ORACLE: A family of Real-Time, Hierarchical, Multimodal classifiers for LSST and ZTF

Ved Shah, Northwestern University

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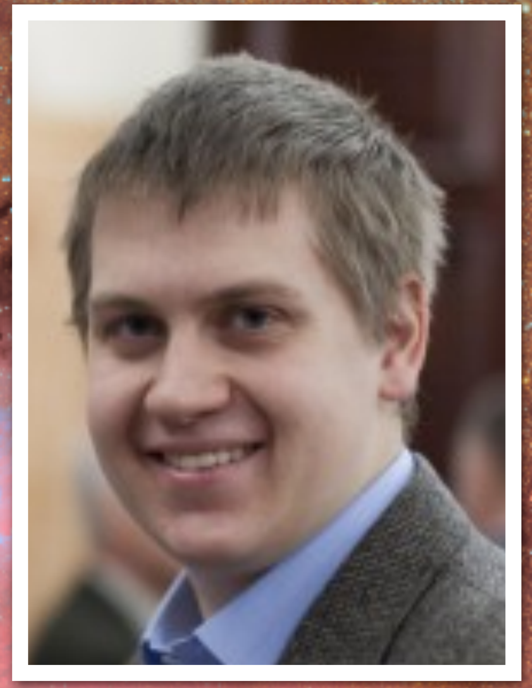
CIERA
CENTER FOR INTERDISCIPLINARY EXPLORATION AND RESEARCH IN ASTROPHYSICS

SkAI
Funded by the U.S. National Science Foundation and the Simons Foundation

Oracle v1 (for LSST)

Alex Gagliano

Gautham Narayan



Konstantin Malanchev

Alex Malz

Oracle v2 (for ZTF and LSST) + Model Deployment

Nabeel Rehemtulla

Adam Miller

Michael Coughlin

Sushant Sharma Chaudhary

+ The BOOM Team

1. Introduction and Motivation

Motivation

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- **Hierarchical classification** is a better way of thinking about real time classification problems compared to flat classification

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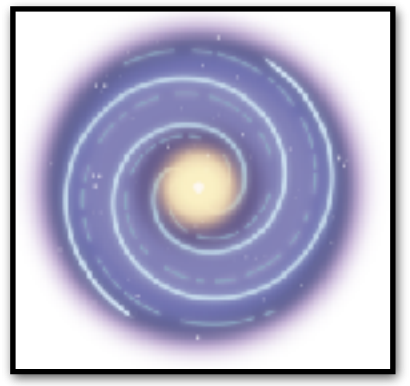
- **Multi-modality** naturally fits into a real-time classification framework and has obvious performance benefits

- We need to carefully consider workflows when **deploying models** on real alert streams

The case for hierarchical classification

Time t1



Science

The case for hierarchical classification

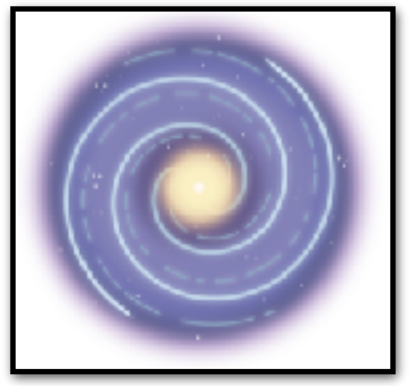
Time t1

Science

The case for hierarchical classification

Time t1

-

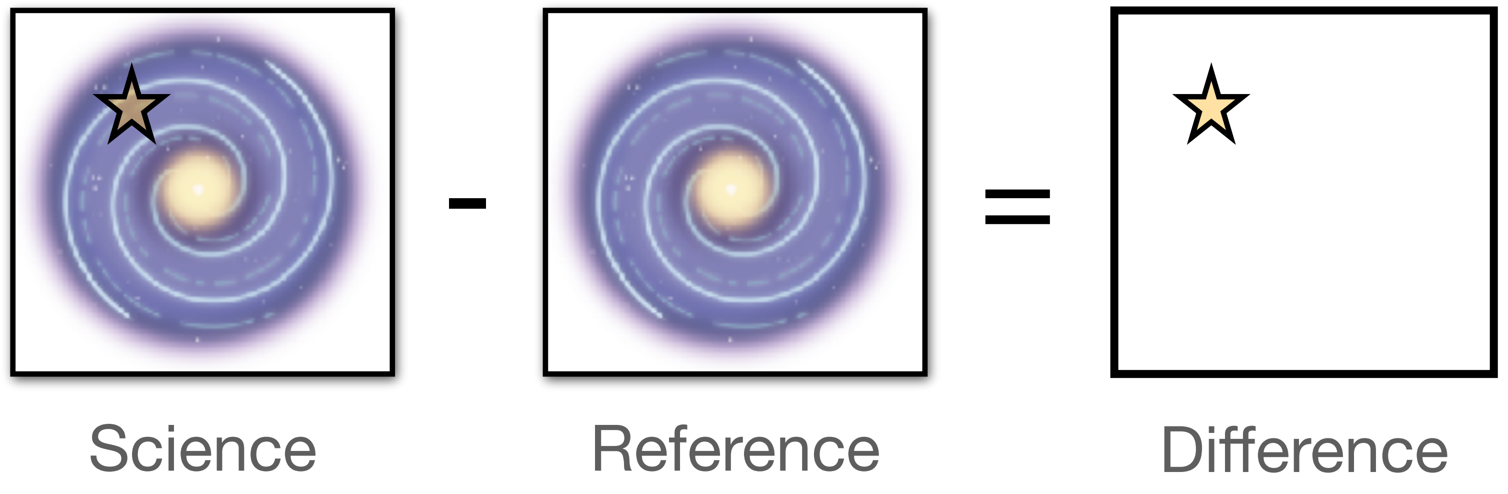


Science

Reference

The case for hierarchical classification

Time t1



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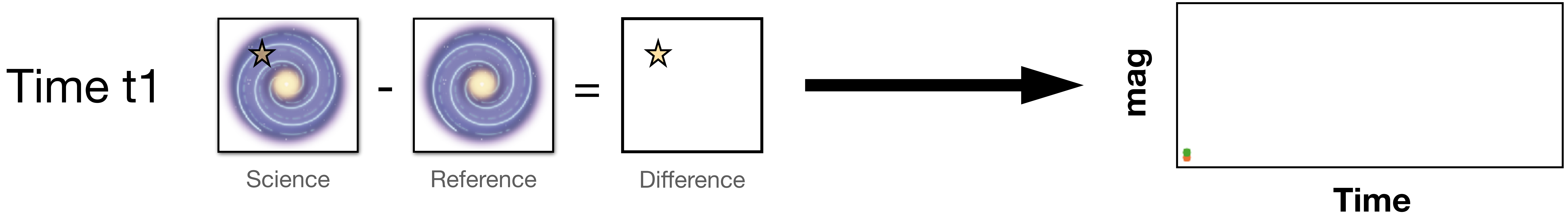

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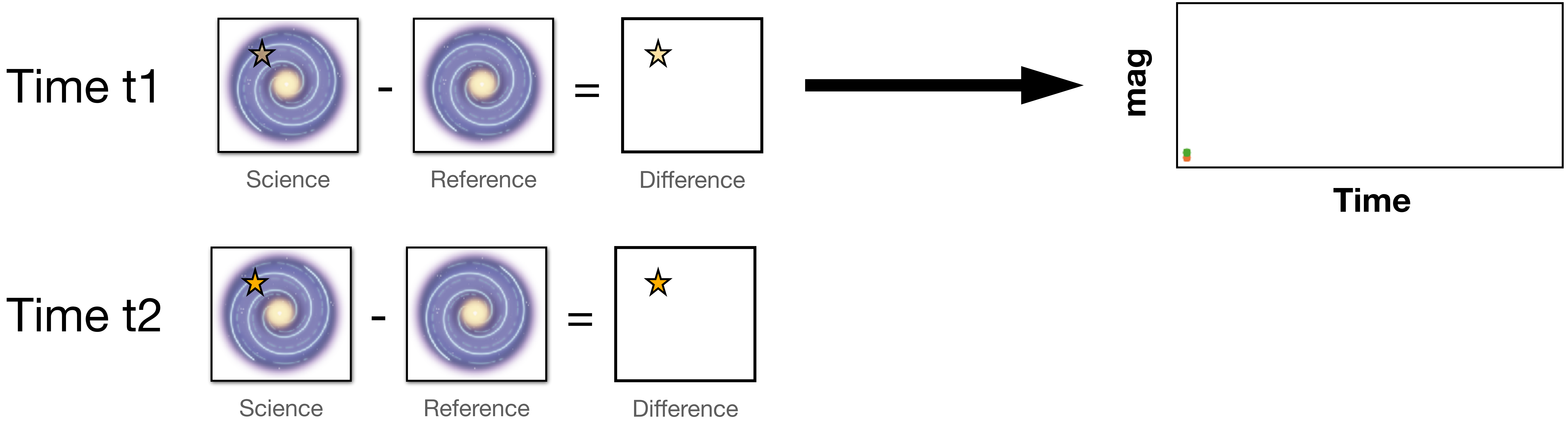

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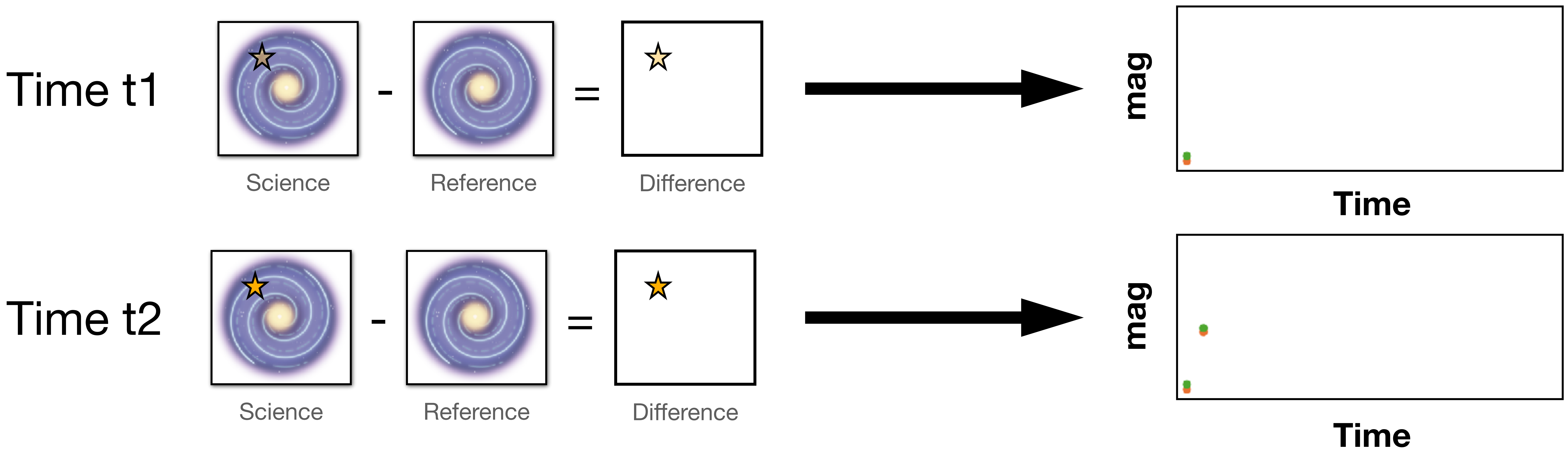

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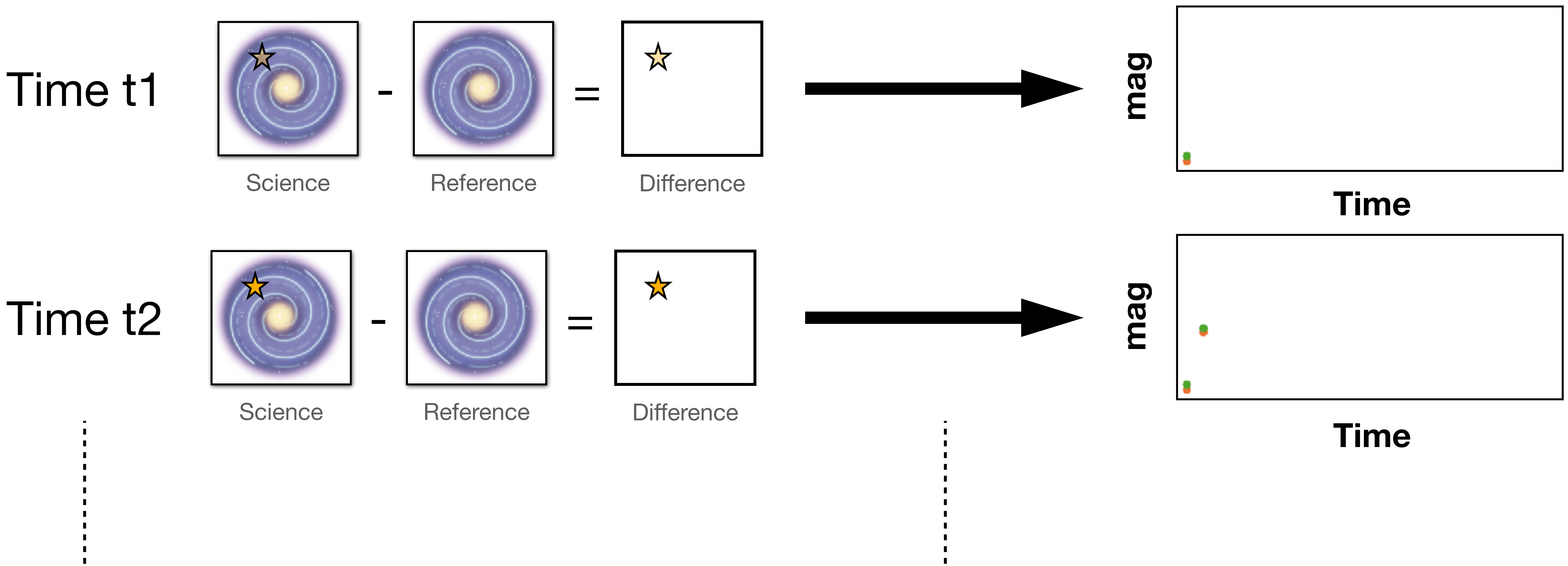

