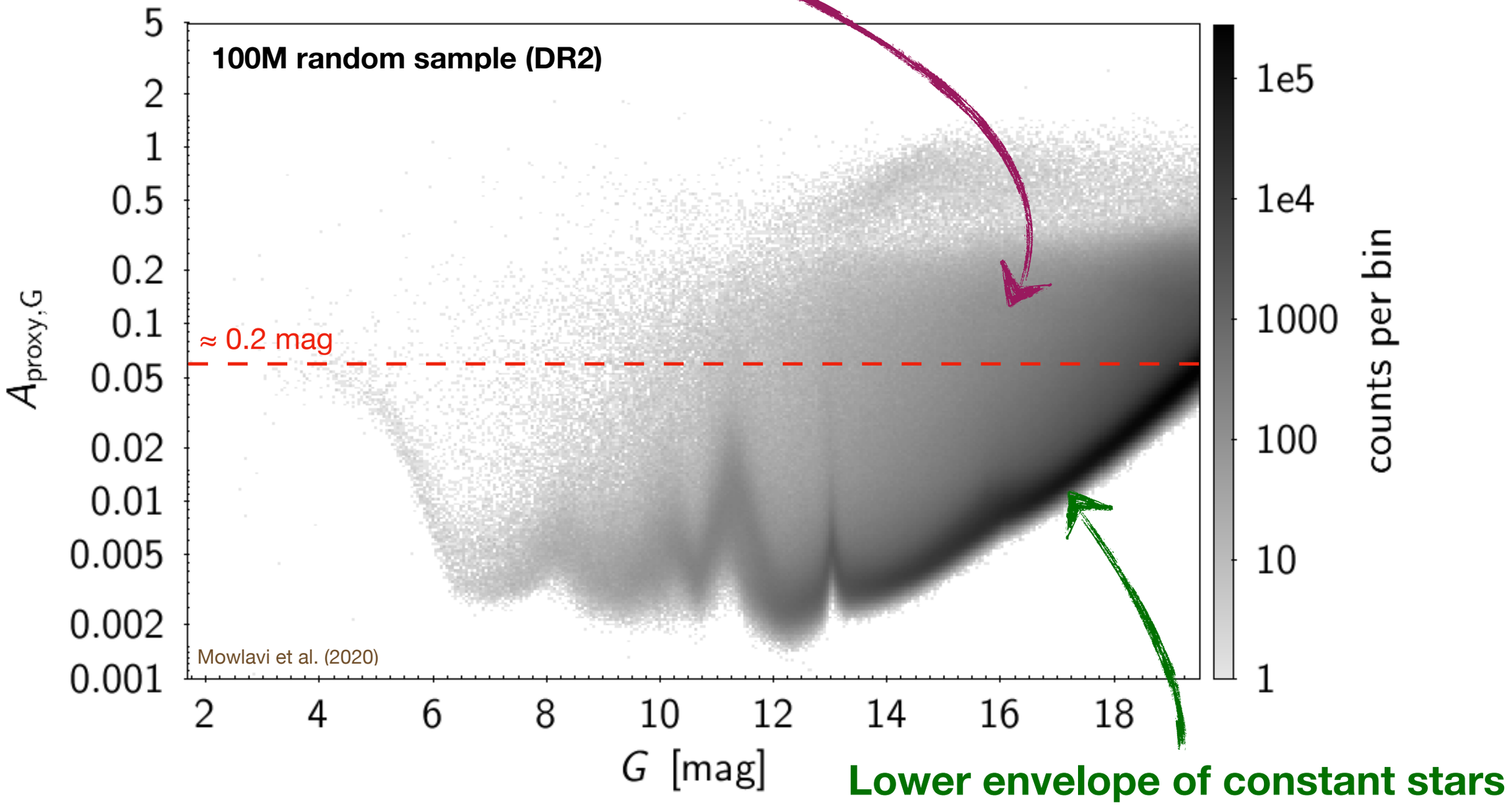
See Mowlavi et al. 2020

Amplitude proxies for G_{BP} and G_{RP} : $A_{\mathrm{proxy,BP}}$ **and** $A_{\mathrm{proxy,RP}}$

