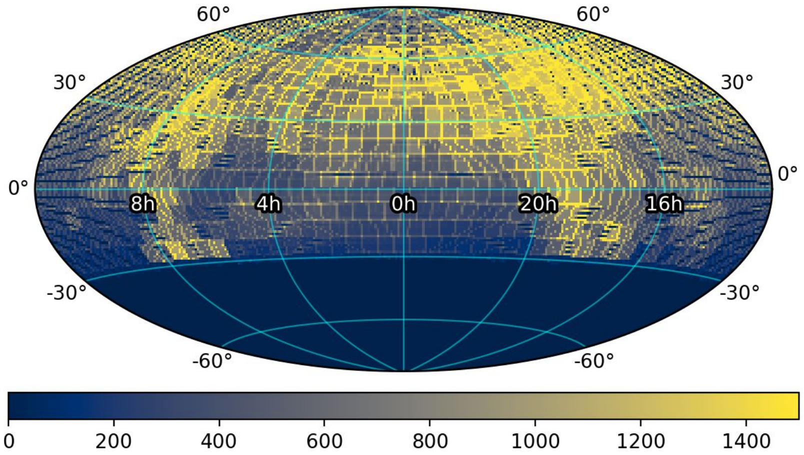
Synergy of Gaia with ZTF and other variability surveys



Caltech

ZTF

Ashish Mahabal
Center for Data Driven Discovery, Caltech

MW-GAIA WG2, Sofia, 2023-06-08

Outline

- **Gaia observing card:**
- **Cadence, depth, filters, resolution, spectroscopy**
  - **Nominally 70 pointings on average in original 5-year schedule**
  - **BP/RP low res spectra**
- **Strengths: Astrometry, spectra for “nearly” everything**
- **Limitations: 1D data sent down, not everything captured, epochs few for many purposes (which?)**

Synergy considerations

Complementary depth

Complementary filters/wavelengths

Complementary cadence

Owing to its astrometry it has been incorporated into TESS pipelines for separating binary stars from exoplanet candidates (Nigraha)

FOV - GW counterparts

Here we are more concerned about stellar variability

Some other surveys

Pan-STARSS - deeper, many colors, few epochs

CSS/CRTS - no color info (but long time baseline)

ATLAS

ASAS-SN

Evryscope/Argus

TESS - transits; photometry for isolated stars. Some possibilities demonstrated in this meeting.

LSST

Black Gem

ZTF

Summary of Gaia/ZTF seminar series

Preliminary talk schedule

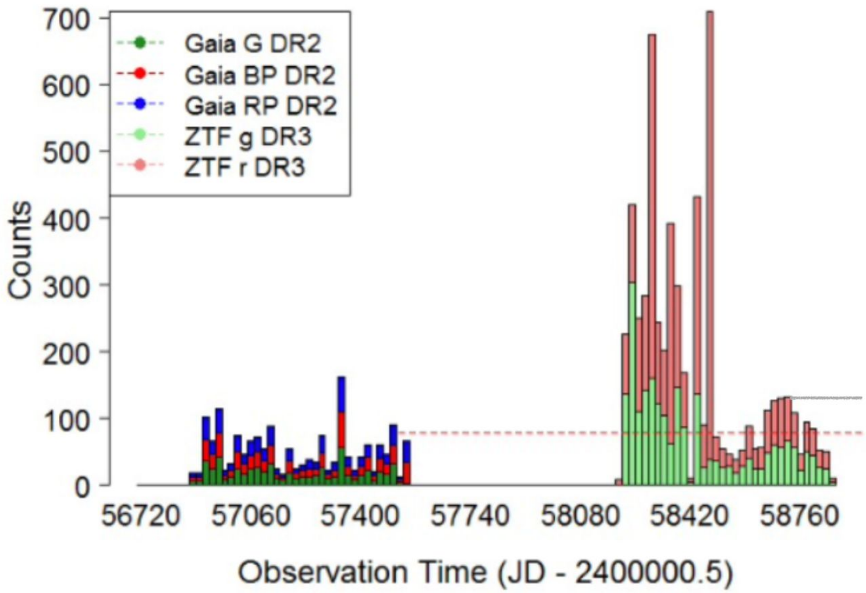
All talks are on Tuesdays at 5 pm (CET)

	start (CA)	start (Europe)		
March 16	9 am	5 pm	Laurent Eyer (University of Geneva)	General presentation on Gaia (recording)
March 30	8 am	5 pm	Matthew Graham (Caltech)	Overview of ZTF (capabilities, data products, ...)
April 13	8 am	5 pm	Laurent Eyer	Special focus on white dwarfs detected by Gaia
April 27	8 am	5 pm	Eric Bellm	ZTF surveys, past and present
May 11	8 am	5 pm	Nami Mowlawi	Large Amplitude variables with Gaia DR2 data (recording)
May 25	8 am	5 pm	Jan van Roestel, Ashish Mahabal	Classification of ZTF variable sources, current status and plans
June 8	8 am	5 pm	Marc Audard	Outliers in Gaia data and validation of the Gaia catalogue of variable sources
June 22	8 am	5 pm	Dan Perley	The ZTF Bright Transient Survey
			Yuhan Yao	Tidal disruption events with ZTF
September 7	8 am	5 pm	Krzysztof Nienartowicz	Data Handling of the Gaia data at the Geneva data processing center
September 21	8 am	5 pm	Kevin Burdge	White dwarf binaries from ZTF
October 5	8 am	5 pm	Panos Gavras (ESA)	Variability detection of the Gaia time series
October 19	8 am	5 pm	Ilaria Caiazzo	Massive, magnetized, fast rotating white dwarfs from ZTF
November 2	9 am	5 pm	Lorenzo Rimoldini	The classification of variable sources in the Gaia consortium
November 16	8 am	5 pm	Przemek Mróz, Antonio Rodriguez	Image difference photometry and the search for microlensing events
December 14	8 am	5 pm	Berry Holl	Features of the Gaia scanning law

ZTF - Gaia synergy

From Eyer

Gaia DR2
DR3 ZTF

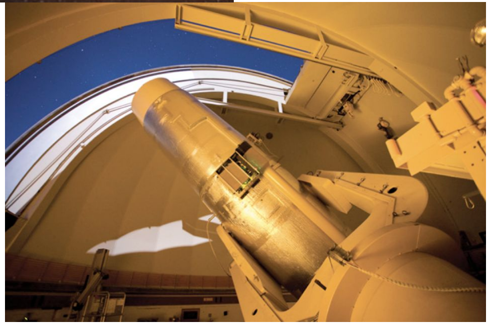


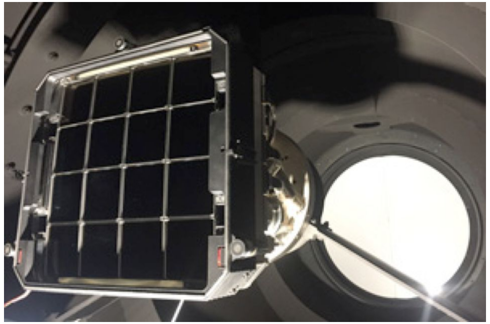
With Gaia DR3 close to start of ZTF (2018), and with ZTF DR17, far ahead in time

In a way, ZTF is look-ahead for unreleased Gaia data!

ZTF Zwicky Transient Facility

Systematic Exploration of the Dynamic Sky





- 1.2m automated Telescope @ Palomar, CA
- 47 deg2 FOV
- mlim~20.5 in 30 sec exposures
- g, r, i filters
- 1.4 TB data nightly
- ~20000 sq deg every 2 nights in g and r

ZTF Zwicky Transient Facility
Systematic Exploration of the Dynamic Sky

PI:	Shri Kulkarni
Co-PI:	Thomas Prince, Mansi Kasliwal, Matthew Graham, Richard Dekany
Project Scientist:	Matthew Graham
Survey Scientist:	Eric Bellm
Project Manager:	Richard Dekany
Lead Camera Engineer:	Roger Smith
P48 Operations:	Tom Barlow
Data Archive Director:	George Helou
→ Science Data System Lead:	Ben Rusholme
Machine Learning Lead:	Ashish Mahabal
Data Quality Scientist:	Andrew Drake

+ real stars

Ashish Mahabal

ZTF Zwicky Transient Facility

Systematic Exploration of the Dynamic Sky

DR16:

https://irsa.ipac.caltech.edu/data/ZTF/docs/releases/ztf_release_notes_latest

Filter(s)	#PSFcat-*sci* sources	#Aperturecat-*sci* sources	#PSFcat-*ref* sources	#Aperturecat-*ref* sources
g	179,661,606,131	114,144,715,027	2,527,614,585	794,988,671
r	506,885,000,022	315,778,300,845	3,393,409,691	1,153,239,938
i	58,976,476,111	33,687,367,330	1,414,109,235	455,279,857
g + *r* + *i*	745,523,082,264	463,610,383,202	7,335,133,511	2,403,508,466

Table 3: Number of sources in CCD-quadrant-based catalog files in DR16, according to extraction and image type

Ashish Mahabal

Zwicky Transient Facility
Systematic Exploration of the Dynamic Sky

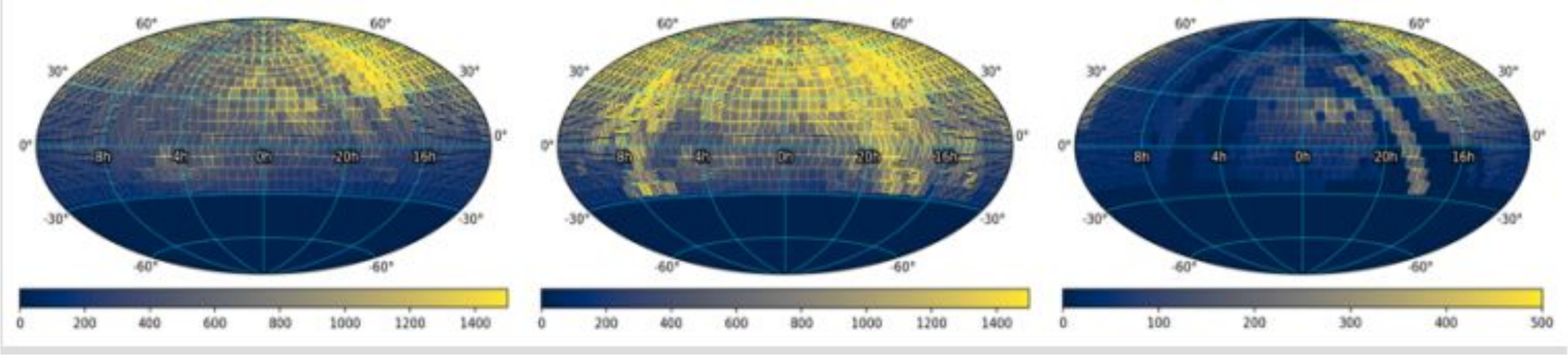


Figure 1 - Sky coverage and number of observation epochs in DR16 in g, r, i filters.