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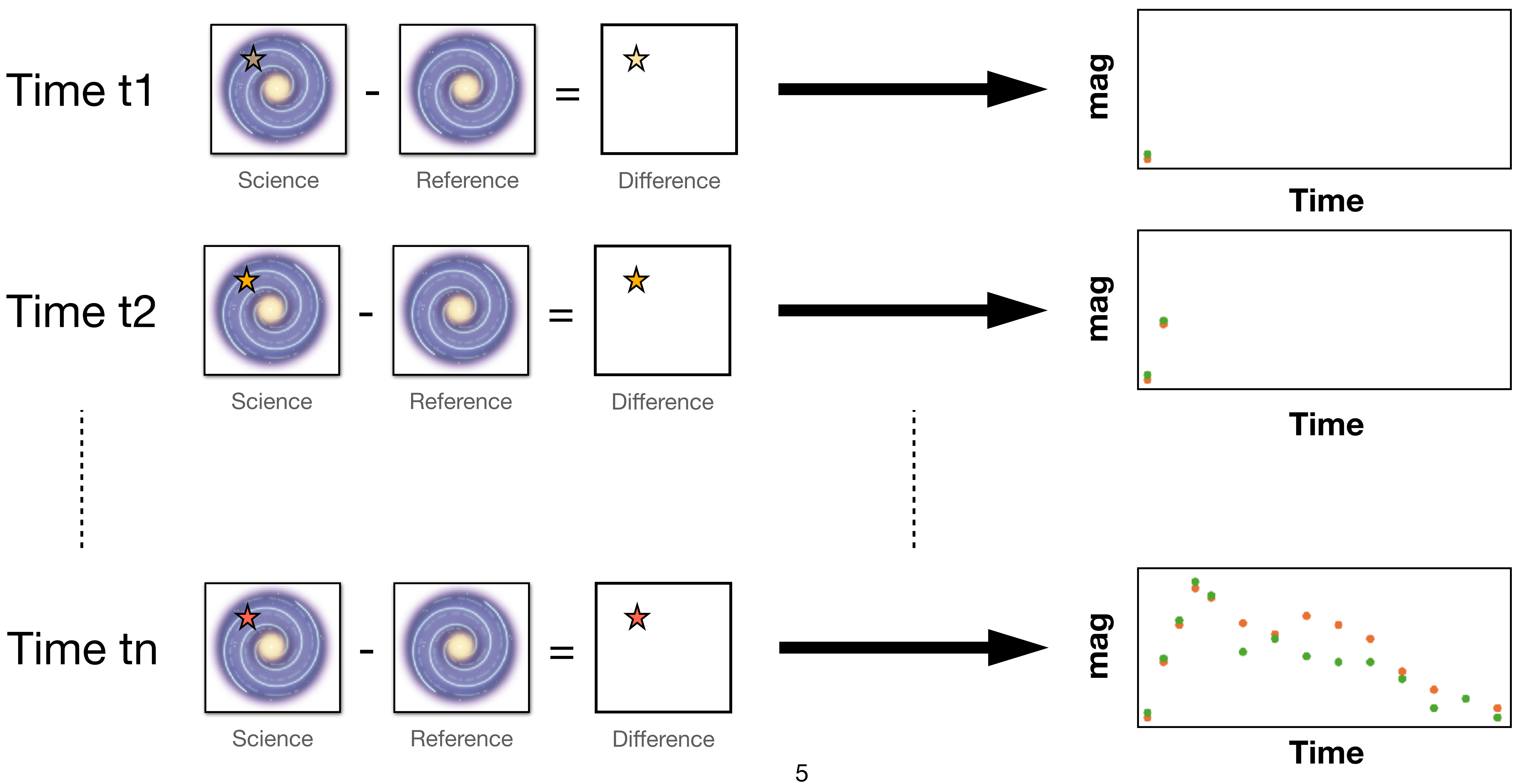

The case for hierarchical classification

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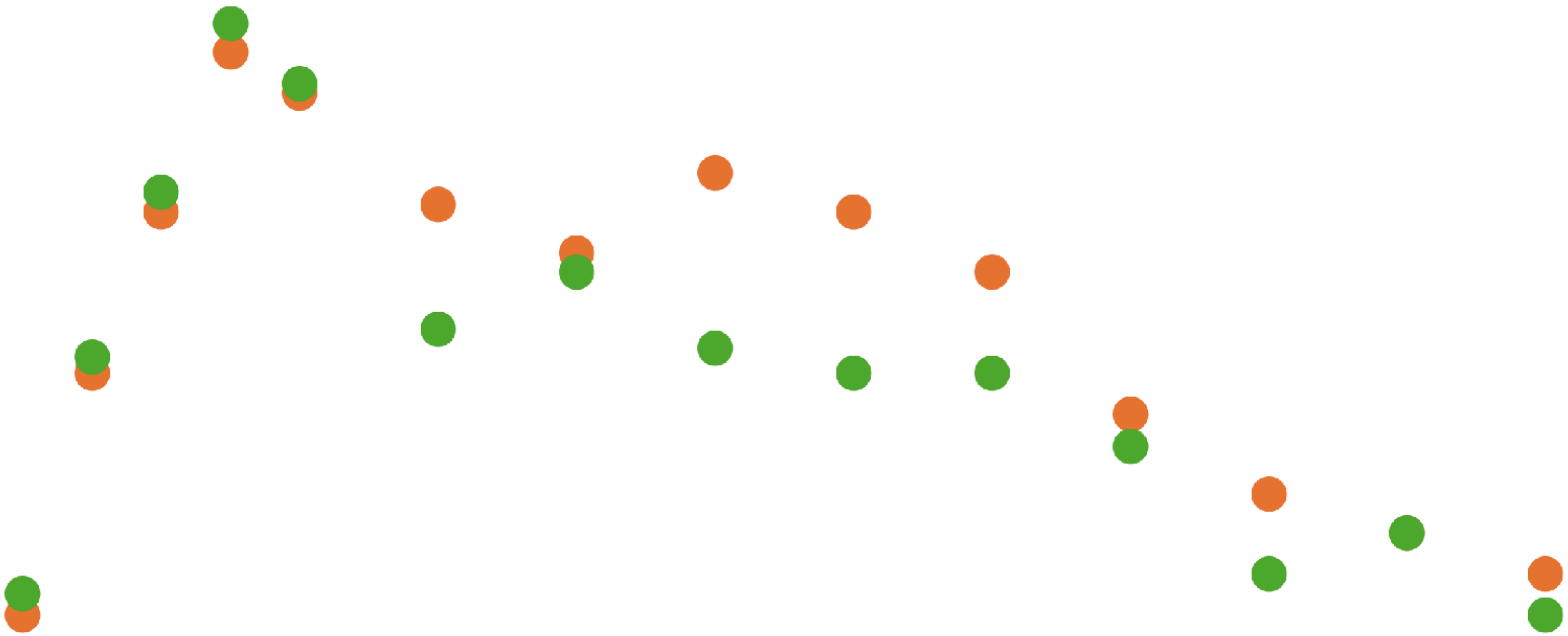

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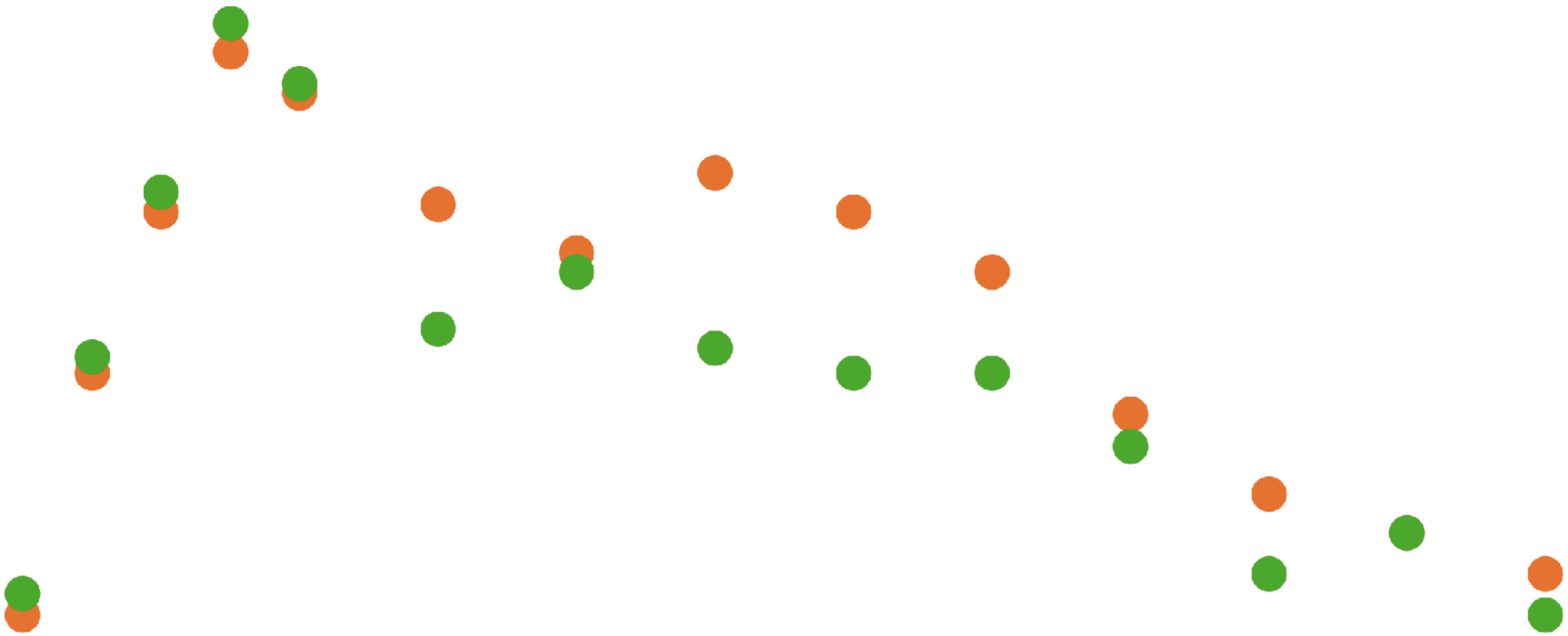

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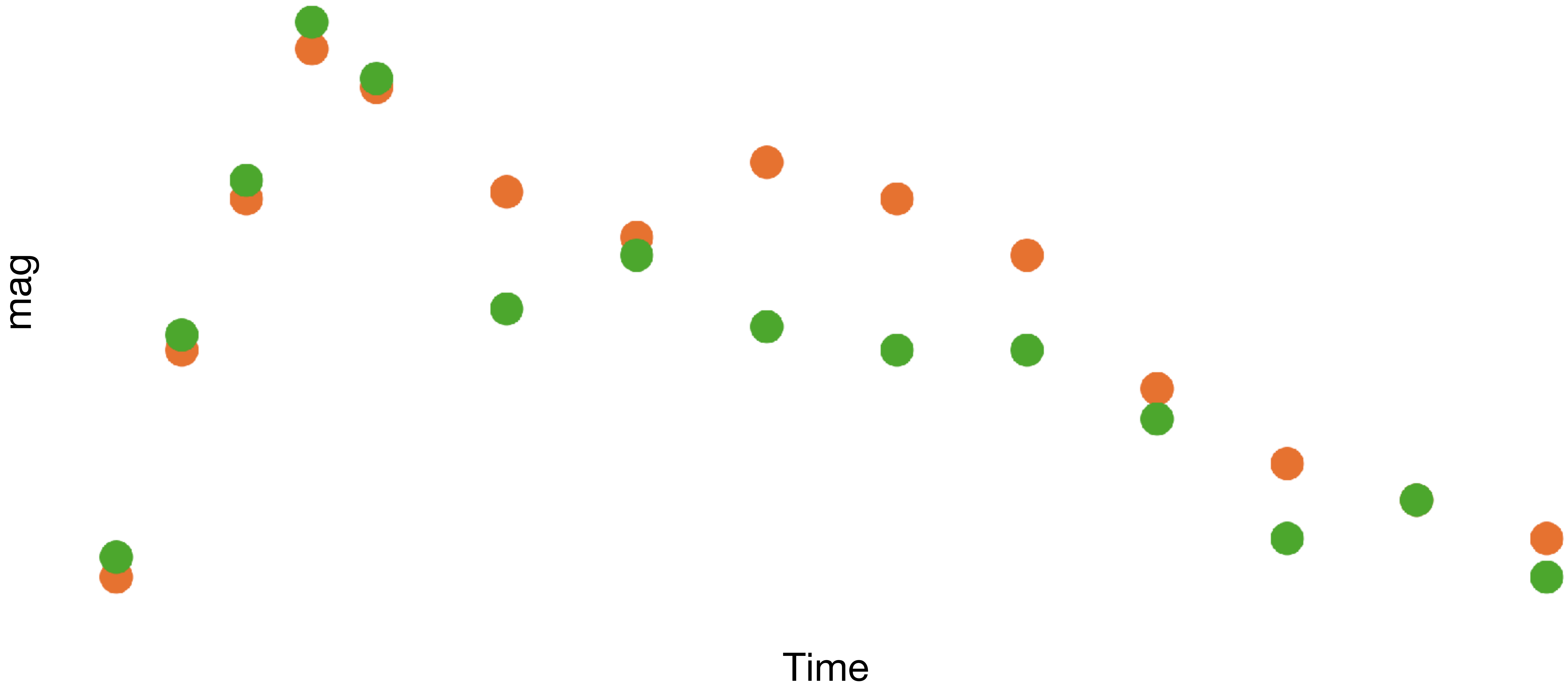