→ Multi-wavelength variability studies

Variable sources in the *Gaia* archive

Large-amplitude variables (LAVs)



23’315’874 LAV candidates in DR2 (with range(G) ≳ 0.2 mag)

Includes **1742** of the **14’945 GSA sources** (as of 15/01/2021)

Variable sources in the *Gaia* archive

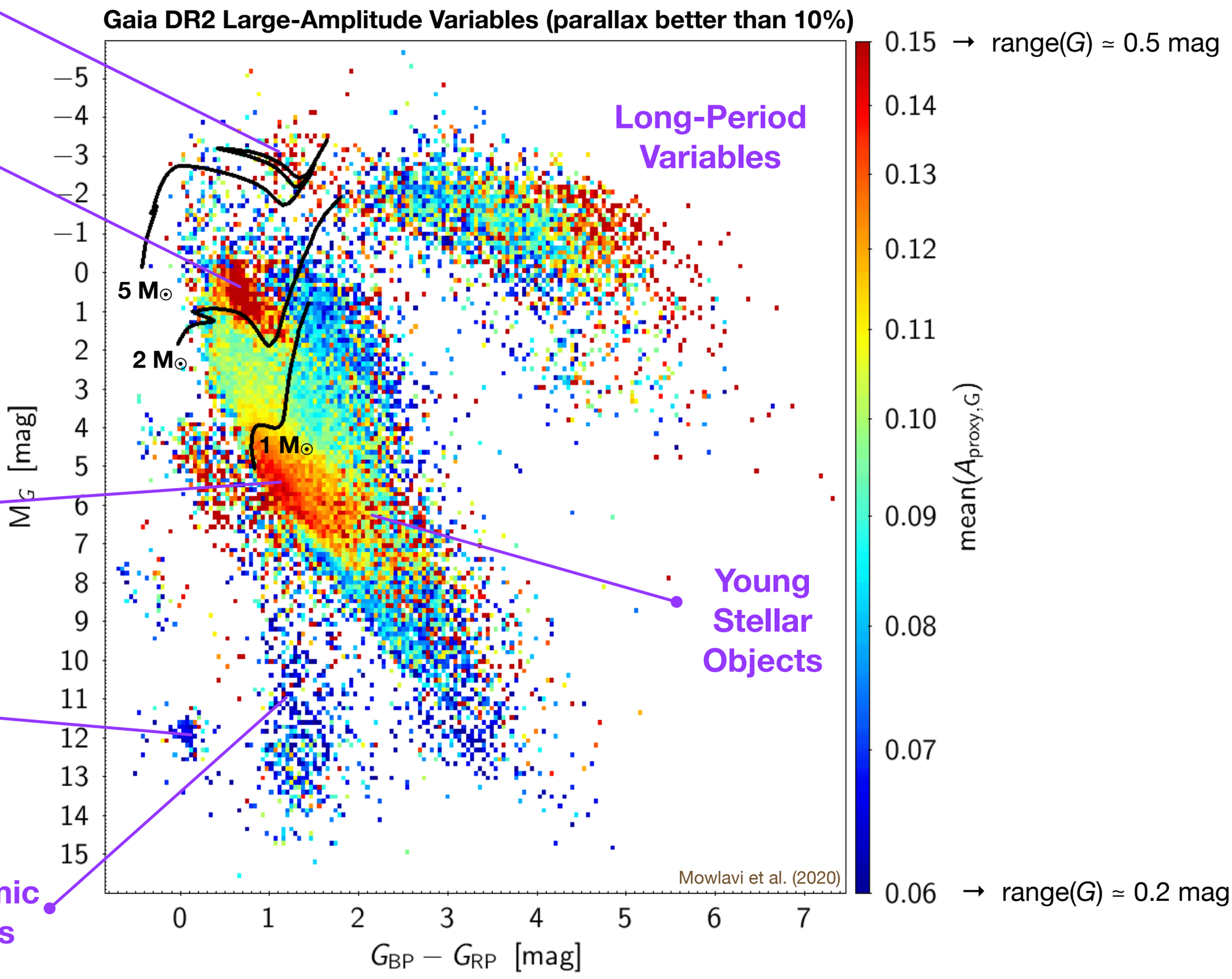
Cepheids

RR Lyrae

Eclipsing Binaries

White Dwarfs

Cataclysmic Variables



Variable sources in the *Gaia* archive

$A_{proxy,BP}$ (G_{BP})