Example Query using the APIs

```
wget "https://irsa.ipac.caltech.edu/ibe/search/ztf/products/sci?
POS=255.9302,11.8654&WHERE=obsjd>2458219.9678+AND+obsjd<2458228.8155+
      AND+infobits<33554432" -O out.tbl
```

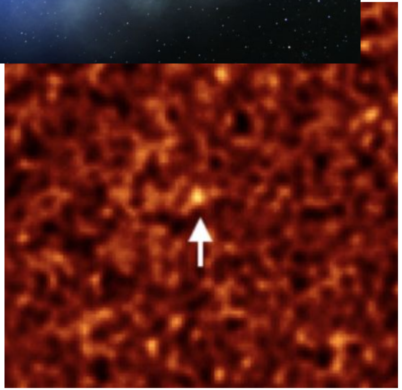
Ashish Mahabal

Main science drivers of ZTF

A fast, wide-area time-domain survey:

- Fast, young, and rare flux transients
- Counterparts to gravitational wave sources
- Low-z Type Ia SNe for cosmology
- Variable stars & eclipsing binaries
- Solar System objects

https://www.ztf.caltech.edu



Zach Van der Bosch

Why and how do we use ZTF?

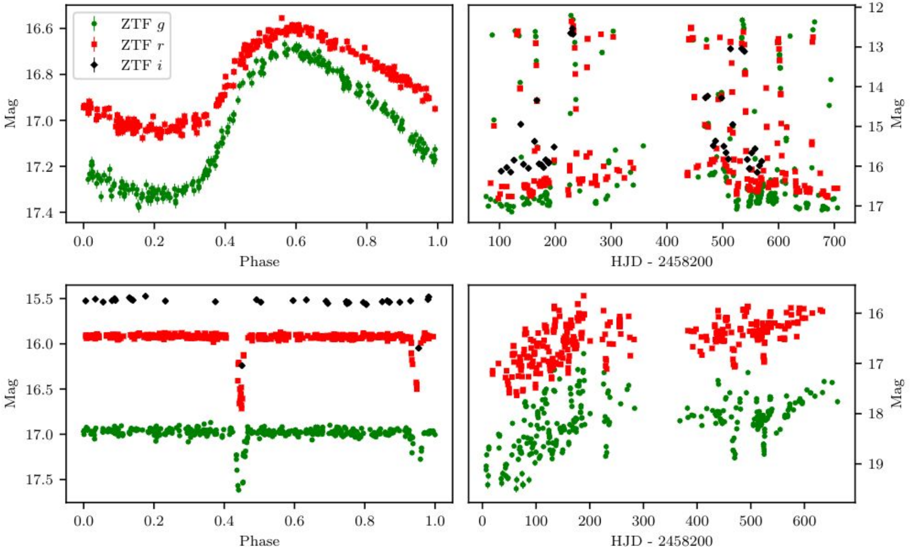
1. Stellar remnants
2. Binary star physics and evolution
3. Accretion processes
4. High energy astrophysics
5. Stellar structure
6. Extrasolar asteroids/comets
7. Age/luminosity/period relations

Single Object

and

Population Studies

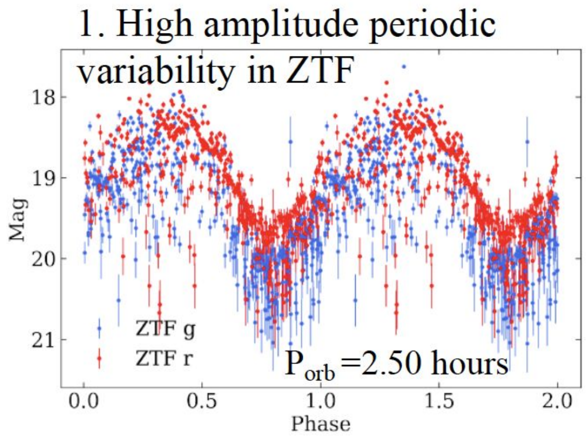
1. Mostly **archival photometry** searches for (periodic) variability
   a. Orbital periods
   b. Rotations periods
   c. Pulsations periods
   d. Irregular dips/transits/eclipses
2. **Real-time (alert)** searches for outbursting stars

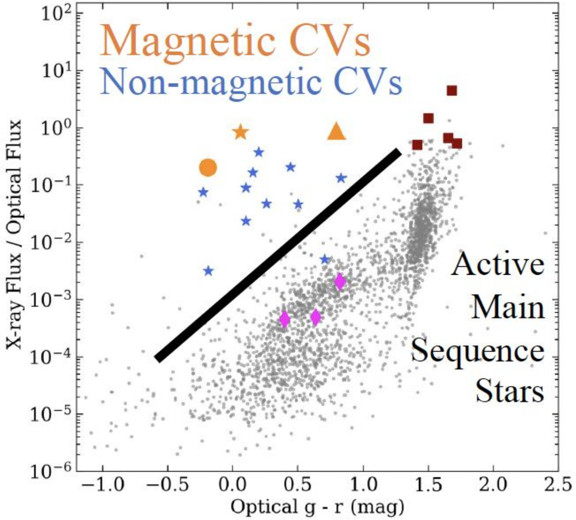


Tony Rodríguez (Caltech)

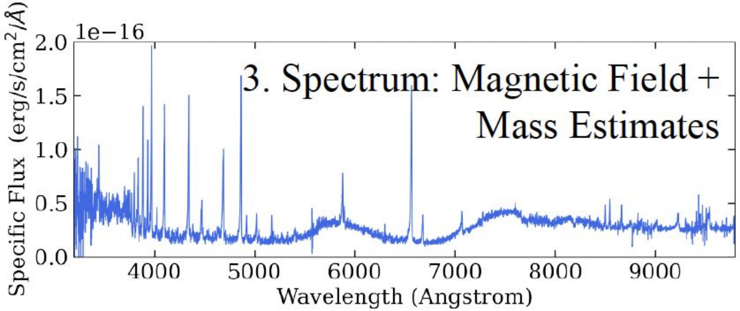
Discovery of Polars from SRG/eROSITA + ZTF

- ~120 polars known
- ~200—300 in eRASS1
- Questions to answer:
  - X-ray luminosity function
  - Mean mass of WD
  - Orbital period distribution





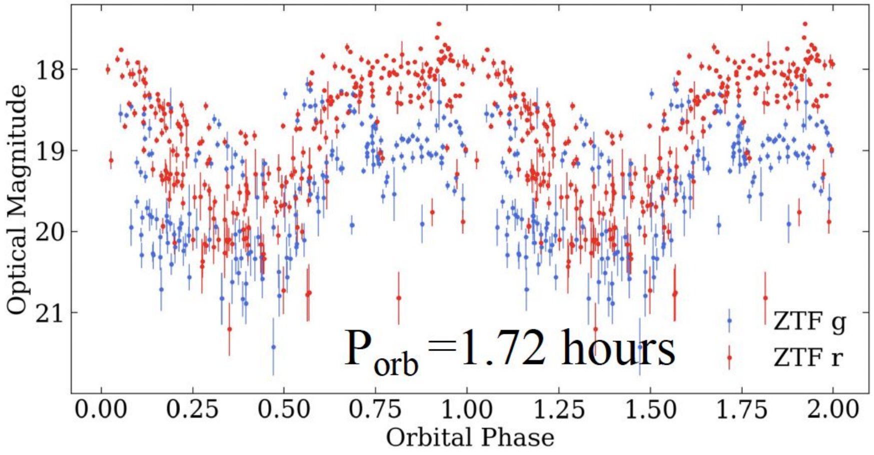
2. X-ray/Optical Flux Ratio Indicates Accretion

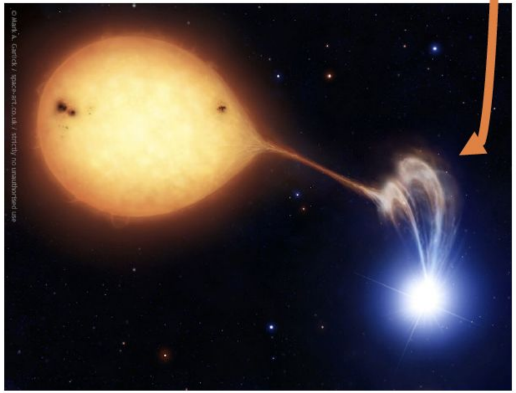


Tony Rodríguez (Caltech)

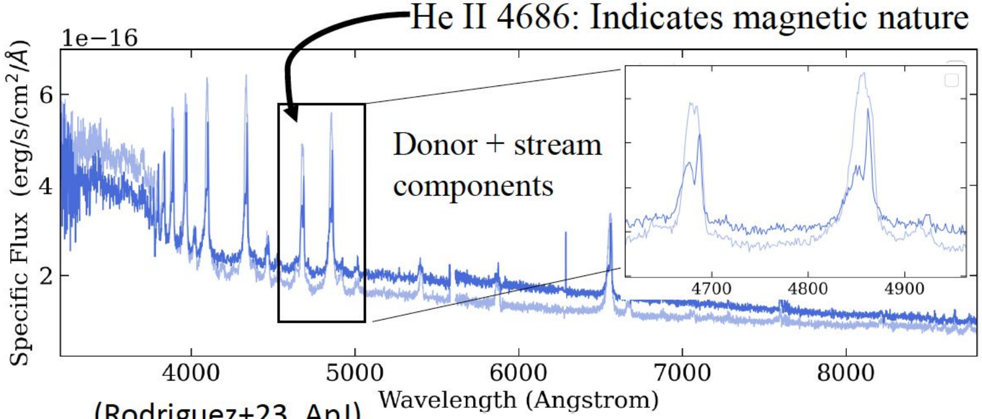
eFEDS/ZTFJ0850+0443

- One of 8 polars showing pre-eclipse absorption from accretion stream.
- $M_{WD} = 0.81 \pm 0.08\ M_{sun}$