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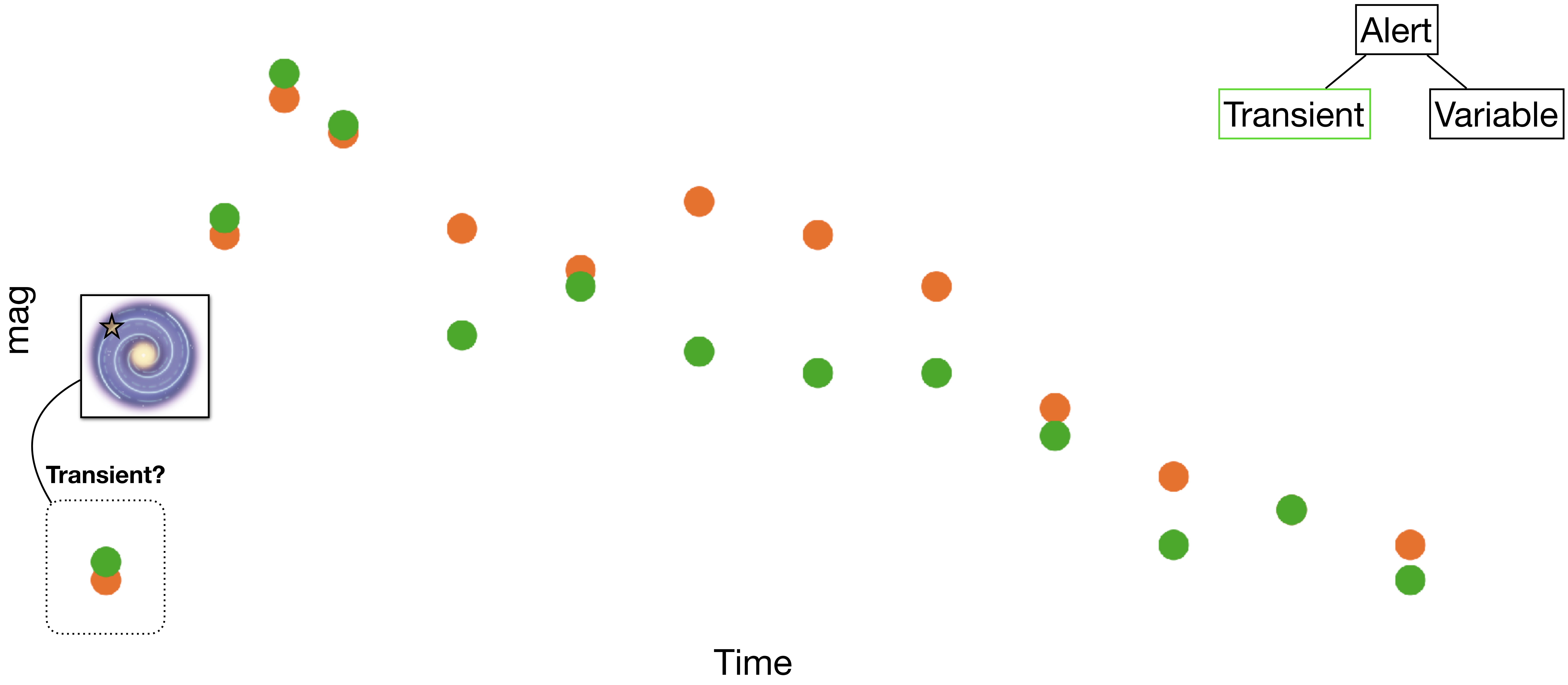
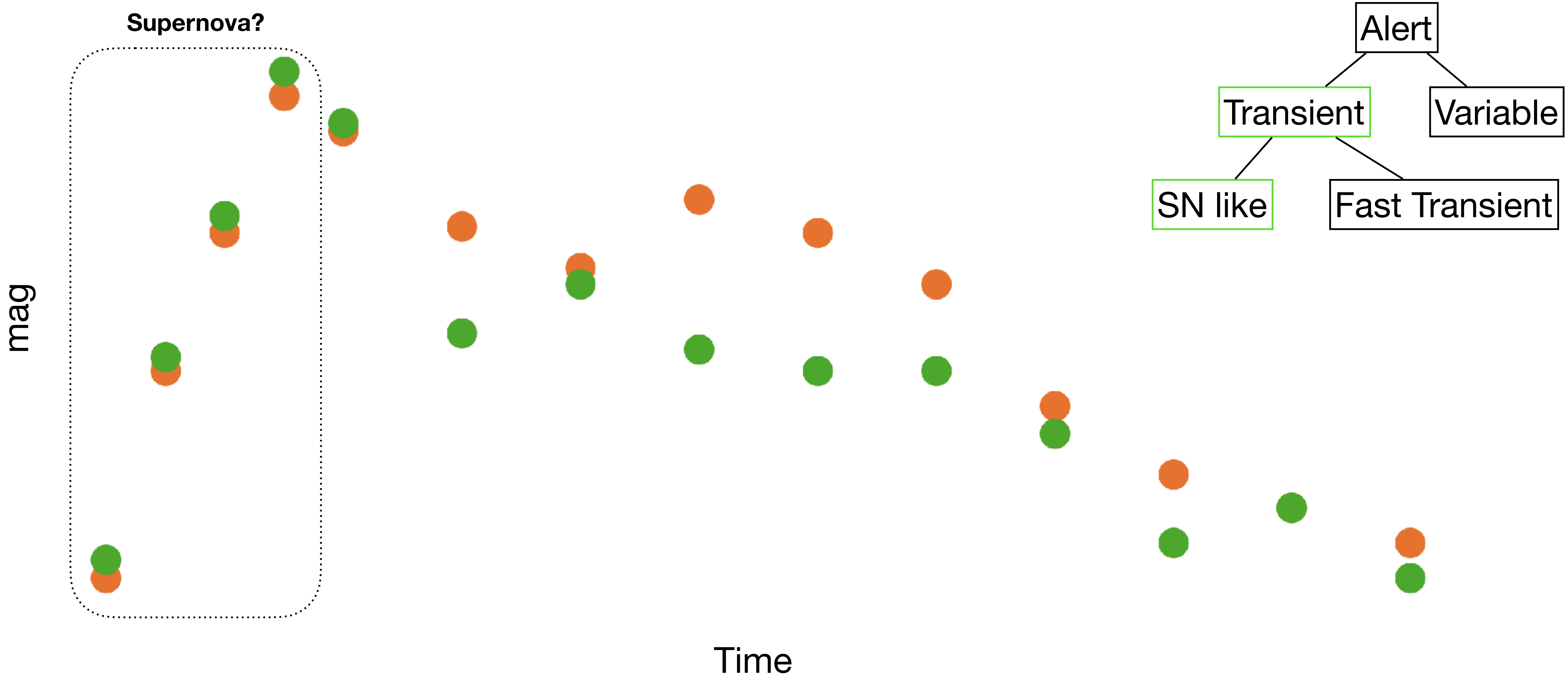


*For illustrative purposes only

The case for hierarchical classification



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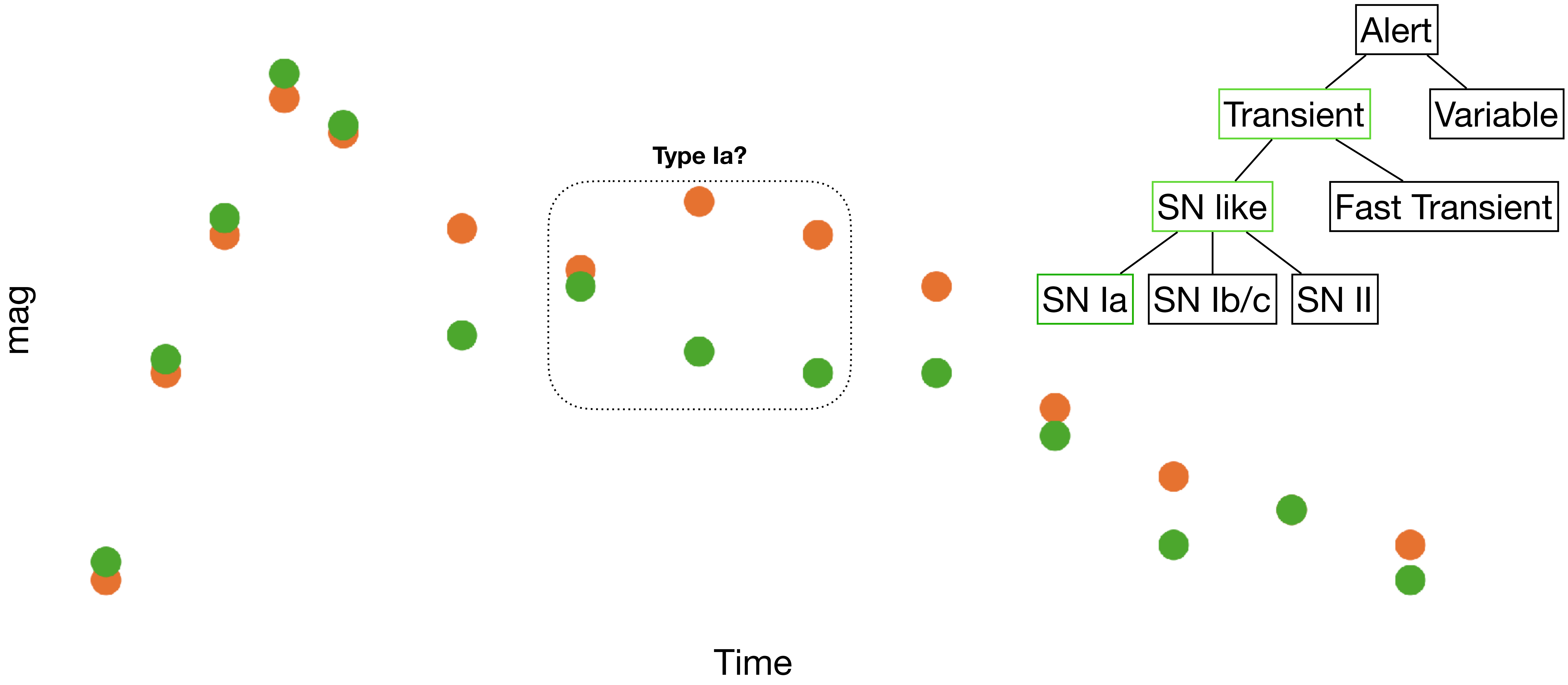

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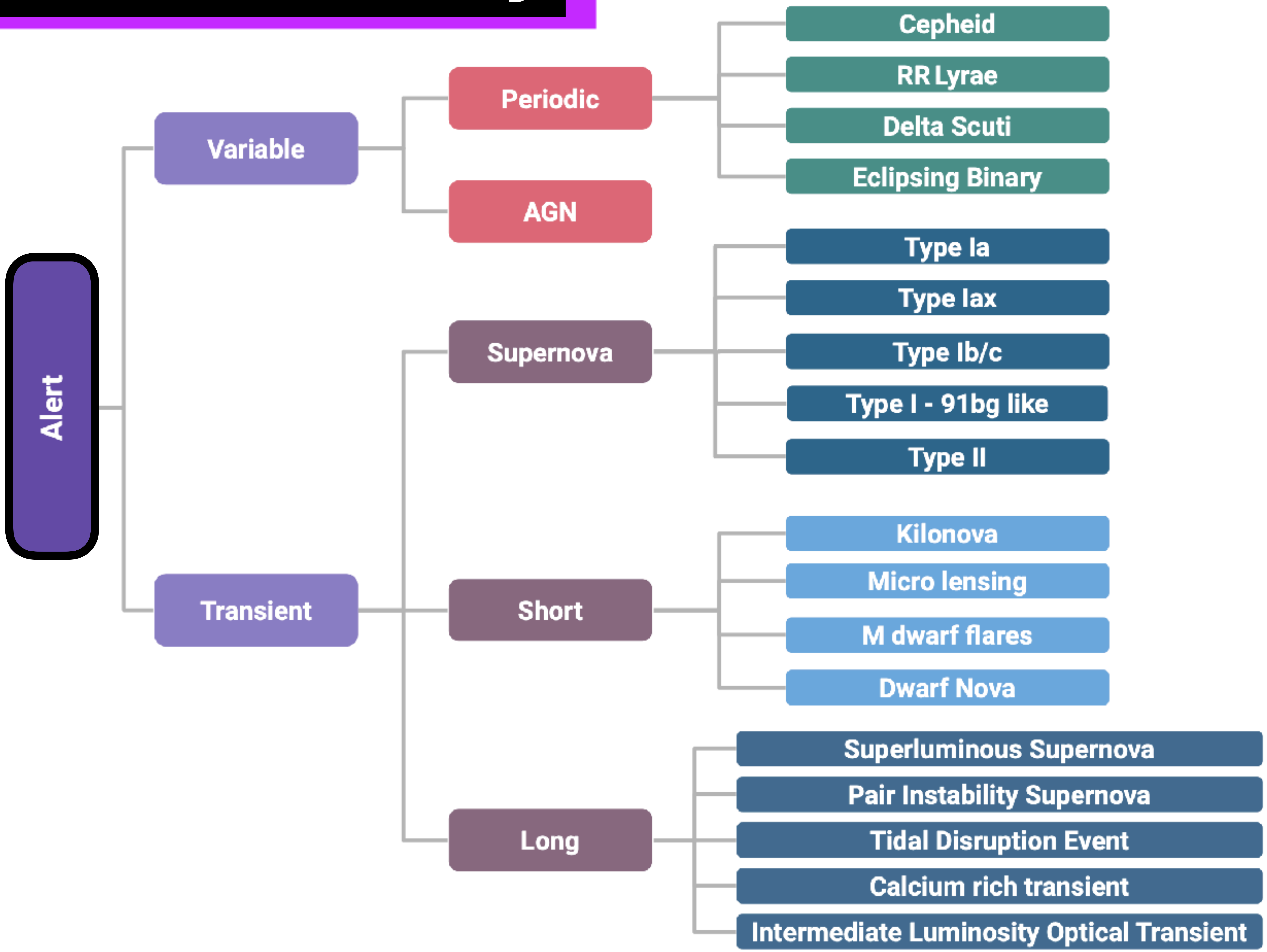
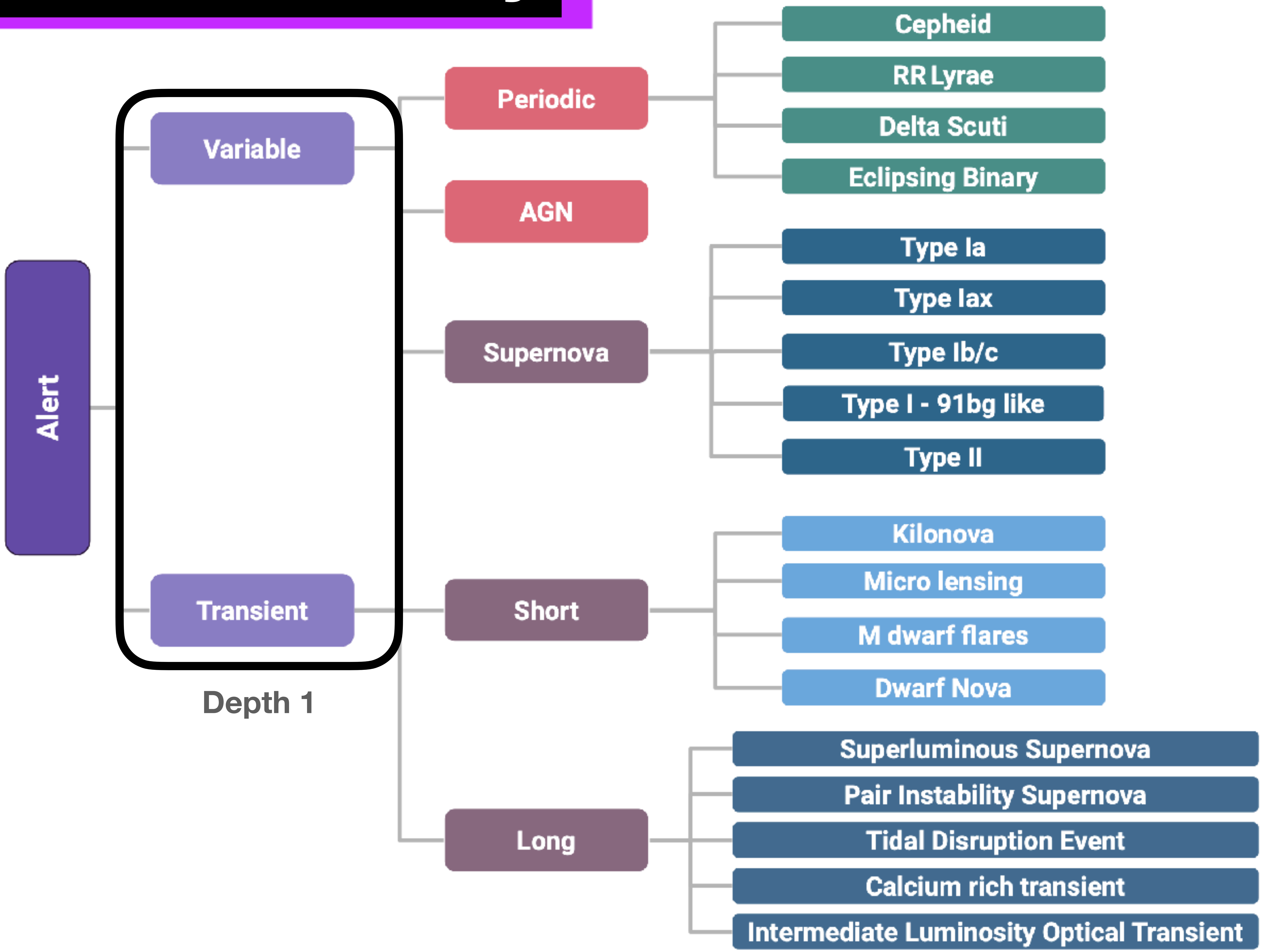
Classification Taxonomy