$A_{proxy,RP}$ (G_{RP})

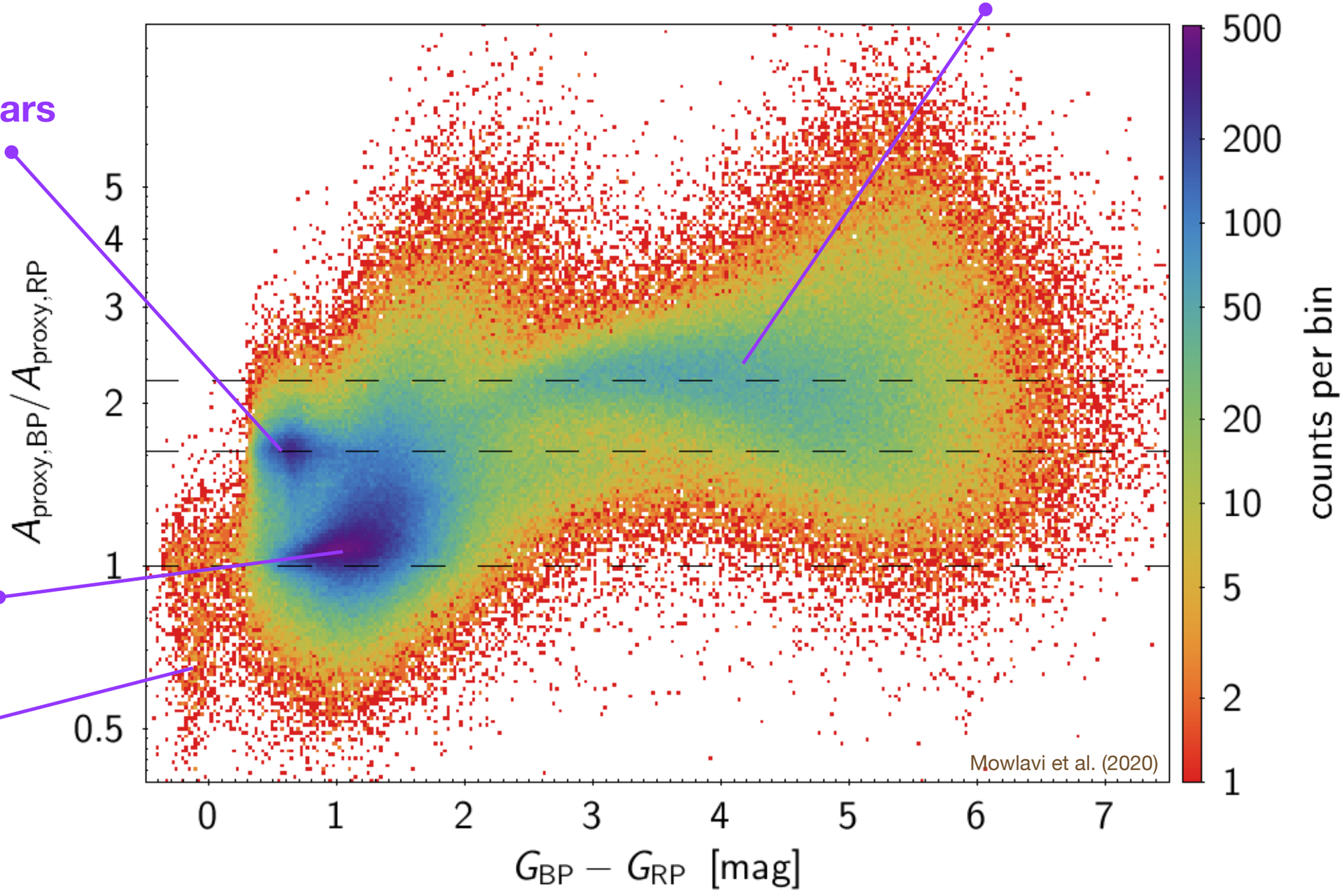
→ **wavelength-dependent variability studies**