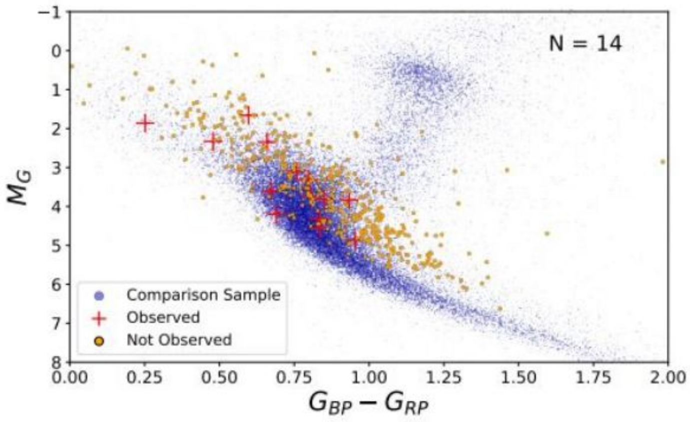
Artist rendition, used with permission of M. Garlick

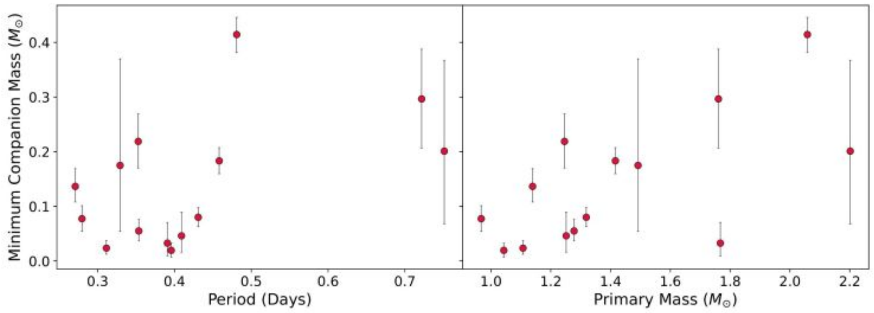


(Rodriguez+23, ApJ)

Spectroscopic Follow-up of NS and BH Candidates in Gaia DR3

Pranav Nagarajan,
Kareem El-Badry, et al.

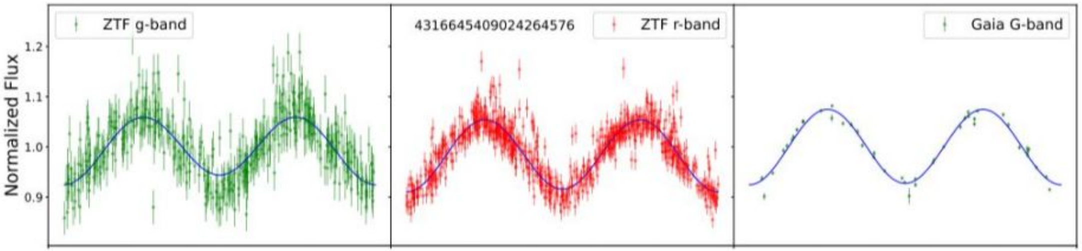


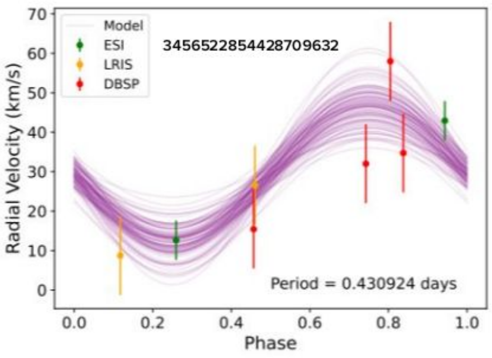


Sample selection of promising targets from Gomel et al. (2022)

Prioritize based on large LC ellipsoidal variability amplitudes...

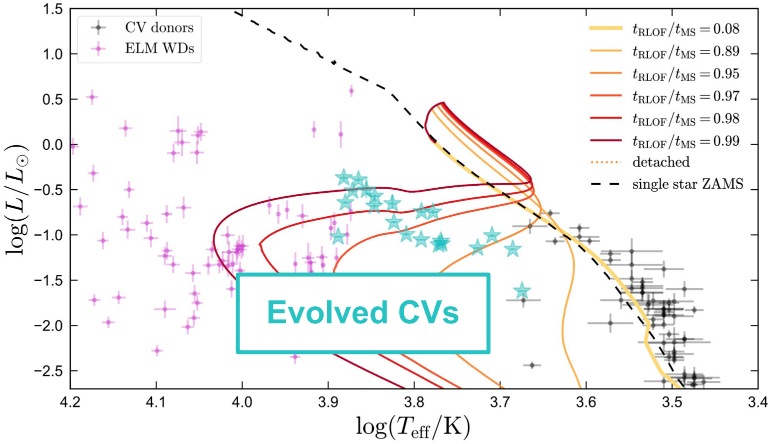
But observe small RV semi-amplitudes! Median inferred companion mass around 0.15 $M_\odot$. PHOEBE modeling suggests (spotted) contact binaries are primary contaminant.



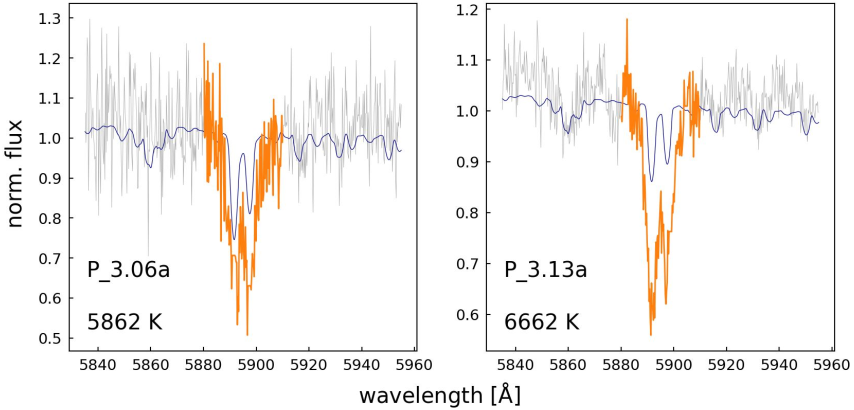


Sodium enhancement in Evolved Cataclysmic Variables

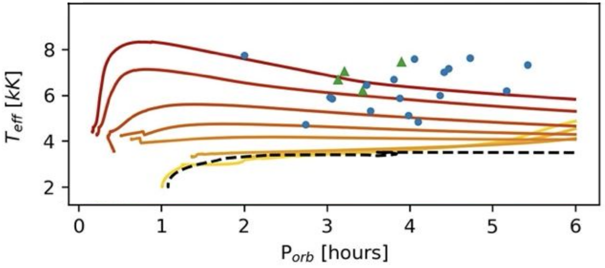
Natsuko Yamaguchi, Kareem El-Badry, Antonio C. Rodriguez, Maude Gull, Benjamin R. Roulston

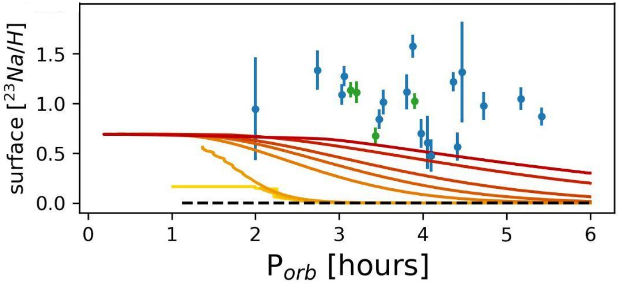


1) 21 evolved CVs found by the Birth of the ELMs survey, with the use of ZTF light curves.



2) Carried out follow-up high resolution spectroscopy and measured Na abundances using the 5900 AA doublet.
→ find significant enhancements:
[Na/H] = 0.3 - 1.5 dex, with a median of 0.956 dex