Shah et al. (2025b)

Classification Taxonomy



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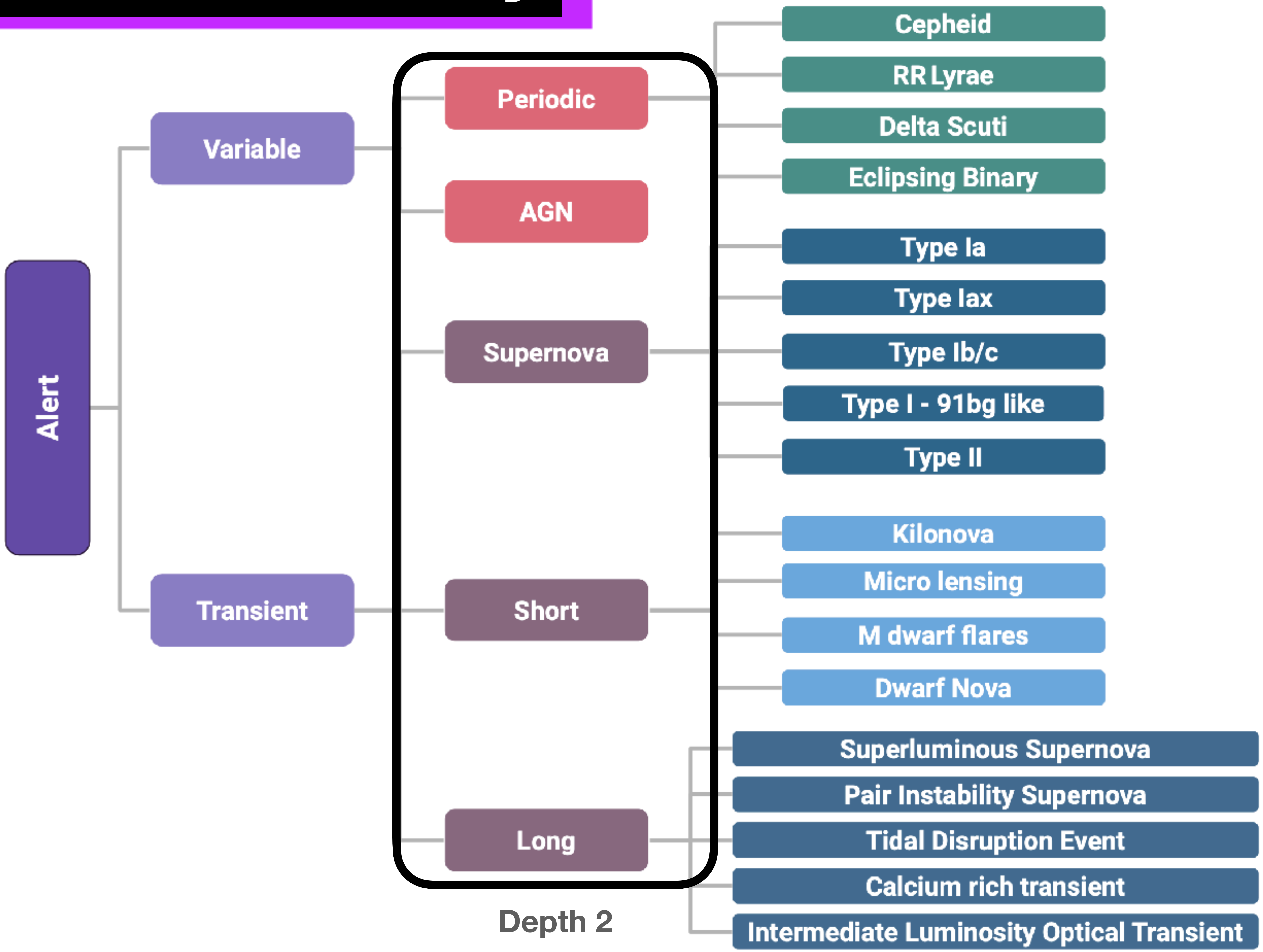
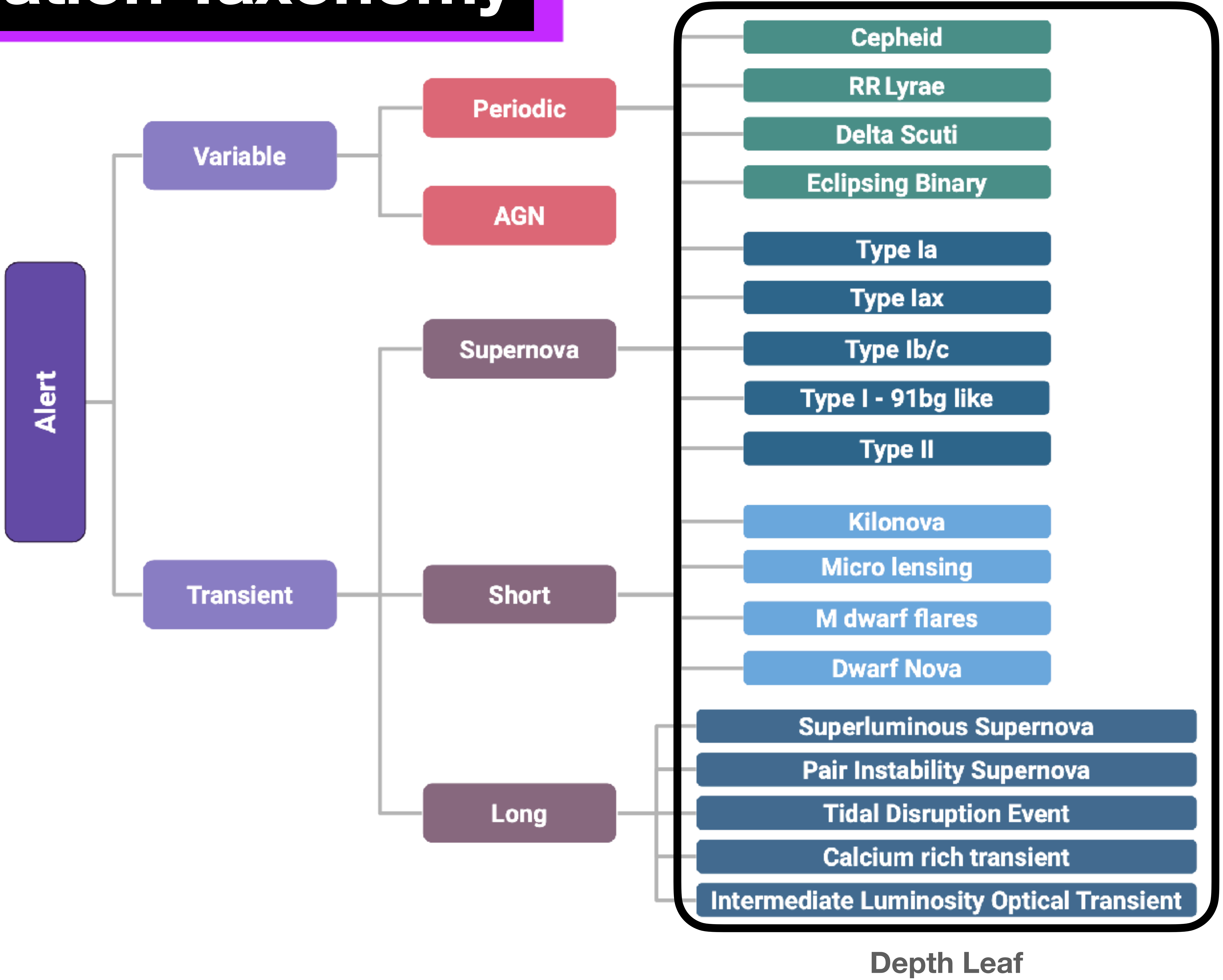


Shah et al. (2025b)

Classification Taxonomy



Shah et al. (2025b)

The case for multi-modality

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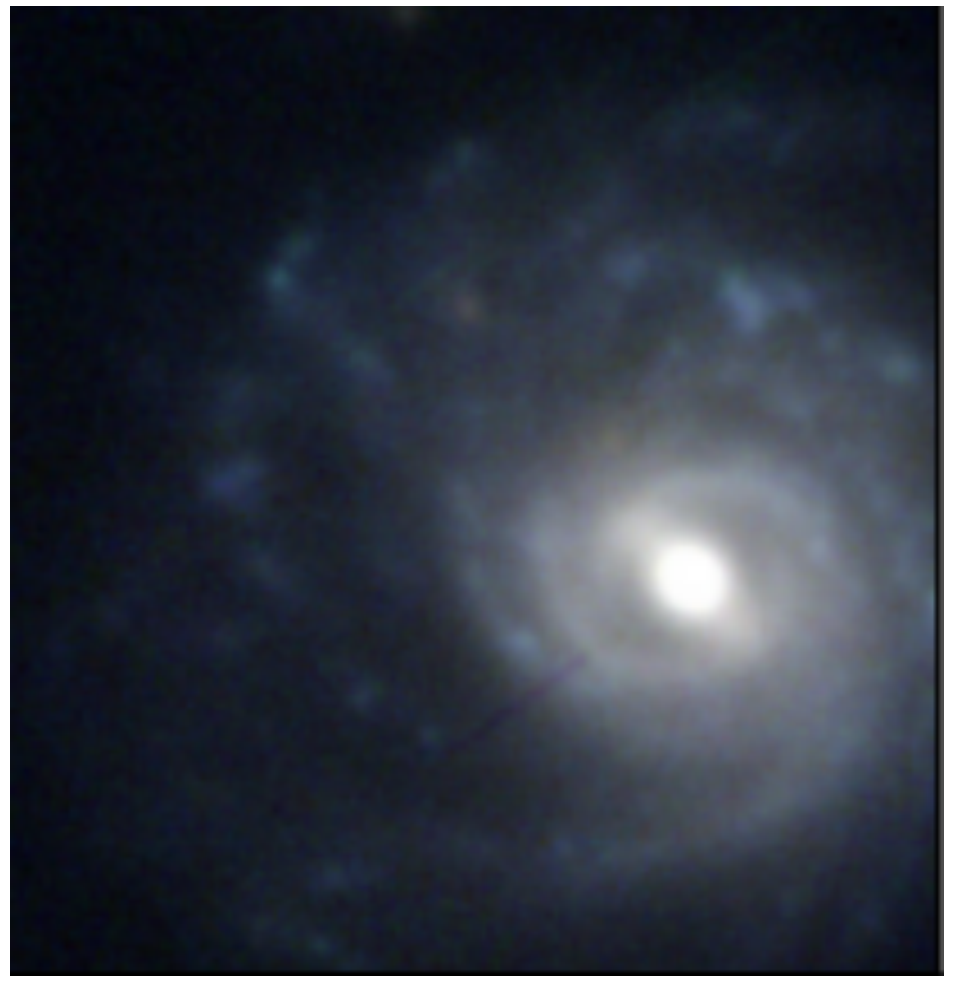
Core Collapse SN:

- Preferentially occur in galaxies that have active star formation



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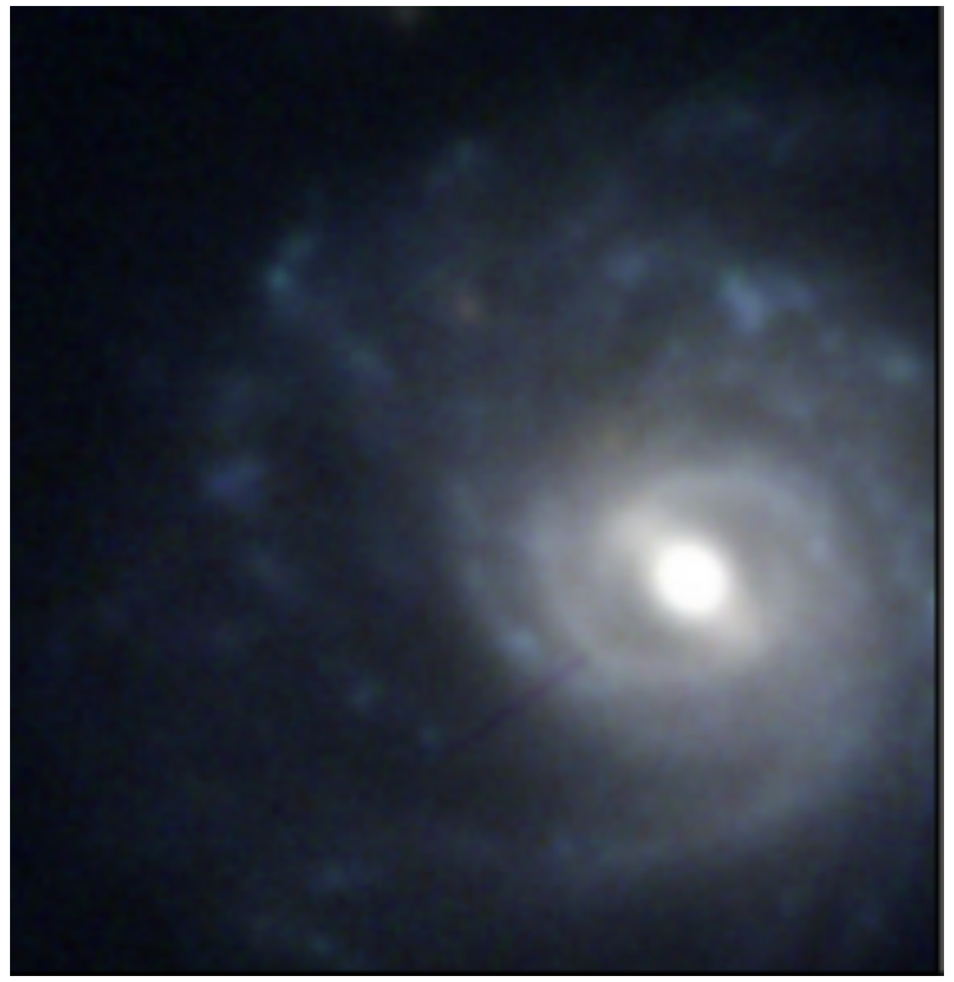

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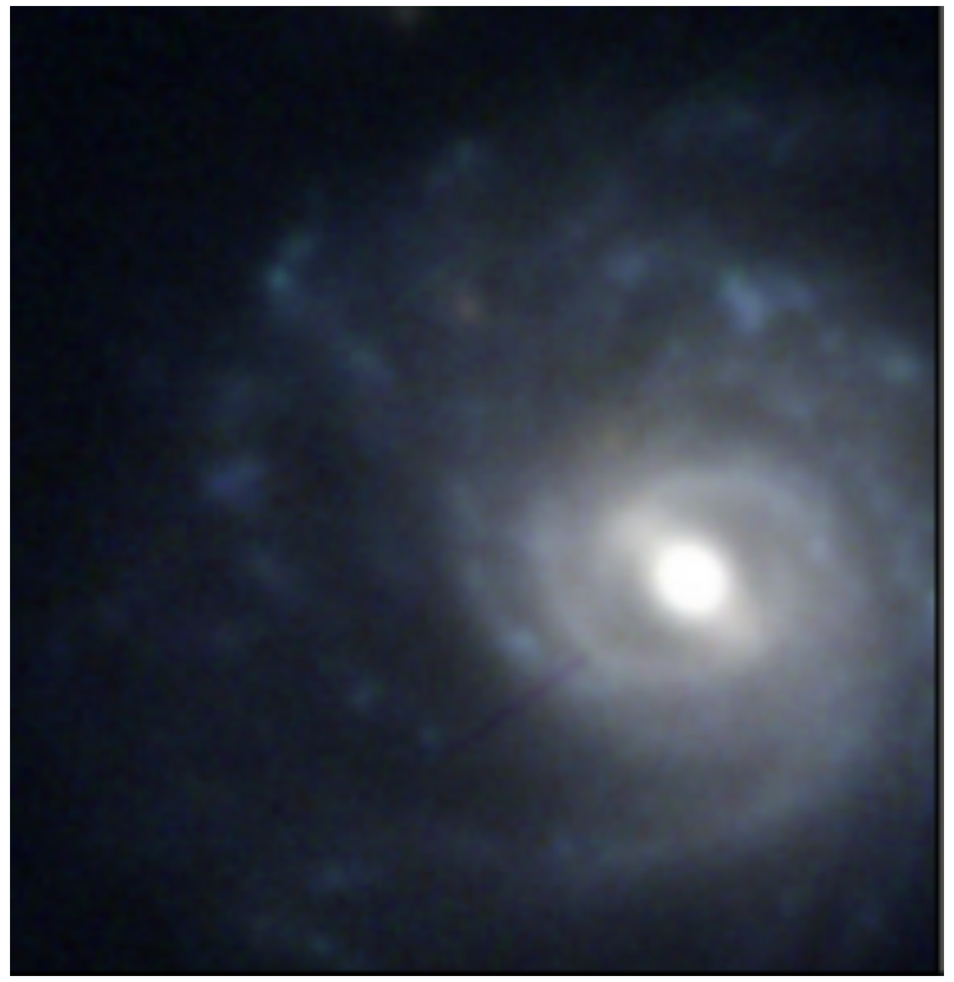


Superluminous SN-I:

- Preferentially occur in low metallicity dwarf galaxies

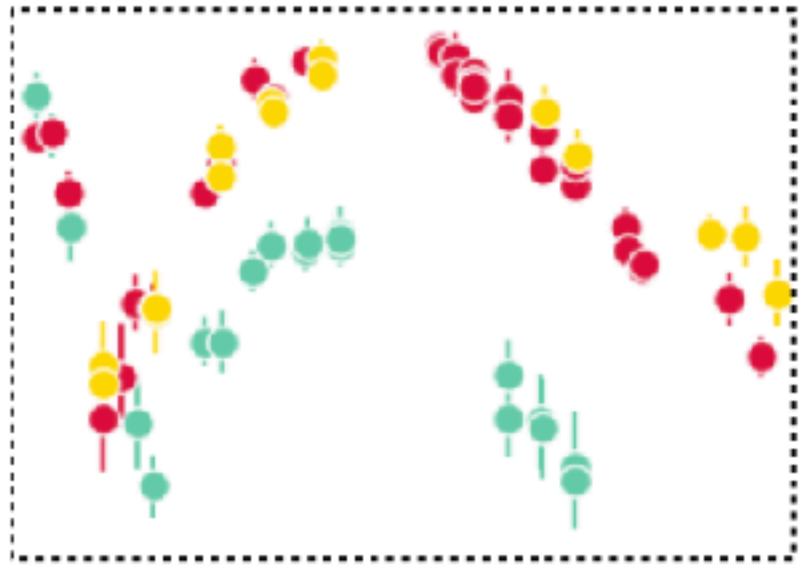
Variable Stars:

- A large fraction of alerts occur in crowded fields with no obvious host

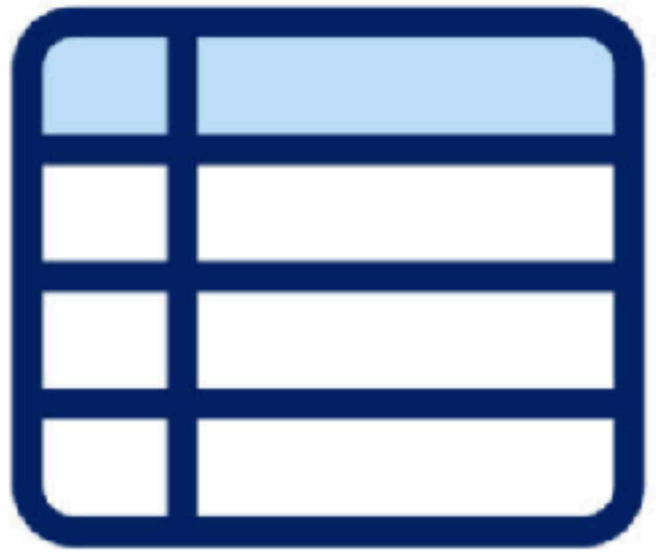
2. Methods

Multi-modal Architecture

5 feature
time series



Contextual
Information

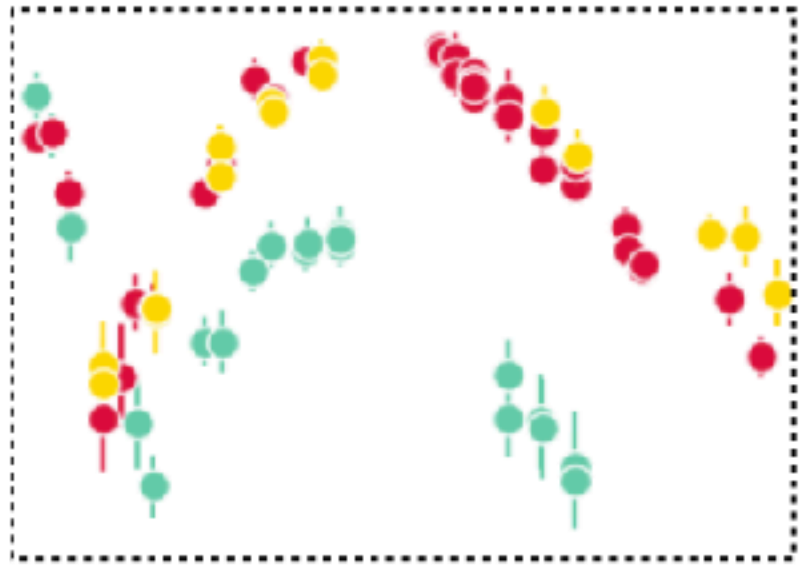


Multi-band
Images

Shah+26

Multi-modal Architecture

5 feature time series



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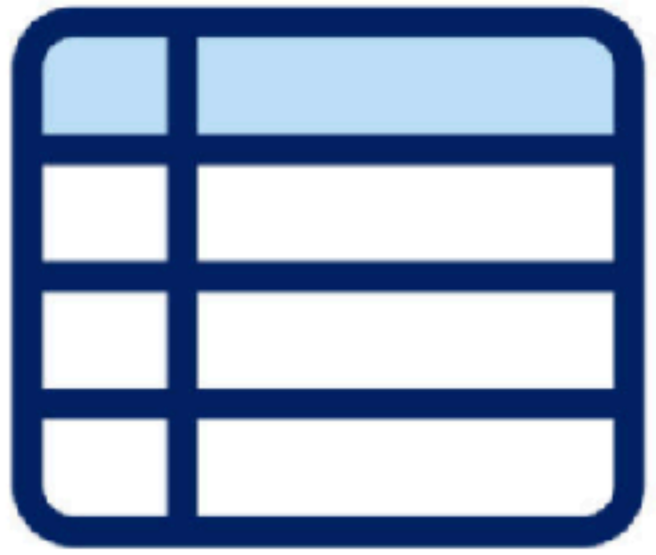


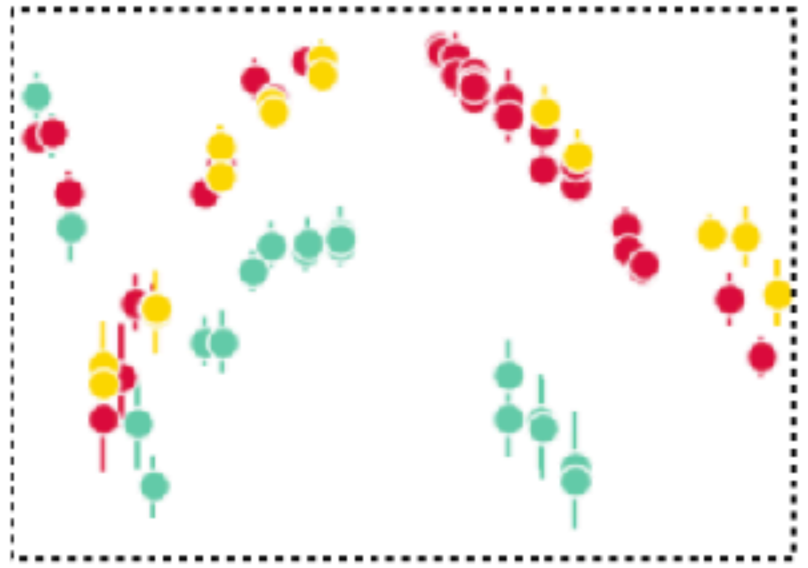
Multi-band Images

Oracle-2 Lite (RNN)