Long-Period Variables

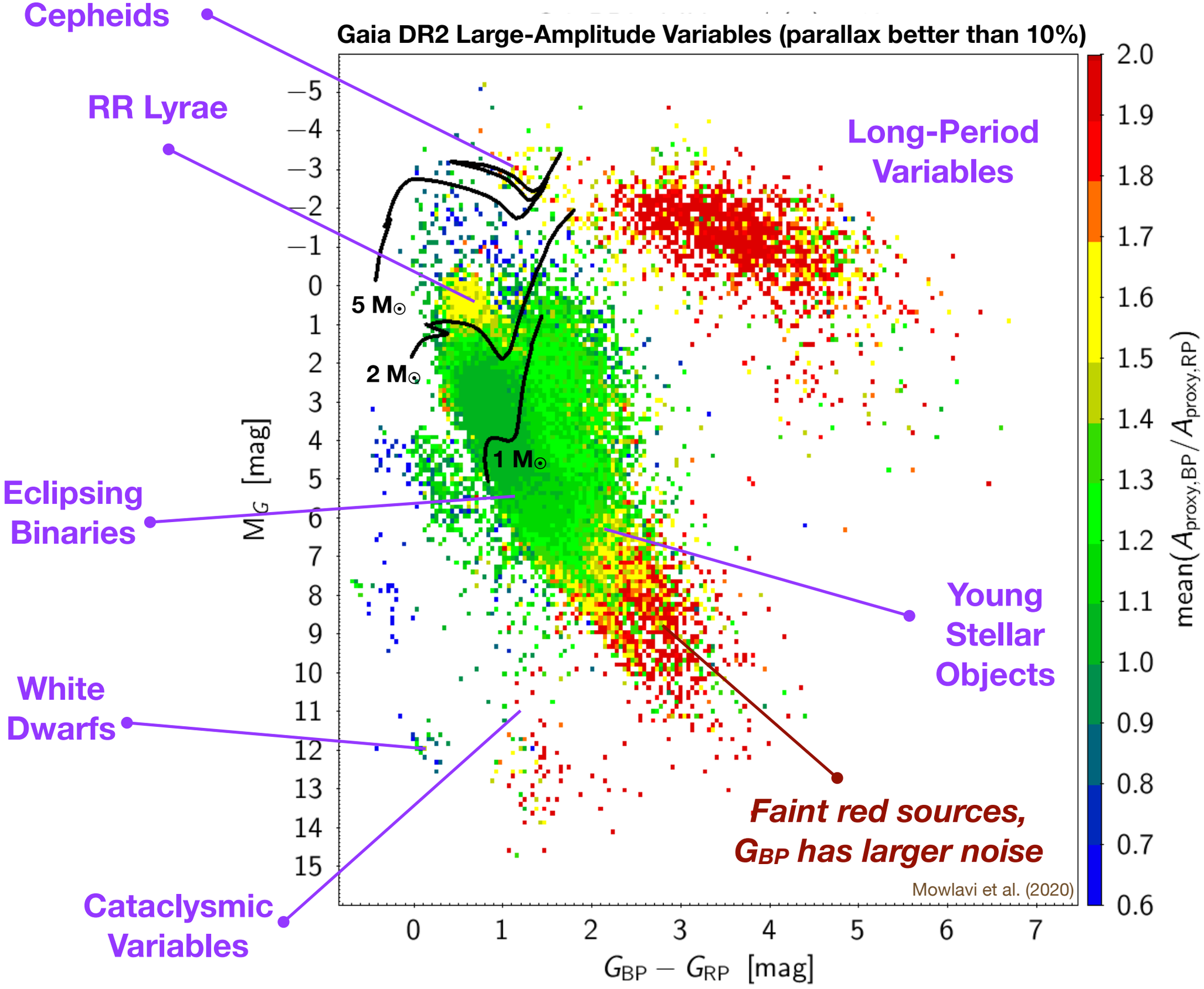
Pulsating stars

Non-pulsating stars, Eclipsing binaries

Emission-line blue stars