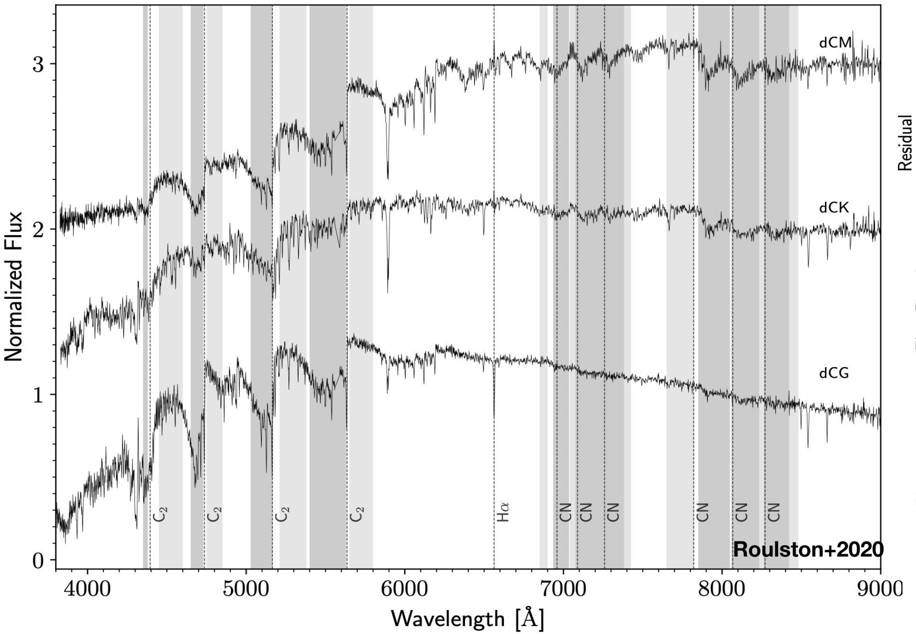


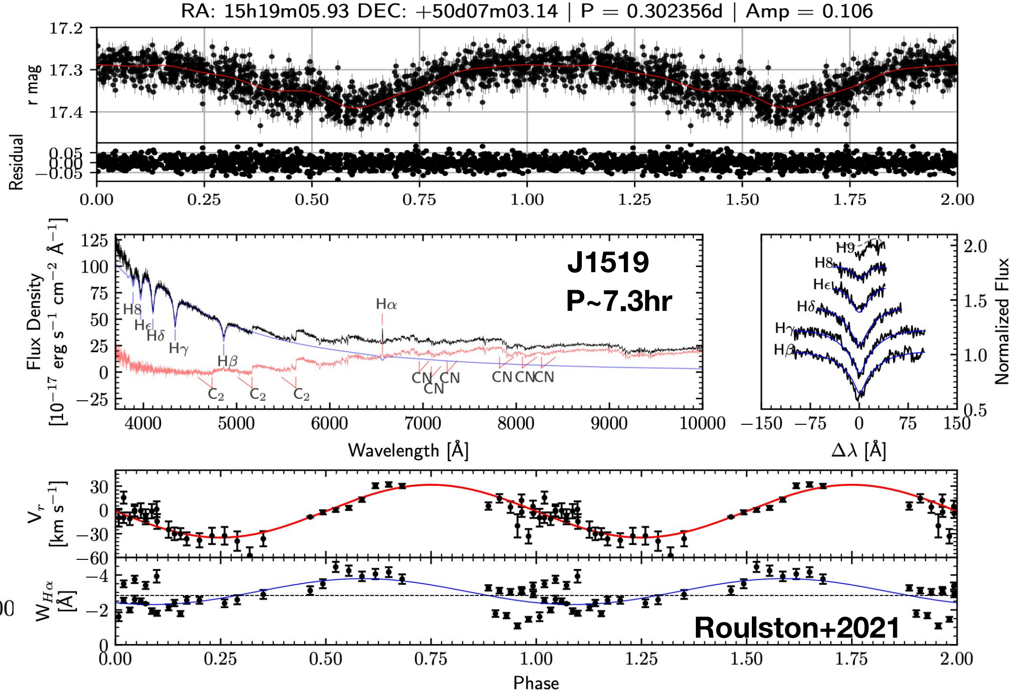


3) Ran MESA models of evolved CVs
→ **predict significant Na enhancement *not seen in normal CVs* but underpredict them** compared to observations

Probing Common-Envelope Evolution with ***Dwarf*** Carbon stars

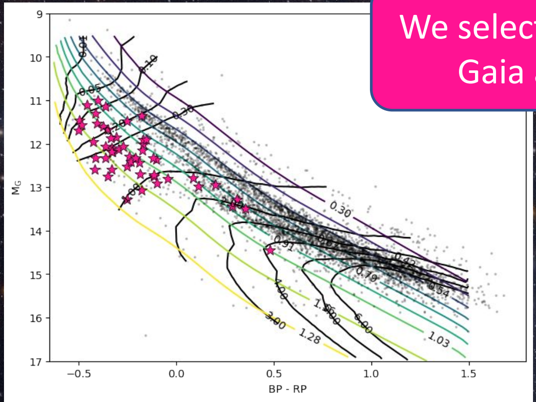
Ben Roulston (Caltech)





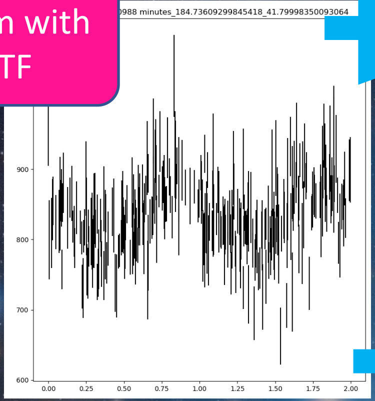
- Main-Sequence stars with C/O>1, enhanced by a binary companion. Show strong carbon molecular bands in optical spectra
- 34 periodic dCs in ZTF with P<2d (down to P~2hrs) —> Post common-envelope binaries
- Would like to expand sample of known dCs using Gaia+? (SEDMv2?) then search for periods in ZTF

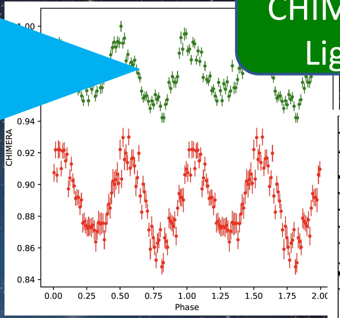
Exotic rotating white dwarfs



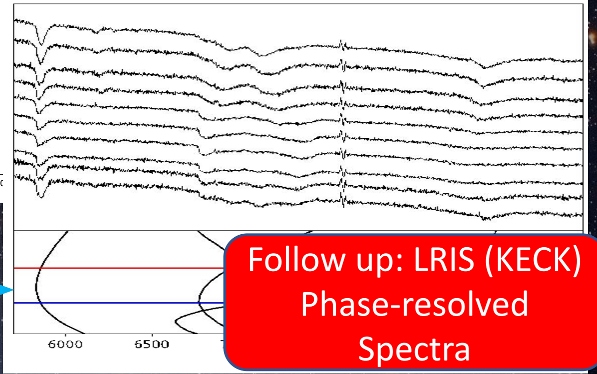
We select them with Gaia and ZTF

+





Follow up: CHIMERA (HALE) Light curves



Follow up: LRIS (KECK) Phase-resolved Spectra

Finding a population of rapidly rotating and highly magnetized WDs

- Candidates **double white dwarf mergers**
- Reveal the characteristics of mergers and constrain merger rates
- Allow to study magnetic WDs

Finding exotic white dwarfs

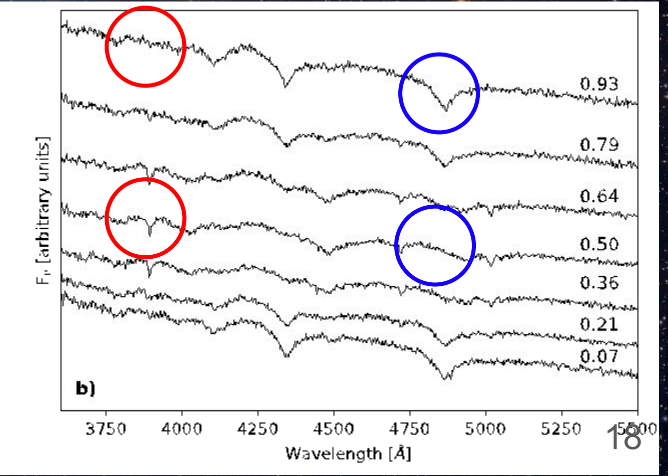
- Janus: **double-faced white dwarf**

Article

A highly magnetized and rapidly rotating white dwarf as small as the Moon

https://doi.org/10.1038/s41586-021-03615-y
Received: 27 October 2020
Accepted: 5 May 2021
Published online: 30 June 2021

Ilaria Caiazzo[1], Kevin B. Burdge[1], James Fuller[1], Jeremy Heyl[2], S. R. Kulkarni[1], Thomas A. Prince[1], Harvey B. Richer[2], Josiah Schwab[3], Igor Andreoni[1], Eric C. Bellm[4], Andrew Drake[1], Dmitry A. Duev[1], Matthew J. Graham[1], George Helou[5], Ashish A. Mahabal[1,6], Frank J. Masci[5], Roger Smith[7] & Maayane T. Soumagnac[8,9]



ZTF and Globular Clusters

Chow-Choong Ngeow (NCU-Taiwan), et al.

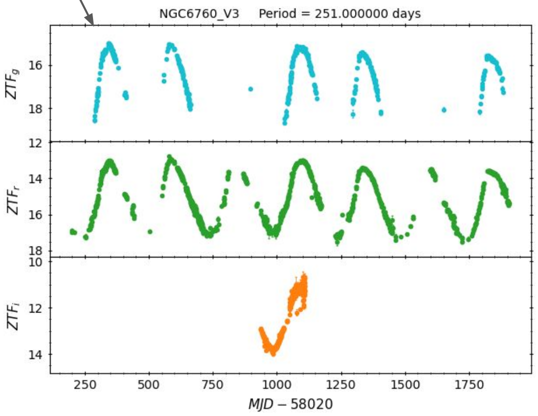
- Goal: calibrate various old population distance indicators in gr(i)-band, most of them for the *first time* → can be applied in, e.g. **LSST**, HSC-SSP, etc surveys observed with gri filters
- Why G.C.? Good → well-determined (and homogeneous) distance, most with low or vanished extinction, some rich in variable stars; Bad → blending (need PSF photometry + small pixel scale)
- Why ZTF? ZTF out-number PS1 in terms of number of observations!

Table 1. Comparison of optical time-domain surveys in the northern sky.