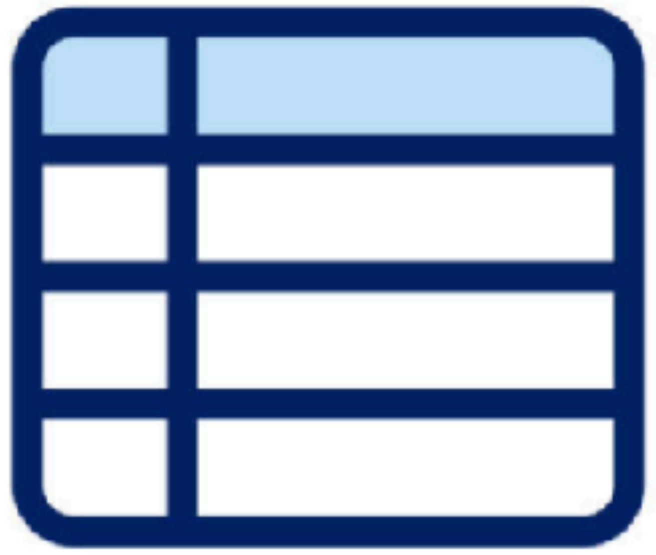
Shah+26

Multi-modal Architecture

5 feature
time series



Contextual
Information



Multi-band
Images

Shah+26

Multi-modal Architecture

5 feature
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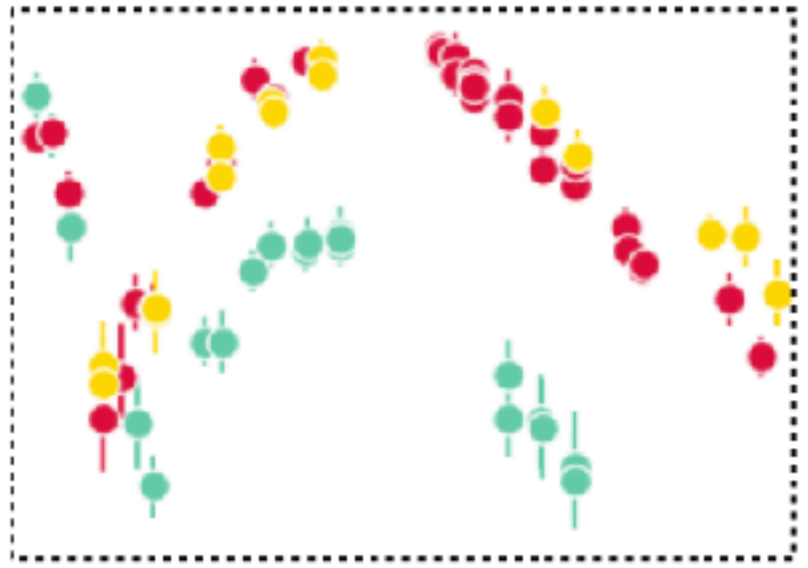
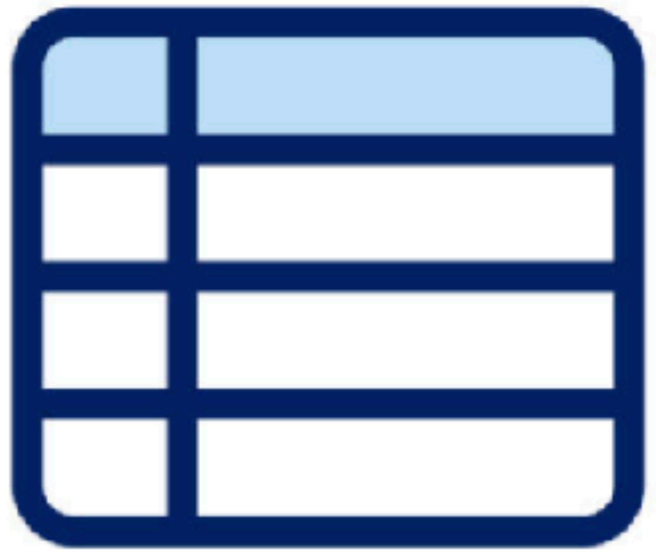


Contextual
Information



Multi-band
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Shah+26

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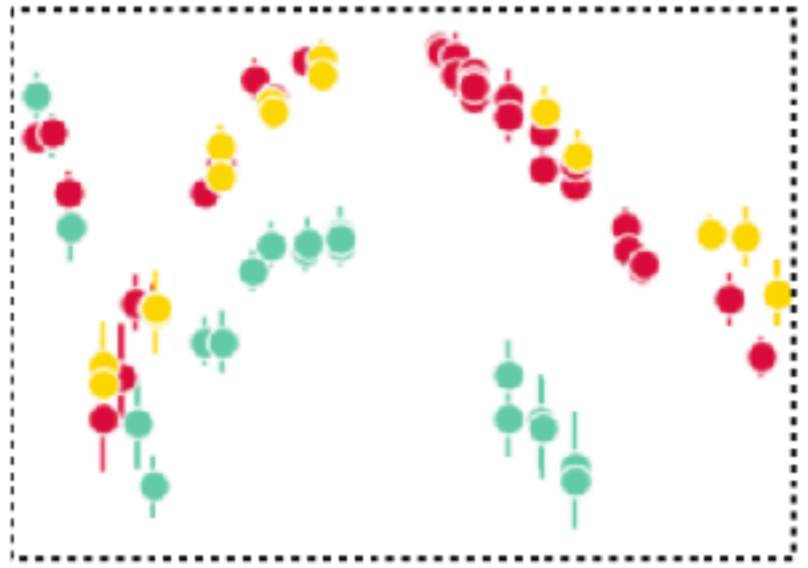

Contextual
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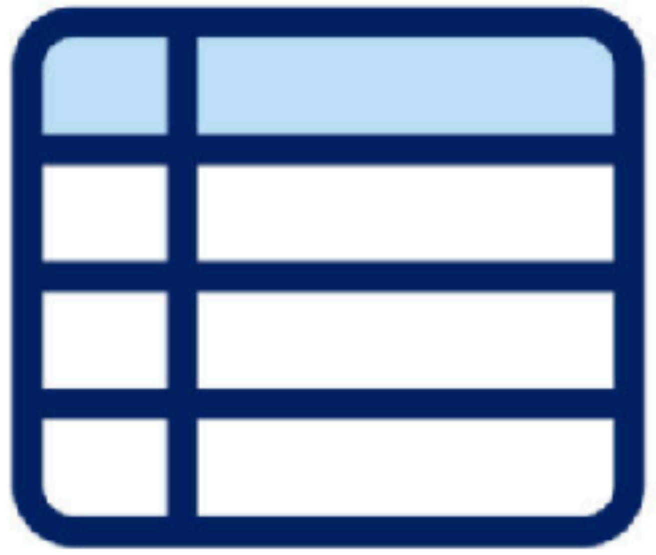


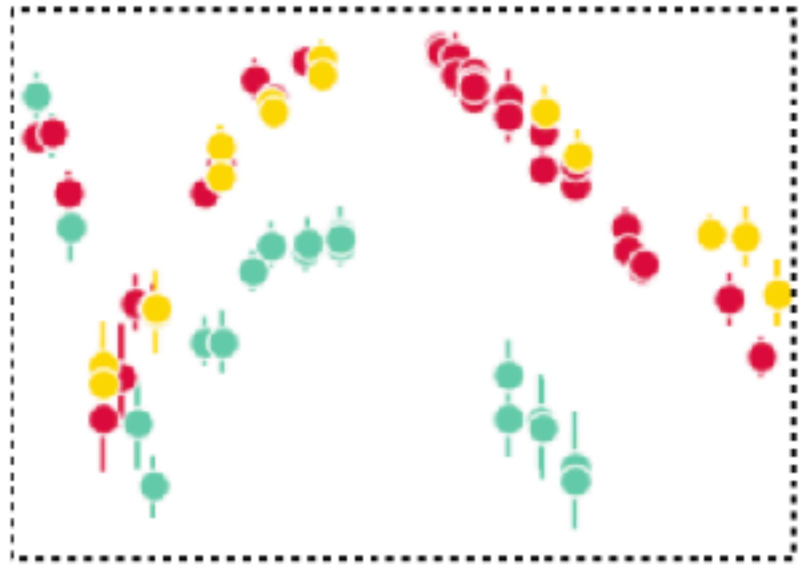
Multi-band
Images

Oracle-2
(RNN + MLP)

Shah+26

Multi-modal Architecture

5 feature
time series



Contextual
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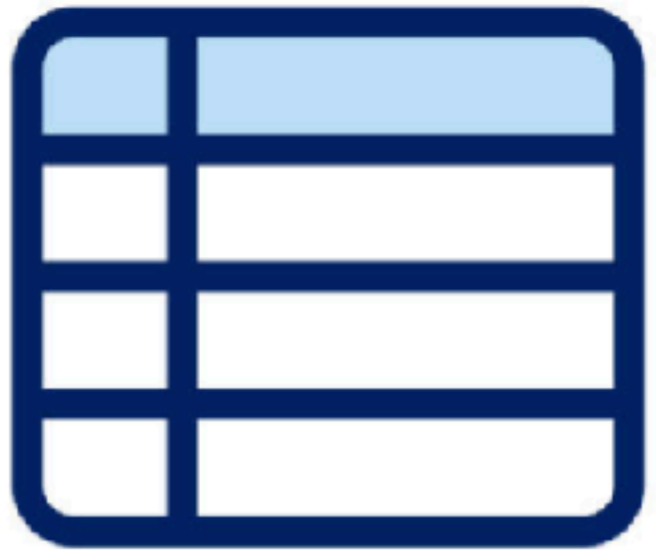

Multi-band
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Multi-modal Architecture

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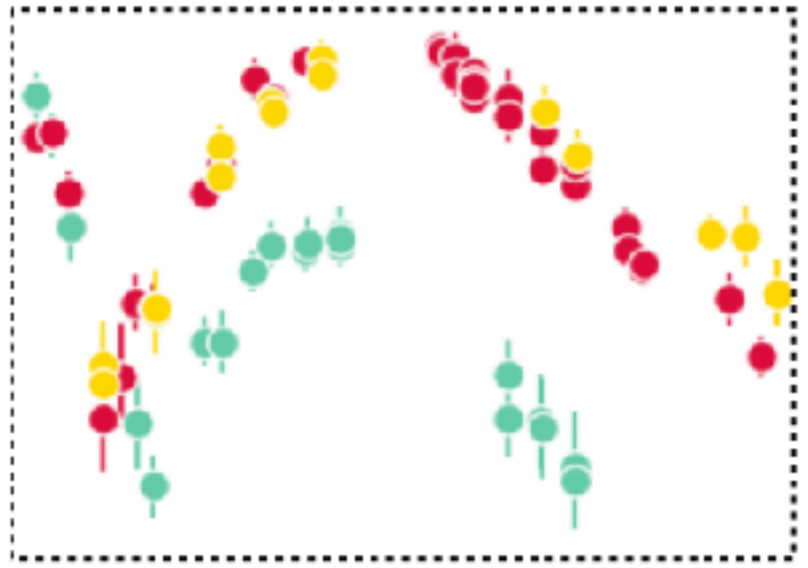

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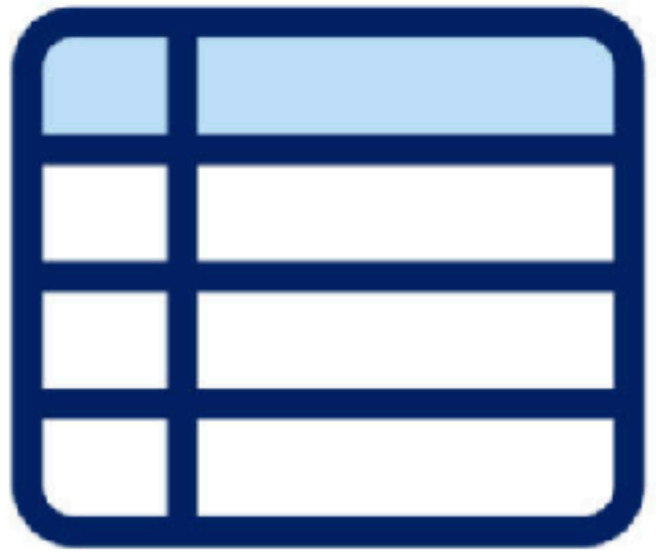

Multi-band Images

Shah+26

Multi-modal Architecture

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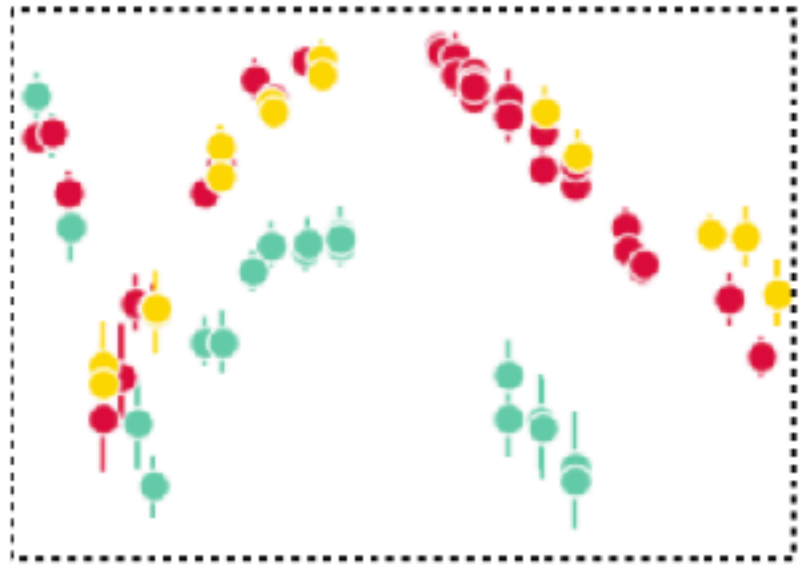
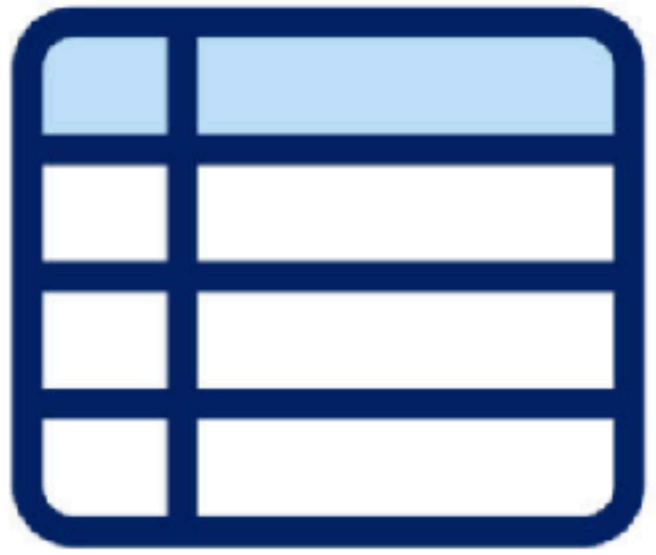


Contextual
Information



Multi-band
Images

Oracle-2 Omni
(RNN + MLP + CNN)