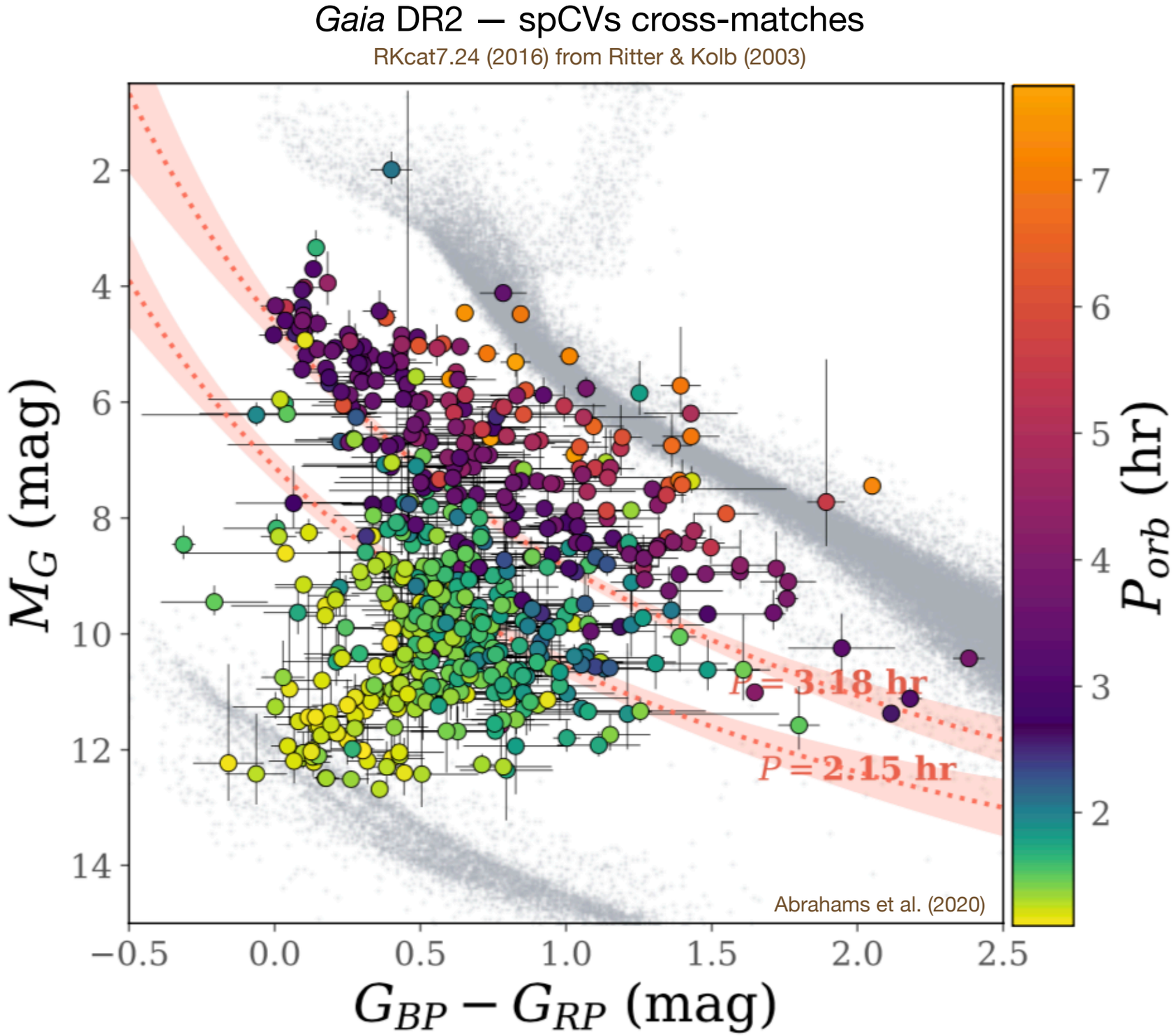
Variable sources in the *Gaia* archive



Variable sources in the *Gaia* archive

A work by Ellianna Abrahams (Berkeley)