Survey[a]	Filters[b]	Pixel Scale[c]	Photometry[d]	Depth
ZTF	*gri*	1.01	PSF & AP	$r \sim 20.6$
PS1 3π	*grizy*	0.258	PSF & AP	$r \sim 21.8$
ATLAS	*oc*	1.86	PSF	$m \sim 19.5$
ASAS-SN	*gV*	8.0	AP	$V \sim 17$
CSS	—	1.5	AP	$V \sim 19.5$
LINEAR	—	2.25	AP	$m \sim 18$
SuperWASP	—	13.7	AP	$V \sim 15$

Best ⇨ (ZTF)

Distance Indicators	Publication	ZTF Data
Contact binaries	AJ 162:63 (2021)	DR 3 + private
RR Lyrae	AJ 163:239 (2022)	DR 7 + private
Type II Cepheids	AJ 164:154 (2022)	DR 10 + private
Yellow Post-AGB stars	AJ 164:166 (2022)	DR 10 + private
Anomalous Cepheids	AJ 164:191 (2022)	DR 11 + private
SX Phoenicis	AJ 165:190 (2023)	DR 13 + private
Miras	Work in-progress	DR16 + private

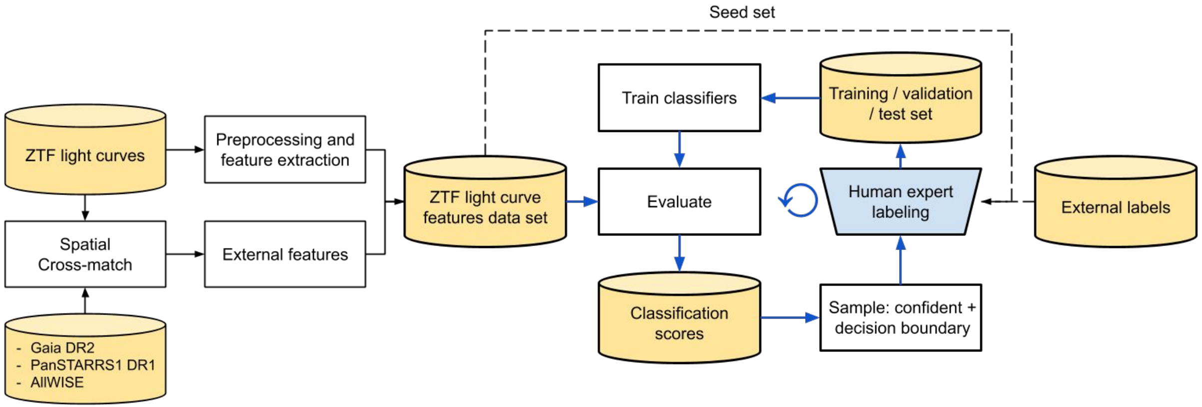


ZTF II/III wish-list:

← **more i-band data**

Our big challenge:
identify objects of interest from the 2 Billion sources

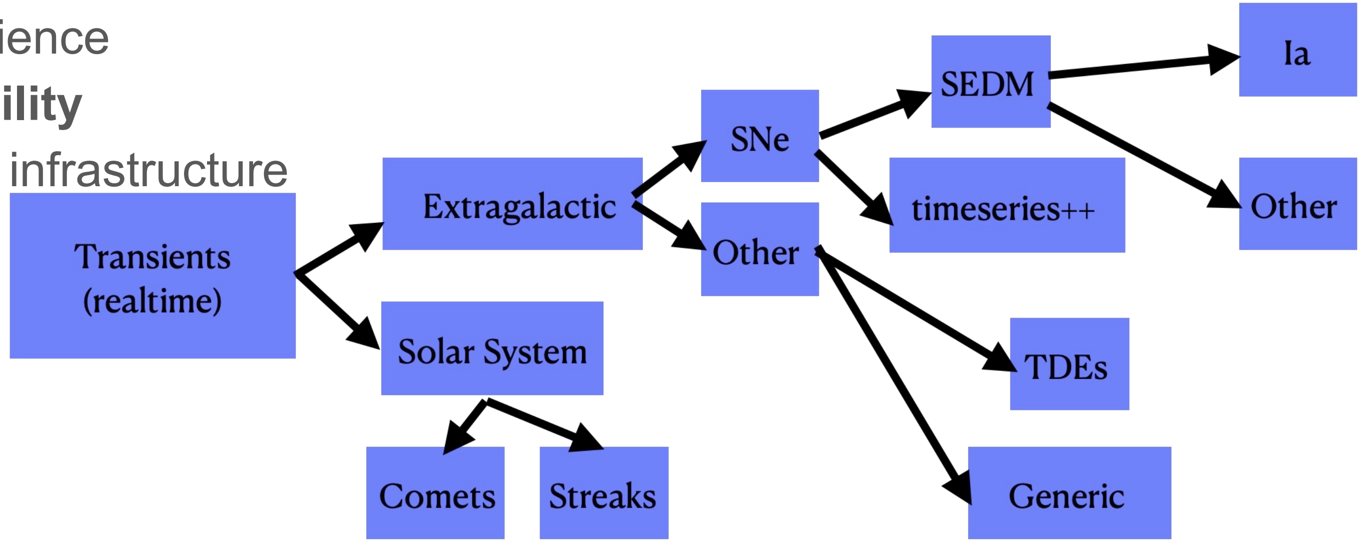
- **External catalogues** (Gaia, PS1, SRG, Fermi, SDSS-V, etc)
- ZTF **alerts** (positive *and* negative)
- Period searches & other **ZTF variability metrics**
- ZTF-SCoPe - machine learning classification of persistent point sources



Highlights - exemplars rather than exhaustive

Also likely biased towards areas I work in, or am better versed in

- Solar System
- Extragalactic science
- **Galactic variability**
- Technology and infrastructure



O4 follow-up

Ashish Mahabal

Source Classification Project (SCoPe)

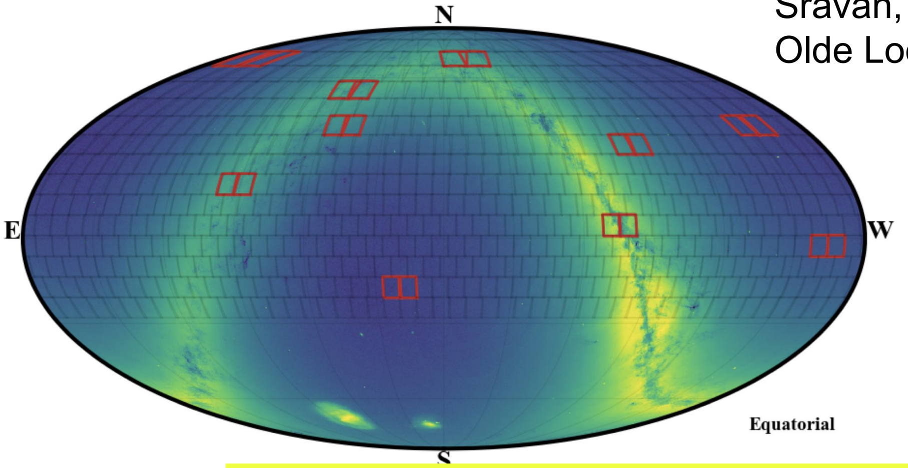



...

- Software/labeling set up based on DR2
- 20 Fields paper (Van Roestel, Duev, Mahabal ++)
- Periods paper (Coughlin, Burdge, Duev ++)

Van Roestel, Duev, Coughlin, Mahabal, Mroz, Hillenbrand, Drake, Graham, Sravan, Szkody, Olde Loohuis, ...

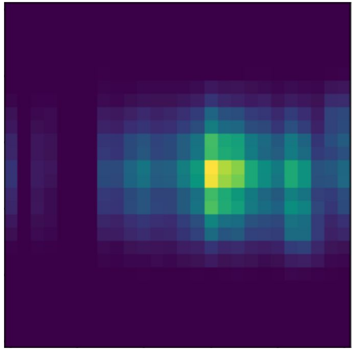
- 34M+ objects
- Features
  - variability characteristics
  - dmdt
  - period searches
  - external data



Van Roestel, Duev, Mahabal et al. 2020

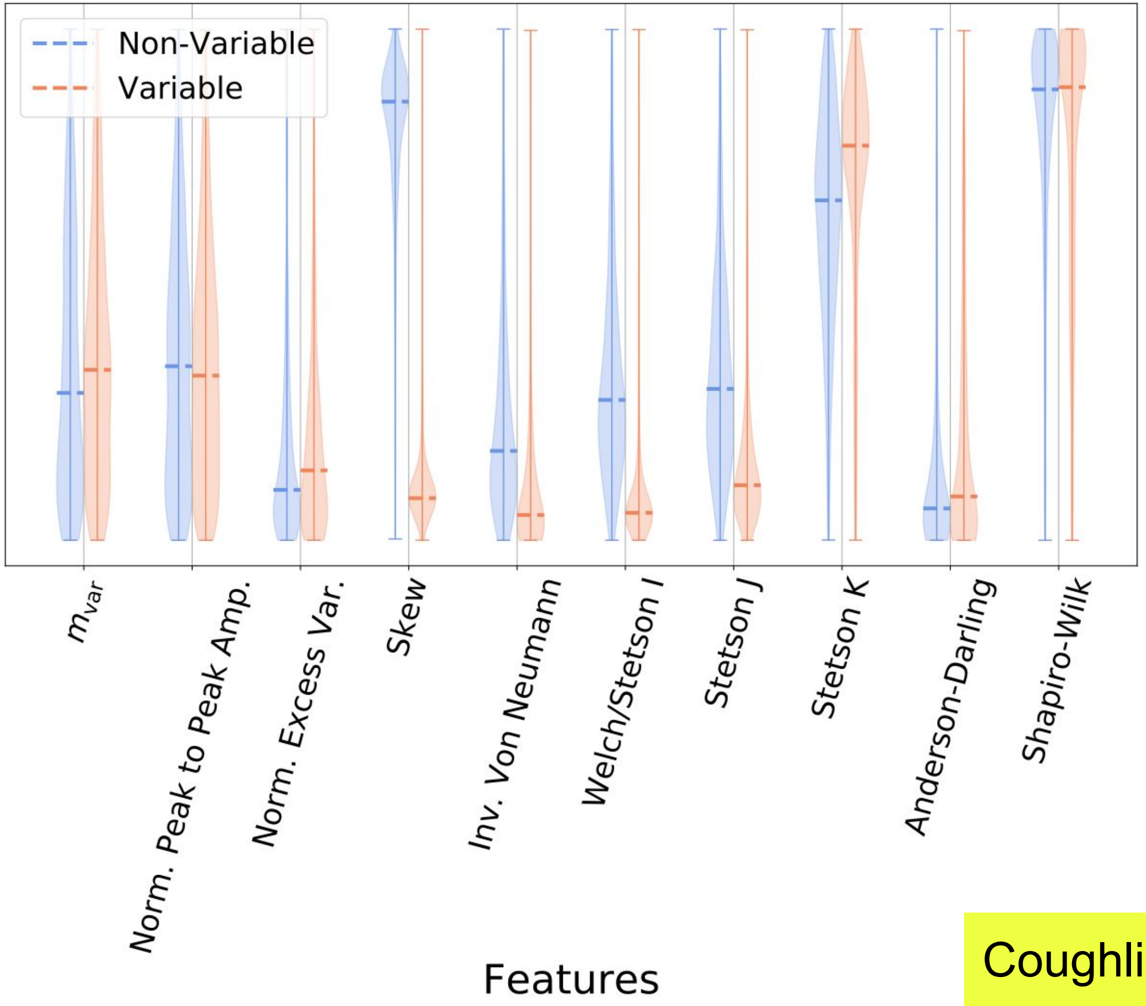
Features

- Light-curves with 50+ epochs period-searched [GPUs + Kowalski]
    - Conditional Entropy (CE)
    - Lomb-Scargle (LS)
    - Analysis of Variance (AOV)
- Variability features (e.g.Sokolovsky+ 2016)
- Optimized dmdt's
- X-match: 10 catalogs