Shah+26

The Loss Function

Hierarchical Cross Entropy (HXE) - Bertinetto et al. (2019)

$$L_{\text{HXE}}(p, C) = -\sum_{l=0}^{h-1} \lambda(C^{(l)}) \log p(C^{(l)} \mid C^{(l+1)})$$

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The Loss Function

Hierarchical Cross Entropy (HXE) - Bertinetto et al. (2019)

$$L_{\text{HXE}}(p, C) = -\underbrace{\sum_{l=0}^{h-1}}_{\text{Sum over all layers of taxonomy}} \lambda(C^{(l)}) \log p(C^{(l)} \mid C^{(l+1)})$$

The Loss Function

Hierarchical Cross Entropy (HXE) - Bertinetto et al. (2019)

$$L_{\text{HXE}}(p, C) = - \sum_{l=0}^{h-1} \underbrace{\lambda(C^{(l)})}_{\text{Level weight term}} \log p(C^{(l)} \mid C^{(l+1)})$$

where $\lambda(C^{(l)}) = \exp(-\alpha d(C))$

The Loss Function

Weighted Hierarchical Cross Entropy (WHXE) - Villar et al. (2023)

$$L_{\mathrm{WHXE}}(p, C) = -\sum_{l=0}^{h-1} W(C^{(l)})\ \lambda(C^{(l)})\ \log p(C^{(l)} \mid C^{(l+1)})$$

The Loss Function

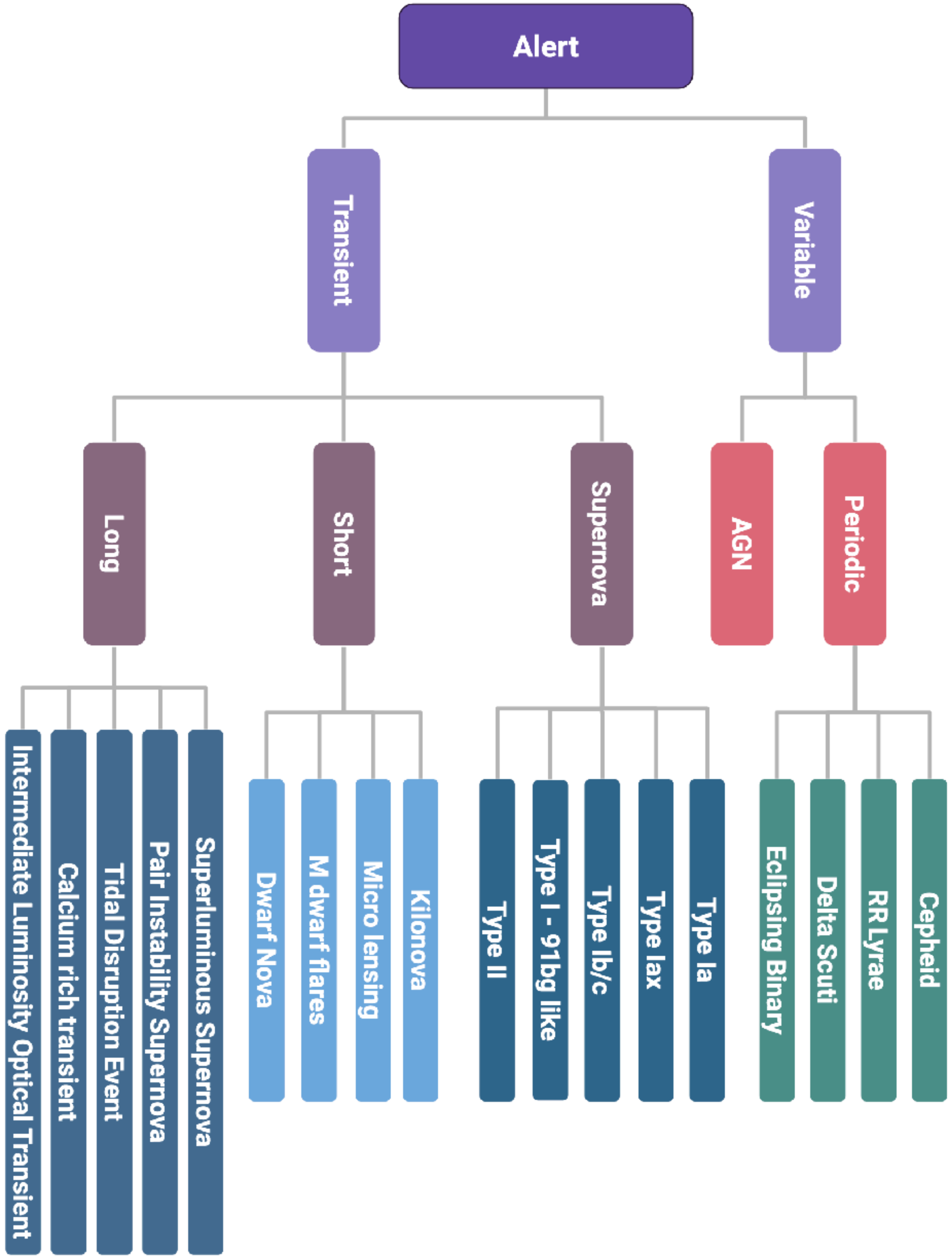
Weighted Hierarchical Cross Entropy (WHXE) - Villar et al. (2023)

$$L_{\text{WHXE}}(p, C) = -\sum_{l=0}^{h-1} \underbrace{W(C^{(l)})}_{\text{Class weight term}} \lambda(C^{(l)}) \ \log p(C^{(l)} \,|\, C^{(l+1)})$$

where $W(C^{(l)}) \propto \dfrac{1}{N_c}$

Computing class probabilities

$$p(C) = \prod_{l=0}^{h(C)-1} p(C^{(l)} \mid C^{(l+1)})$$



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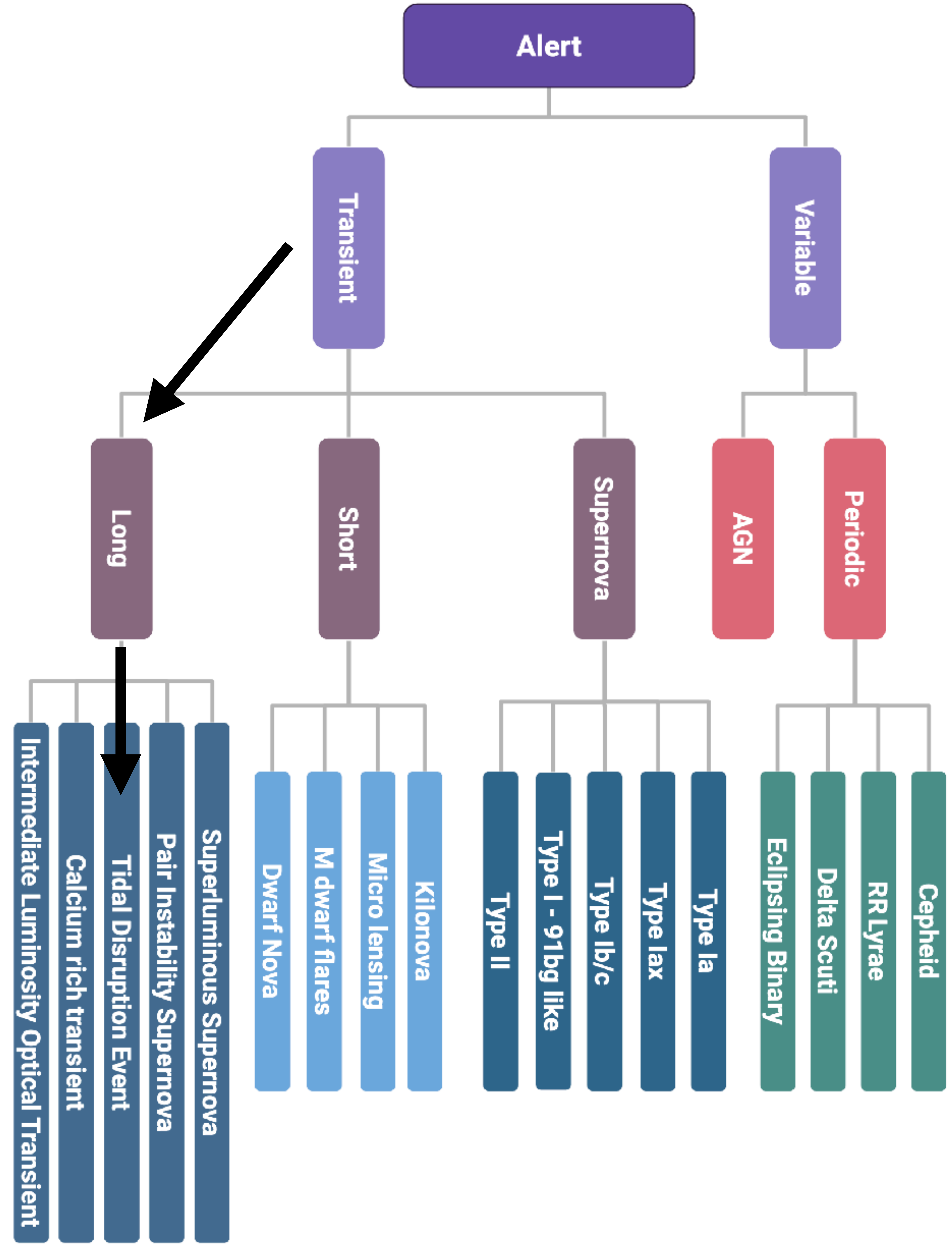
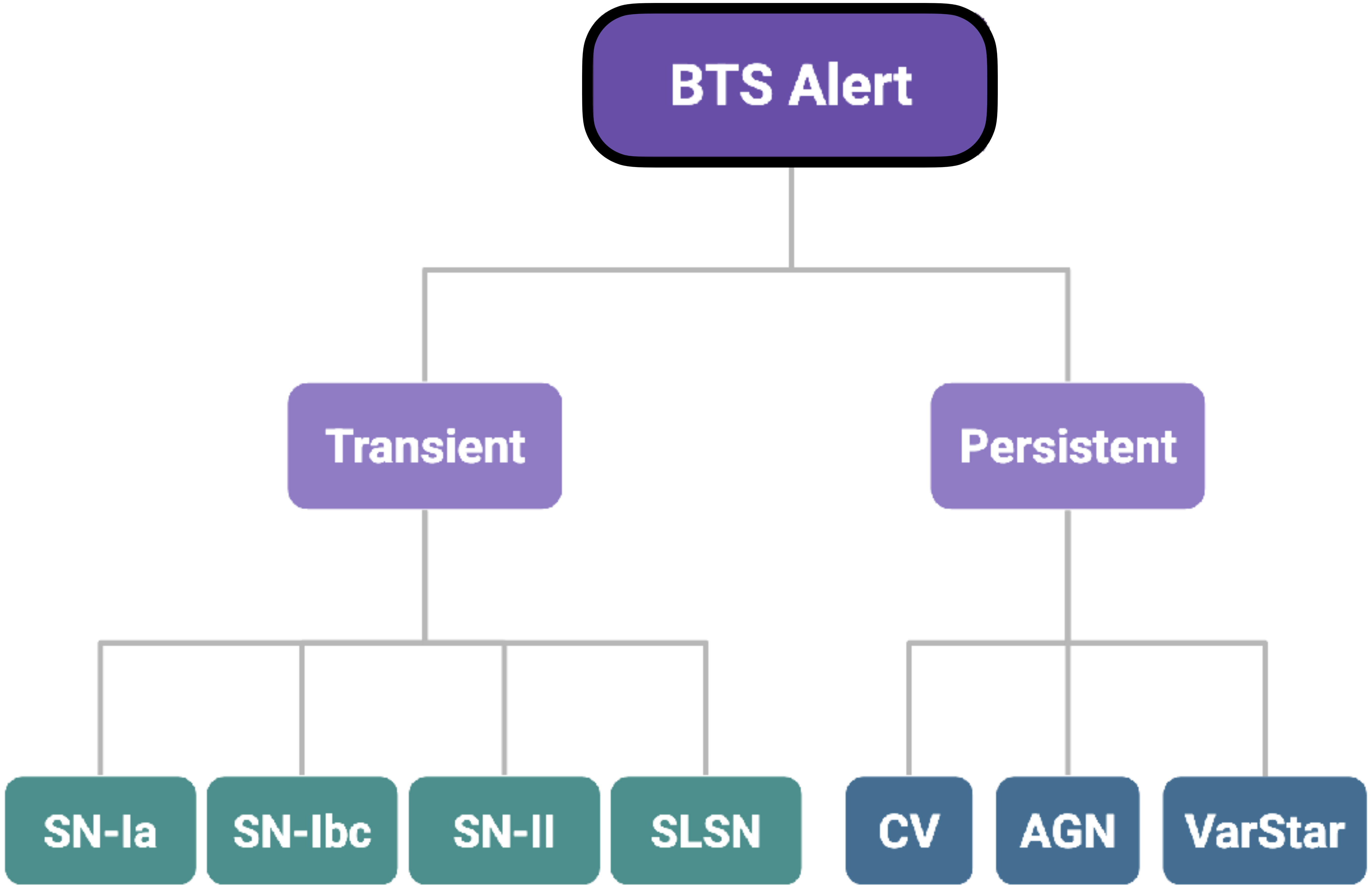