An example :
short-period CVs (spCVs) **with P_{orb} < 8 hr**

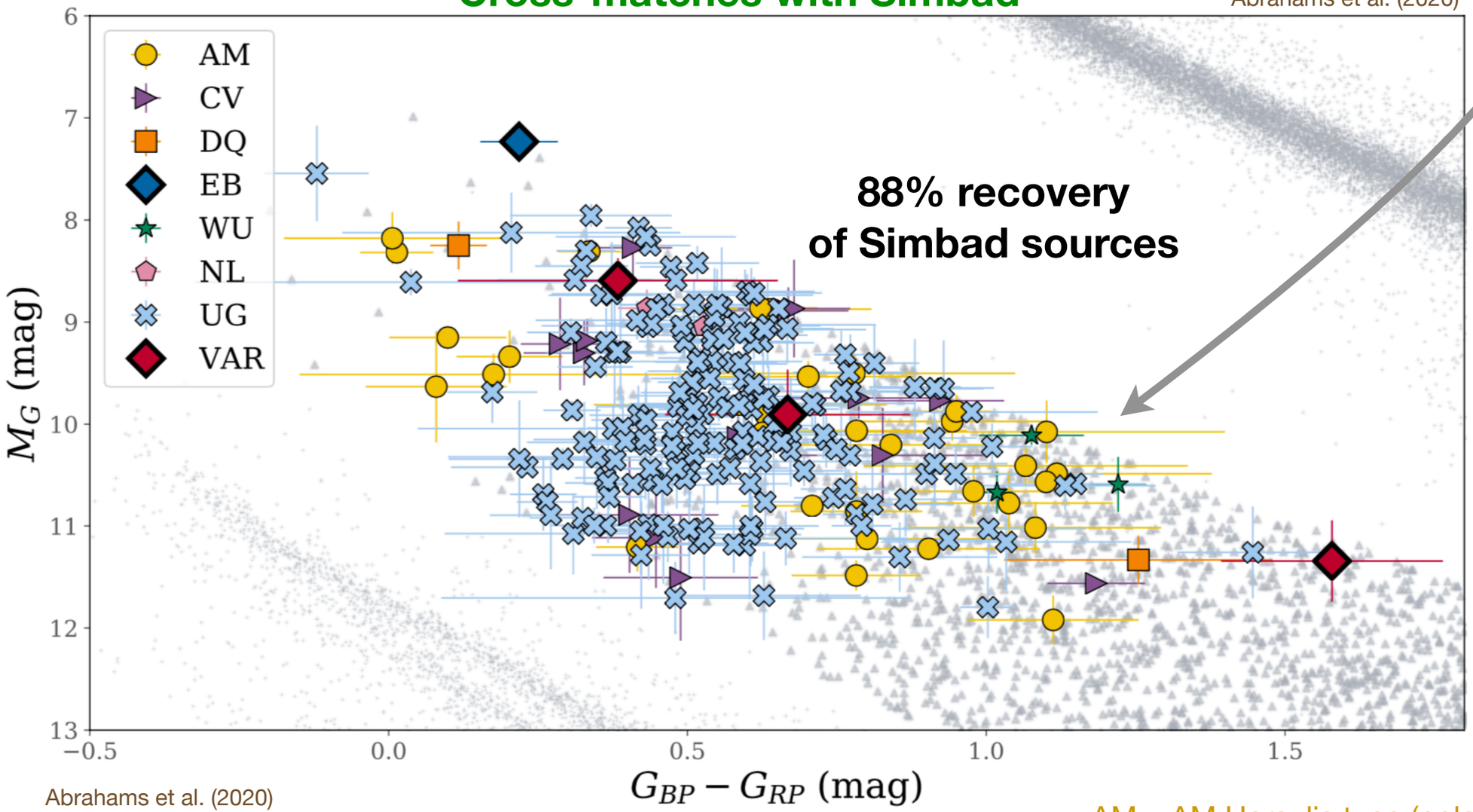


Variable sources in the *Gaia* archive

Using variability amplitude proxy → 3253 short-period CV candidates in DR2

Cross-matches with Simbad

Abrahams et al. (2020)



Abrahams et al. (2020)