_id: 10296001000057
ra: 19.556186750000002
dec: −19.040459849999998
period: 0.11717913349300235
significance: 9.32633052341019
pdot: 0
n: 54
median: 15.3535
wmean: 15.353907407407405
chi2red: 1.7092470481841708
roms: 1.0754716981132069
wstd: 0.02201873656559632
norm_peak_to_peak_amp: 0.0023127789178800525
norm_excess_var: 8.306723761861014e−7
median_abs_dev: 0.014499999999999957
iqr: 0.028750000000000497
f60: 0.034600000000001074
f70: 0.045099999999999696
f80: 0.056300000000000024
f90: 0.06809999999999976
skew: −0.24210490618175218
smallkurt: 5.6190133939968
inv_vonneumannratio: 0.6095639426533307
welch_i: 10.981297710846444
stetson_j: 10.986989388536113

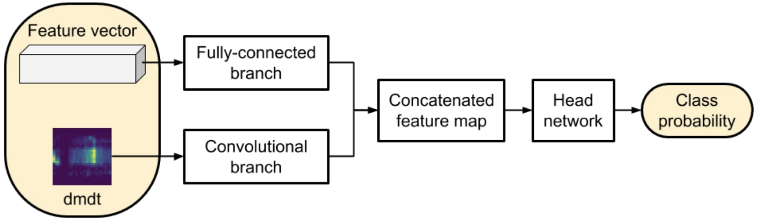
SHOW 23 MORE FIELDS



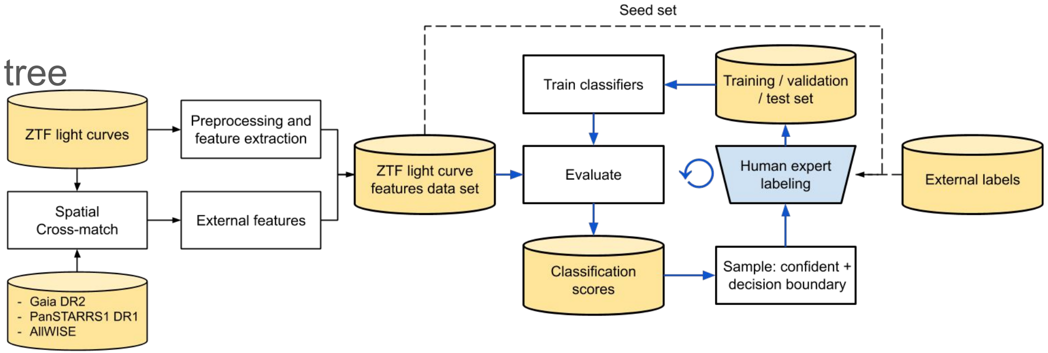
Index	Statistic
1	N
2	m_{median}
3	m_{mean}
4	m_{var}
5	χ^2
6	RoMS
7	Median absolute deviation
8	Normalized Peak to Peak Amplitude
9	Normalized Excess Variance
10-14	Ranges
15	Skew
16	Kurtosis
17	Inverse Von Neumann Statistic
18	Welch/Stetson I
19	Stetson J
20	Stetson K
21	Anderson-Darling test
22	Shapiro-Wilk test
23-35	Fourier Decomposition

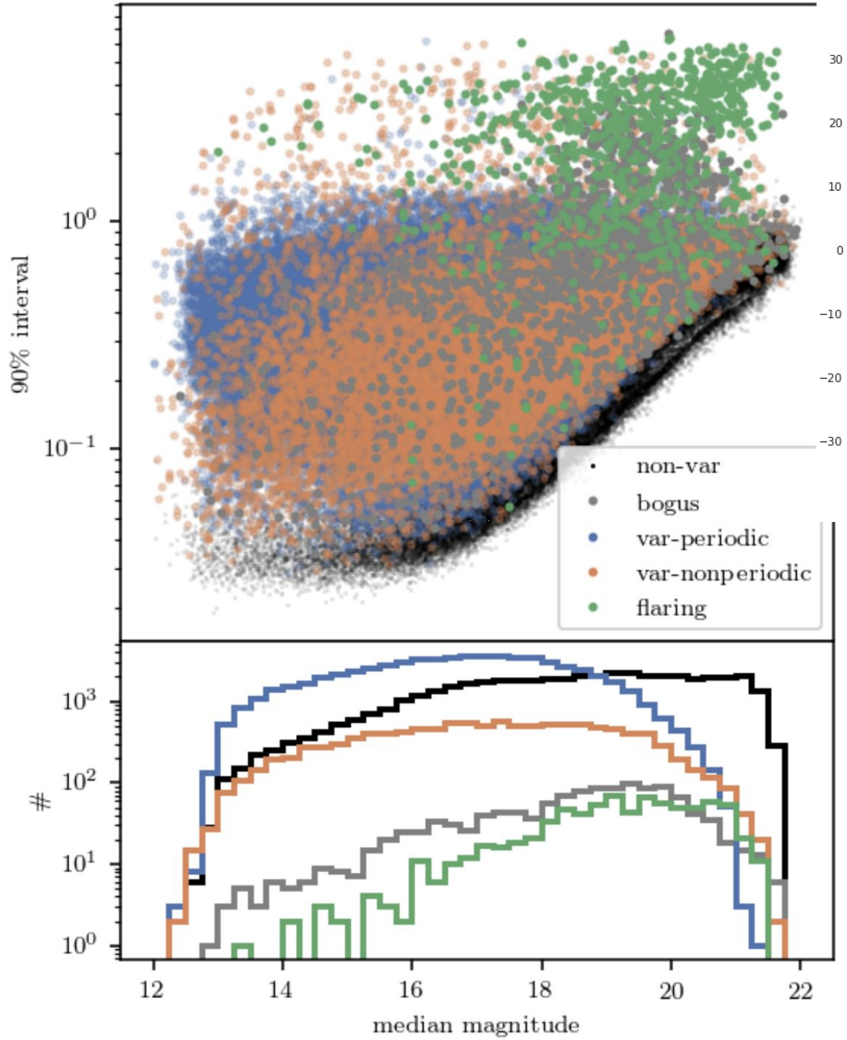
Coughlin et al. arXiv:2009.14071

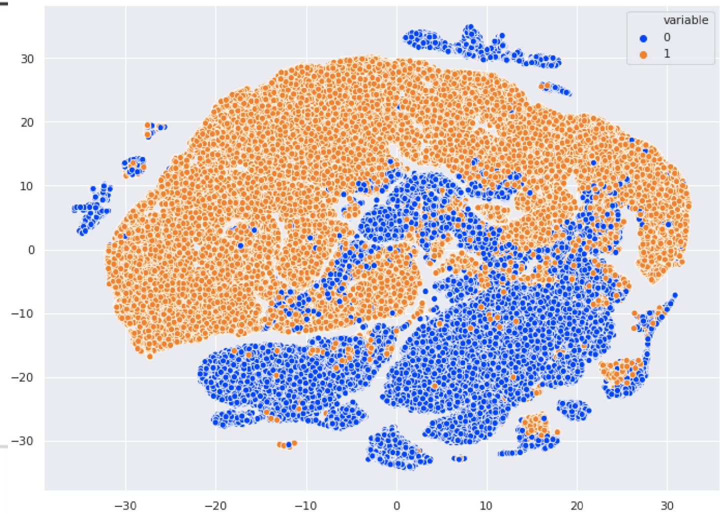
Labels and classifiers



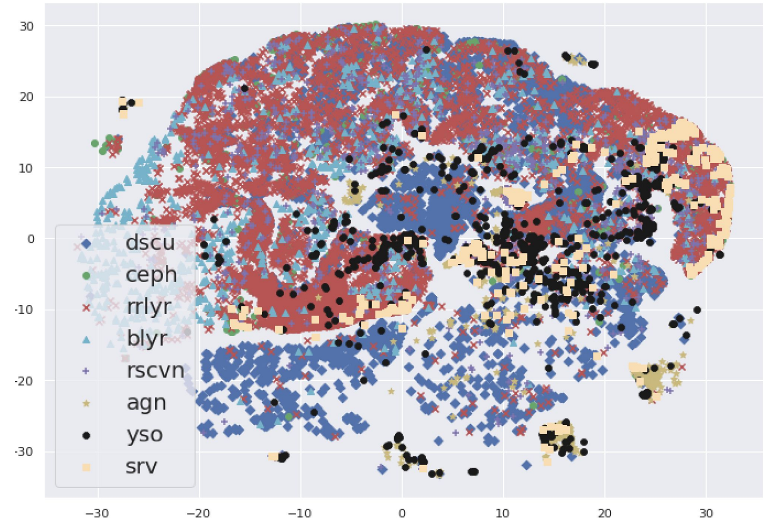
- Over 200,000 individual labeled light curves
  - Labels from CRTS, OGLE, ...
  - Unbalanced classes
  - Values quantized to [0, 0.25, 0.5, 0.75, 1] for label smoothing
- “Seed” classifiers, from subsets then active learning
  - **Select and inspect <random | most confident | close to decision boundary | highest loss> predictions, label, add to training set, retrain, repeat**
  - Marching down the nomenclature tree
- Classifiers
  - DNNs (MLP+CNN)
  - XGBoost
  - Hyperparameter tuning