Also

- *cross-matches with SDSS and PTF*
- *checks with dedicated spectra*

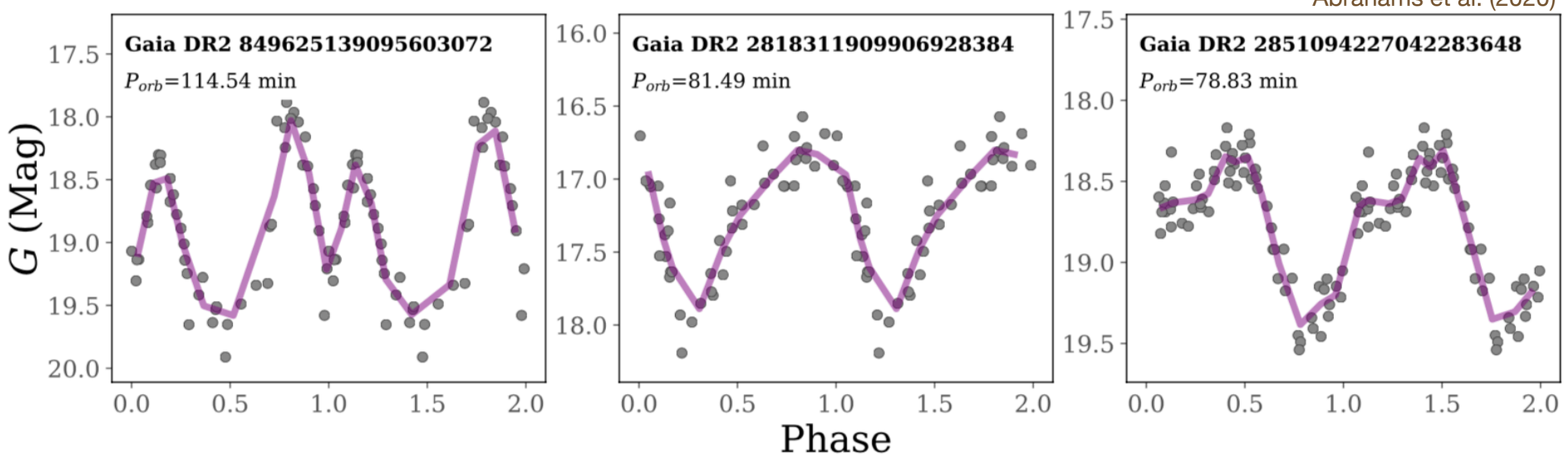
AM : AM Herculis type (polar: magnetic)
CV : Cataclysmic variable
DQ : DQ Herculis type (intermediate polar)
EB : Eclipsing binary
WU : W Uma eclipsing binary
NL : Nova-like system
UG : Dwarf novae (U Geminorum type)
VAR : General variable

Variable sources in the *Gaia* archive

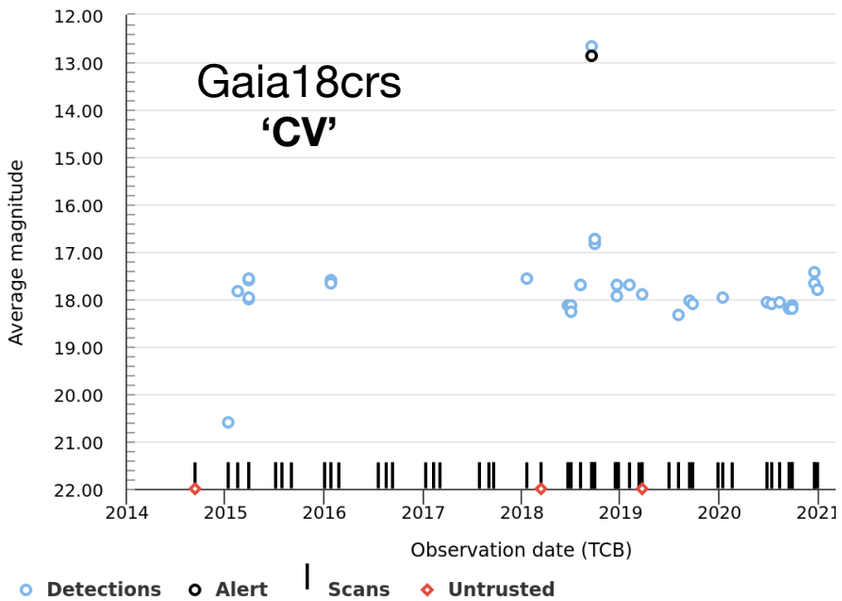
Among the 3253 DR2 short-period CV candidates:

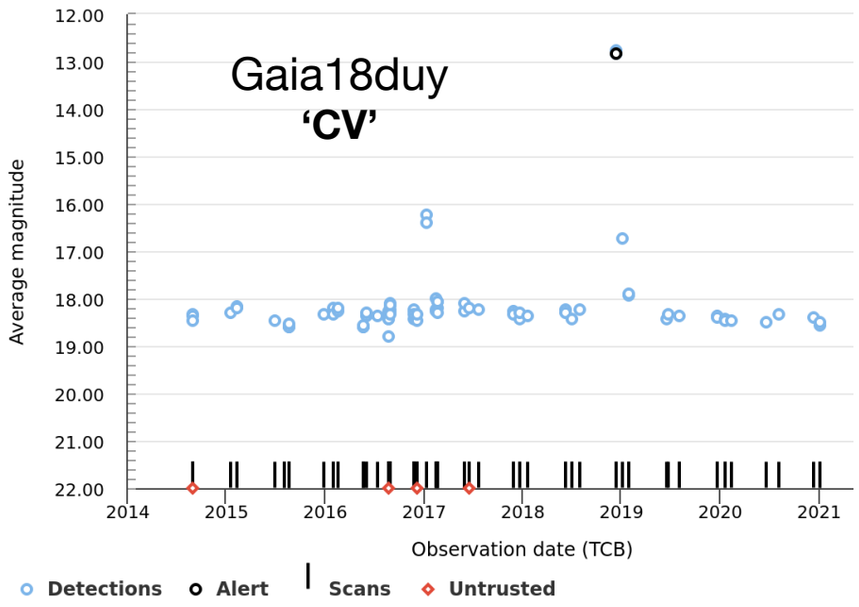
- **21 have LCs in DR2**

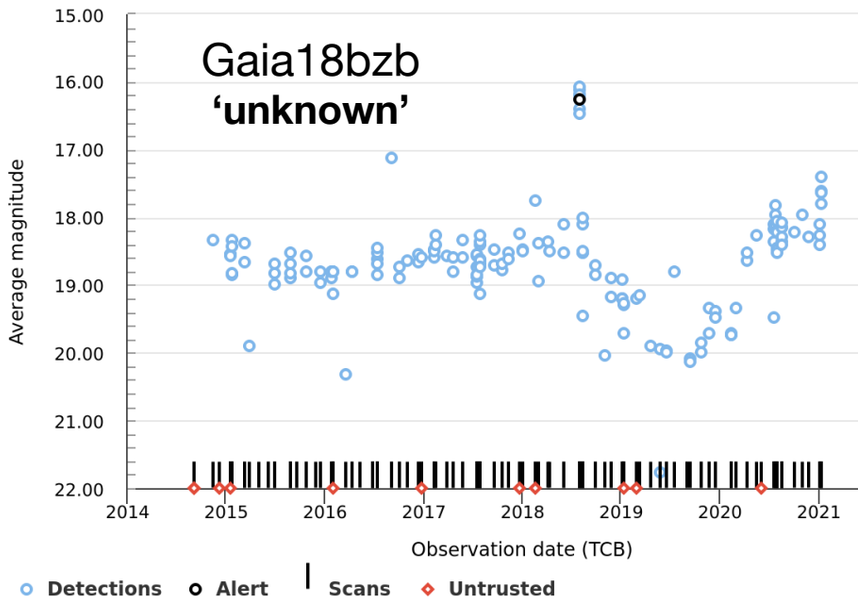
Abrahams et al. (2020)



- **51 are in Gaia Alerts**







Light curves from Gaia Science Alert web page

Conclusions

Gaia : wonderful mission for variability studies

In specific *Gaia* variability catalogues

- Classification → *completeness*
- Specific variability types → *purity*

~7-10 millions variables expected in DR3 (2022)

In full Gaia archive using variability amplitude proxies

In Gaia Science Alert archive

Number of CCD measurements (as of 20/01/2021 @ 07:41:53)

G	: 1,643,565,156,173
BP,RP	: 331,723,253,576
RVS	: 32,450,535,150

(https://www.cosmos.esa.int/web/gaia/mission-numbers)