Training set



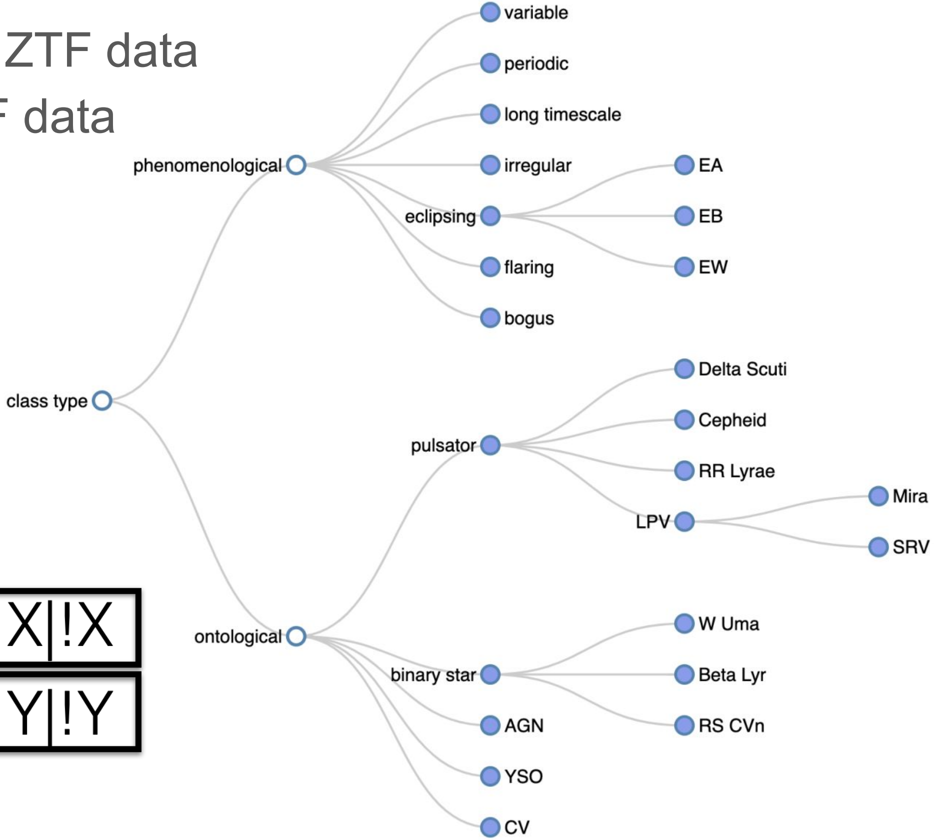
Hierarchical/stackable Classification Through Independent Binary Classifiers

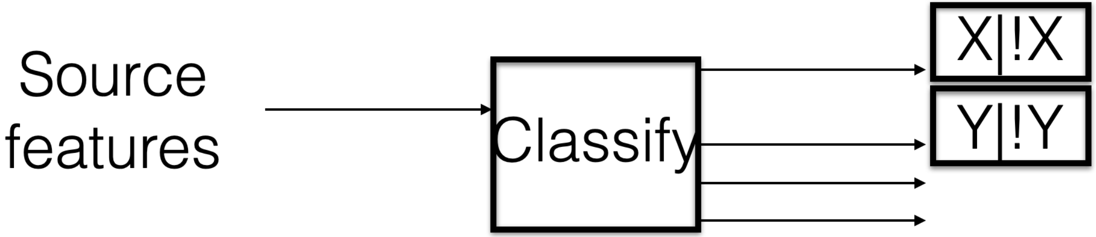
- ***Phenomenological***: based on *just* the ZTF data
- ***Ontological***: based on *not just* the ZTF data

Since the classifiers are independent

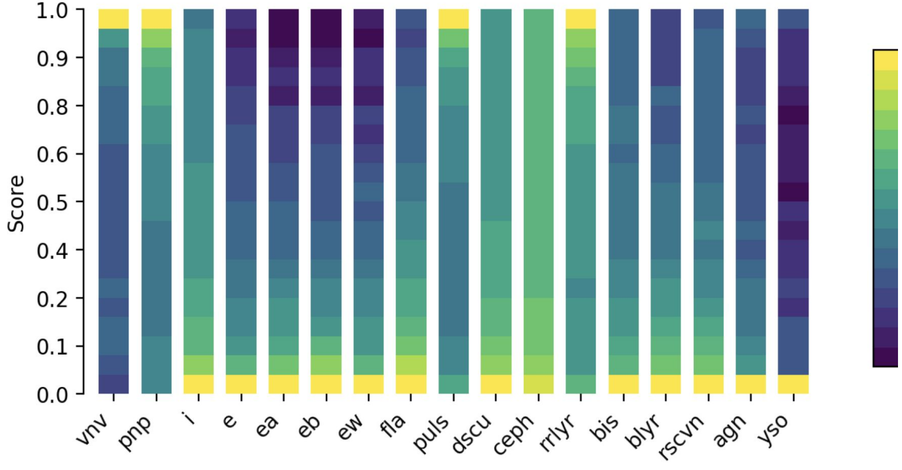
no restrictions on p(sum)

In particular it may not be 1





Performance



RR Lyrae

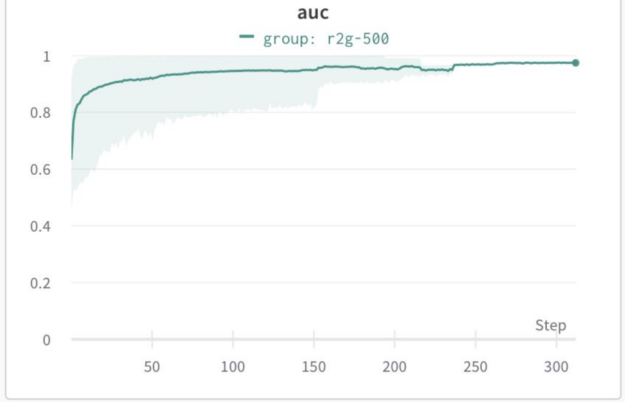
Class	#	Accuracy		Precision		Recall		F1 Score	
		DNN	XGB	DNN	XGB	DNN	XGB	DNN	XGB
e	44721	0.94	0.95	0.9	0.92	0.93	0.95	0.92	0.93
ea	819	0.94	1	0.91	1	0.87	0.02	0.89	0.03
eb	950	0.88	0.99	0.86		0.74	0	0.8	
ew	39079	0.94	0.95	0.91	0.92	0.89	0.93	0.9	0.92
fla	829	0.97	1	1	0.84	0.87	0.82	0.93	0.83
i	1842	0.93	0.99	0.92	0.79	0.84	0.28	0.88	0.42
longt	968	0.95	1	0.93	0.87	0.93	0.38	0.93	0.53
pnp	64910	0.95	0.95	0.95	0.95	0.96	0.96	0.96	0.95
vnv	78083	0.97	0.98	0.99	0.98	0.97	0.98	0.98	0.98
agn	608	0.98	1	0.94	0.94	0.98	0.71	0.96	0.81
bis	44532	0.95	0.96	0.92	0.93	0.93	0.96	0.93	0.94
blyr	836	0.89	0.99	0.8	0.46	0.81	0.9	0.81	0.61
ceph	1075	0.93	1	0.88	0.76	0.89	0.92	0.89	0.83
dscu	6118	0.96	1	0.92	0.96	0.93	0.97	0.93	0.96
puls	18664	0.96	0.99	0.94	0.94	0.93	0.98	0.94	0.96
lpv	968	0.99	1	0.97	0.88	0.99	0.79	0.98	0.84
rrlyr	10866	0.95	0.99	0.93	0.95	0.89	0.95	0.91	0.95
rscvn	1210	0.85	1	0.83	0.77	0.68	0.82	0.75	0.8
srv	420	0.95	1	0.88	0.81	0.98	0.69	0.93	0.74
yso	849	0.99	1	0.99	0.92	0.99	0.99	0.99	0.95

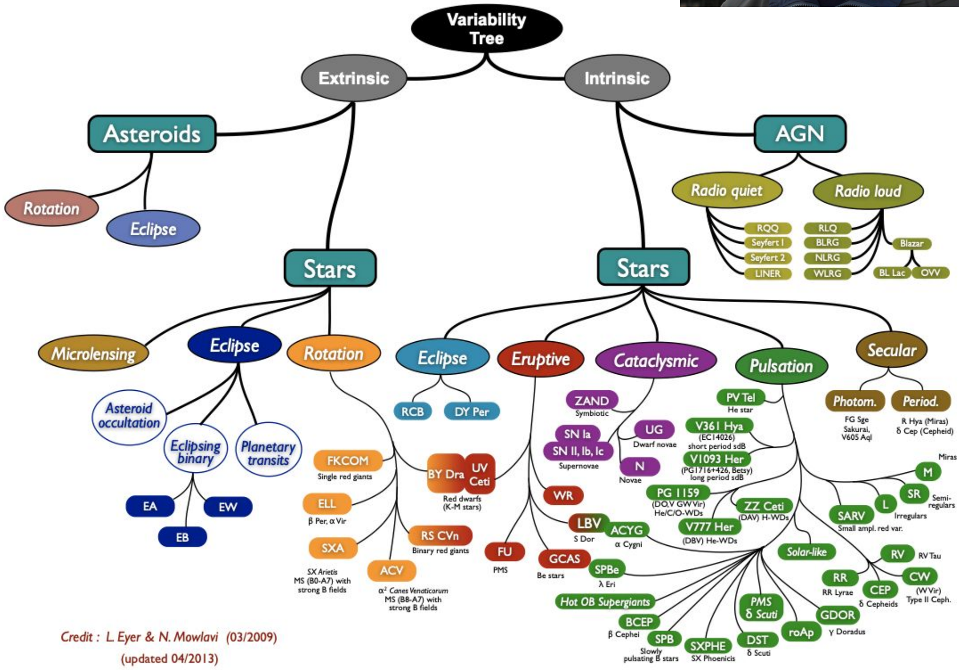
Mahabal et al. 2017 http://arxiv.org/abs/1709.06257v1
Duev et al 2019 http://arxiv.org/abs/1904.05920v2
Duev et al. 2021 https://arxiv.org/abs/2102.13352
Coughlin et al. 2020 https://arxiv.org/abs/2009.14071
Van Roestel et al. 2021 https://arxiv.org/abs/2102.11304
Fremling 2021 https://arxiv.org/abs/2104.12980

Now classifying entire DR

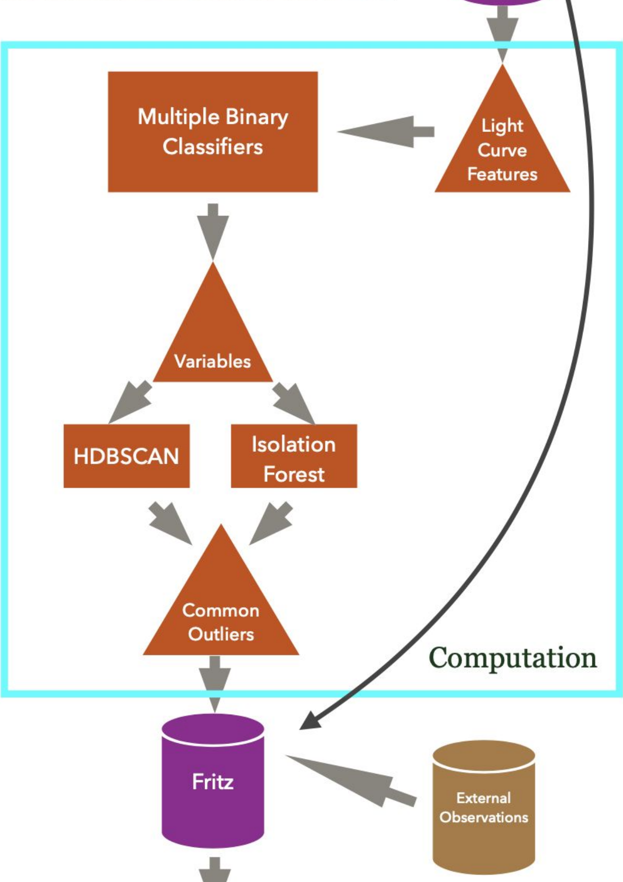
Brian Healy
UoMinnesota

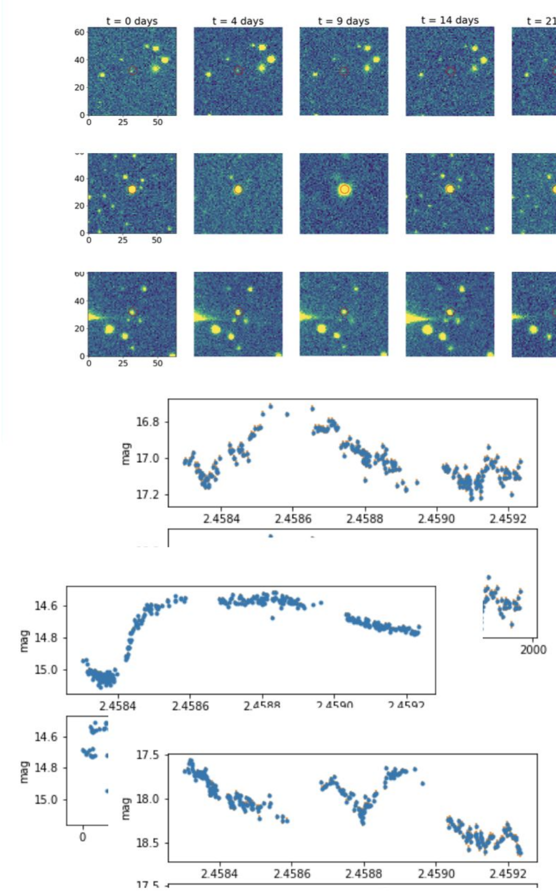
- More classes
- Anomalies (hdbscan)
- Improvements (active learning)
- Metaclassification
- Interpretability
    - ~80,000 sources (training)
    - 37 classes





No Anomaly Left Behind

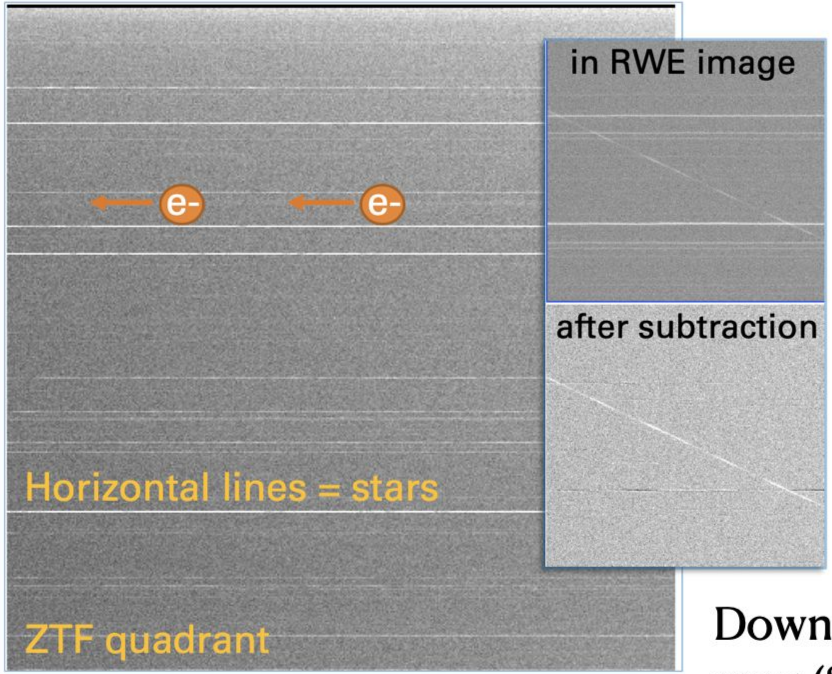




With PPurohit, SParikh, YHassan, T Jegou Du Laz, …

ZTF news

- **Public part funded until end of O4 (Dec 2024)**
- **CMOS possibilities (one problem - non-buttable)**
- **RWE mode**

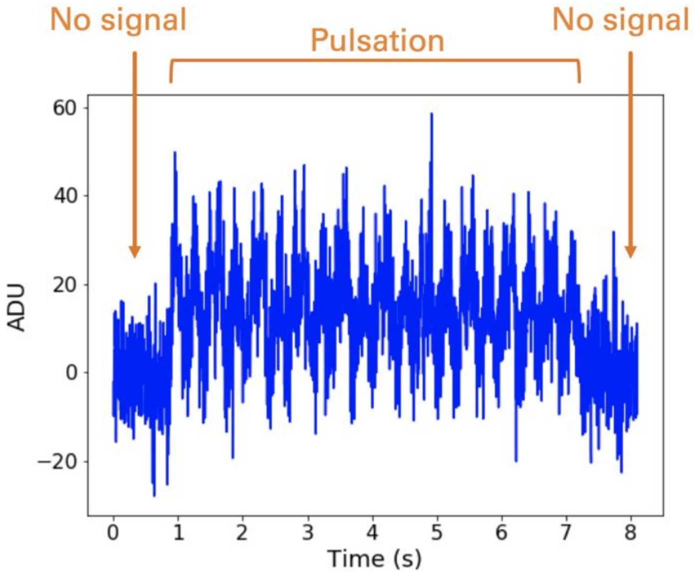


Testing a new ZTF observing mode

few ms time resolution

Finding counterparts to Fast Radio Bursts

Down to ~12.6 mag (SNR=10)



Rapidly spinning space debris

The pulsating object was bright for ~6s

Read While Expose

With Igor Andreoni, Roger Smith, ...

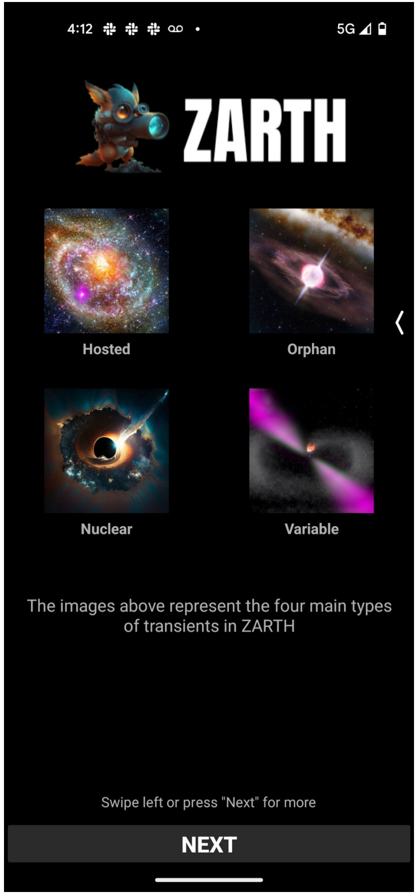
ZARTH - Pokemon GO for ZTF transients

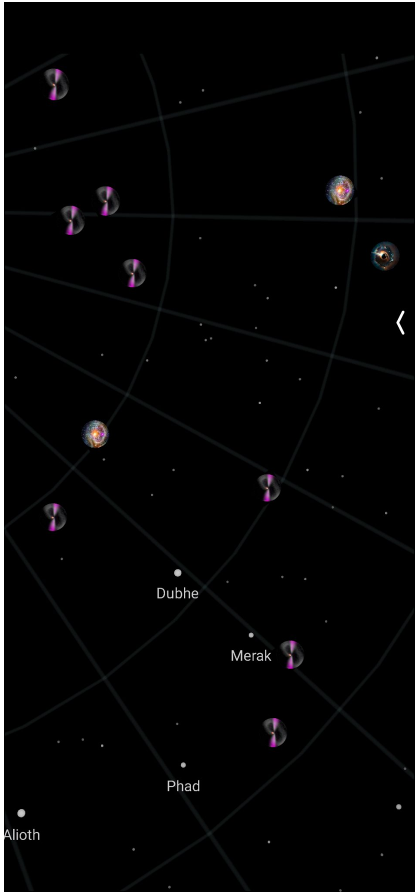
Coming this month to androids

With D Pindawala, A Arora, D Thummar, A Bhavsar, I Kostadinova, …

Made with midjourney

Ashish Mahabal





Summary

- **Combining archives generally underexplored**
- **Combined ZTF - Gaia data have fantastic possibilities**
- **More ML and population level studies**
- **Move towards Rubin/LSST**

Ashish Mahabal
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