3. Results for ZTF

Taxonomy for ZTF model



Shah+26

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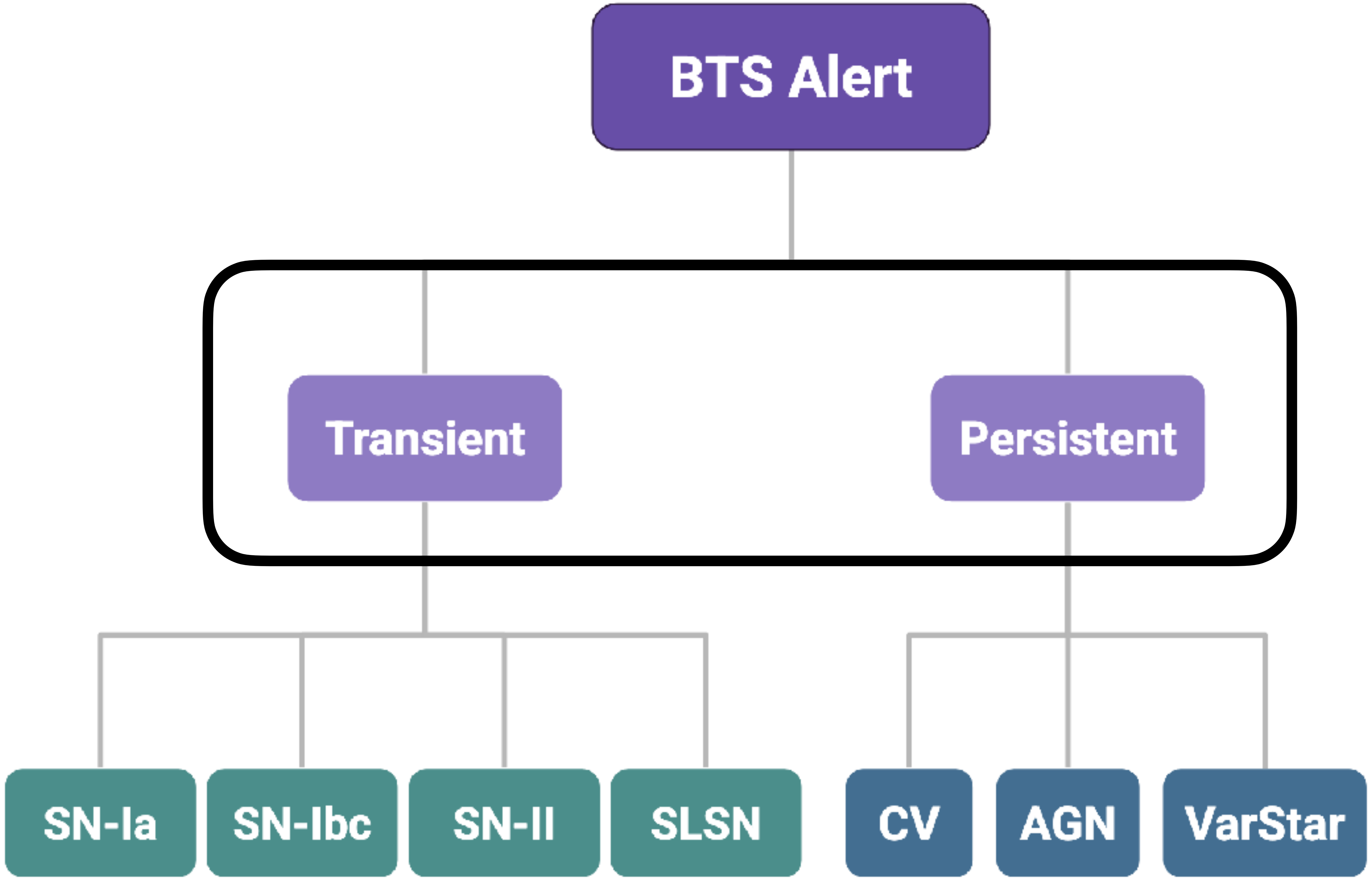

Shah+26

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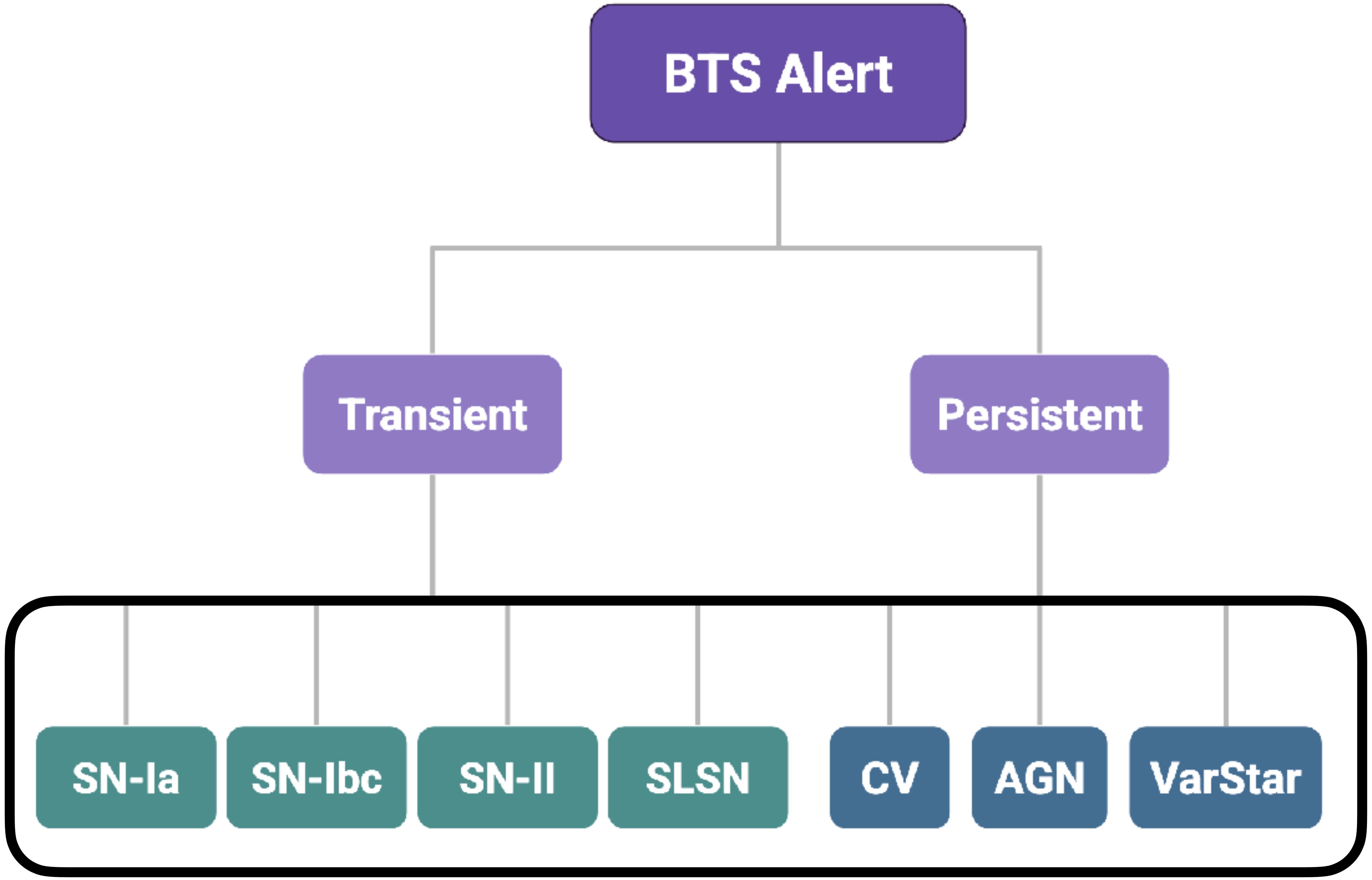
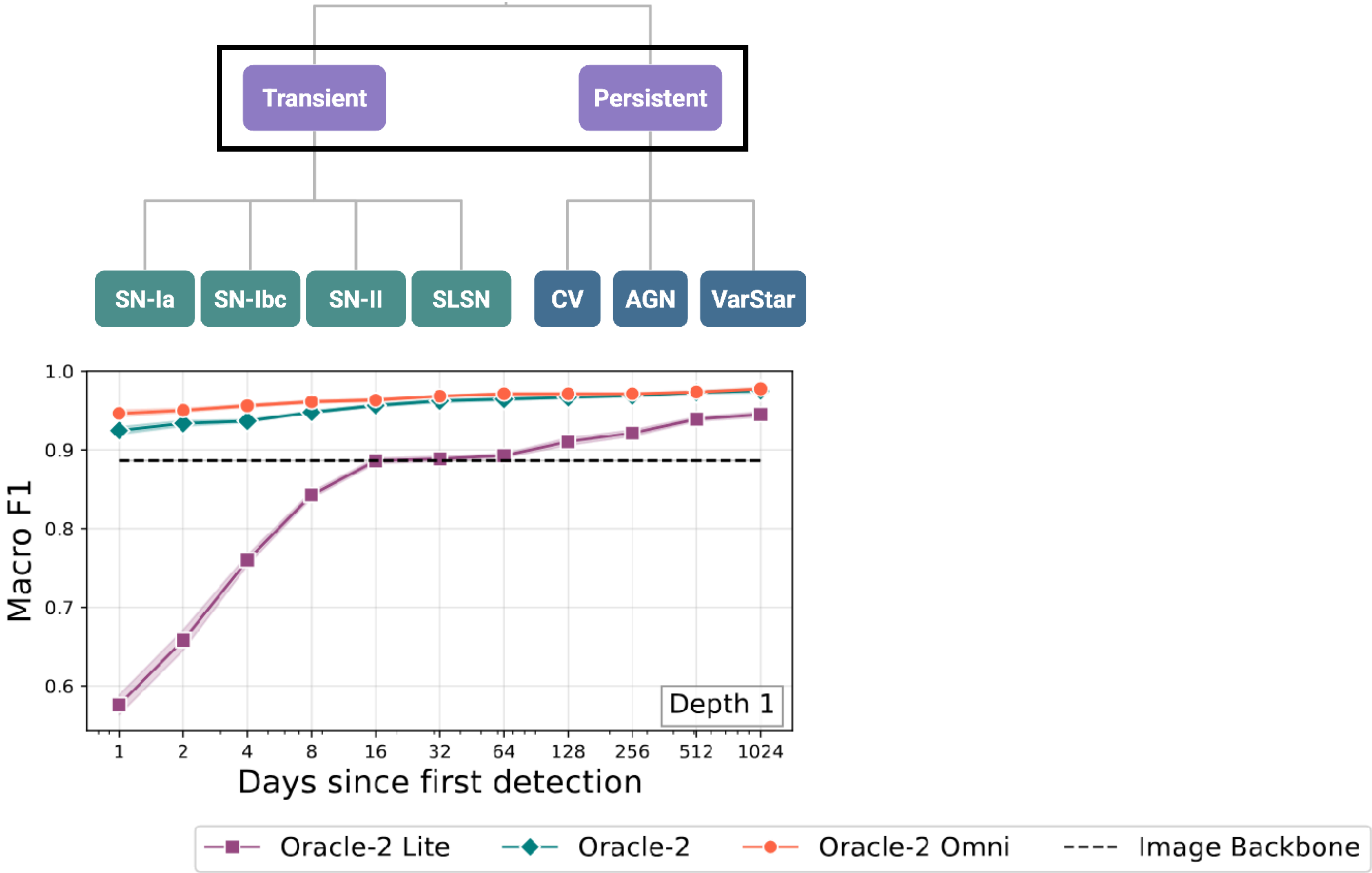


Shah+26

Real time performance for ZTF



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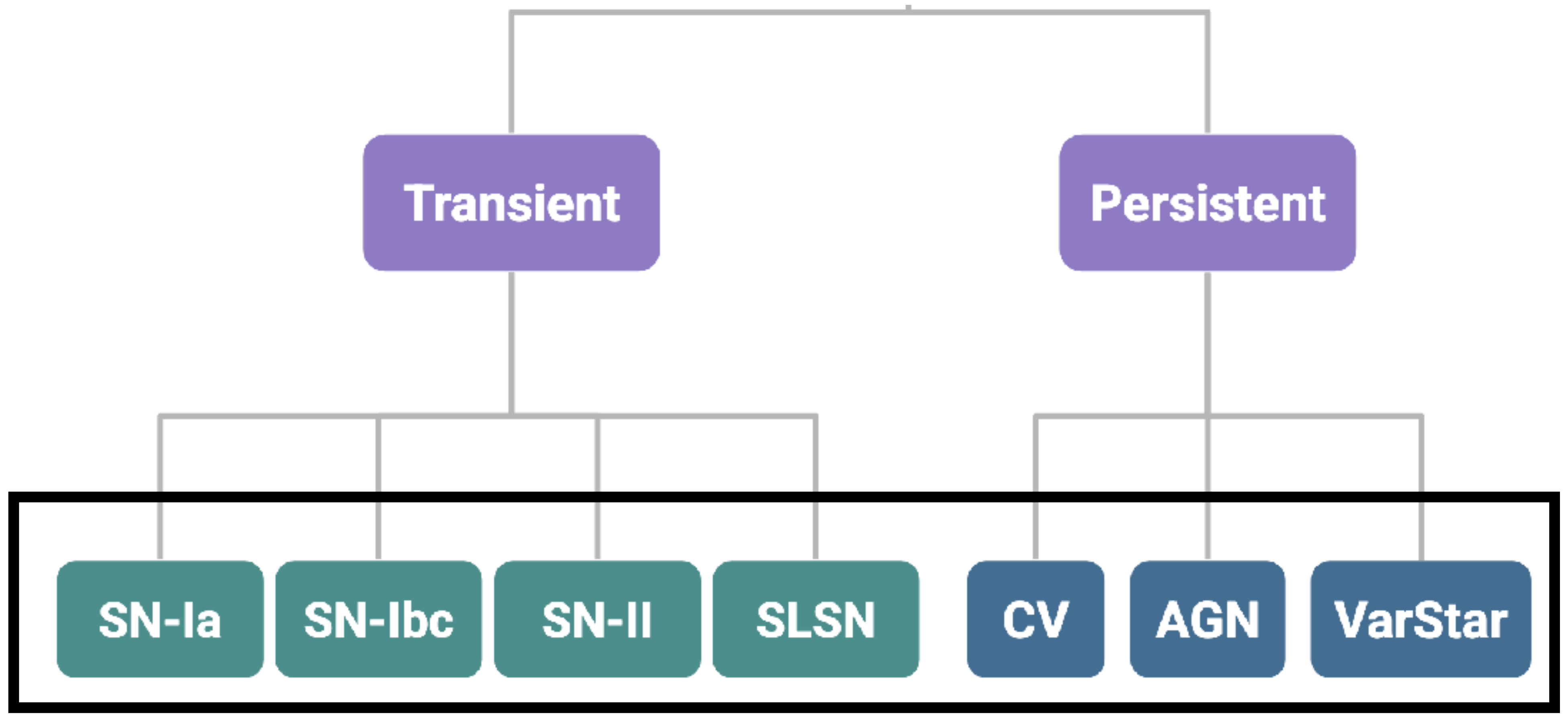

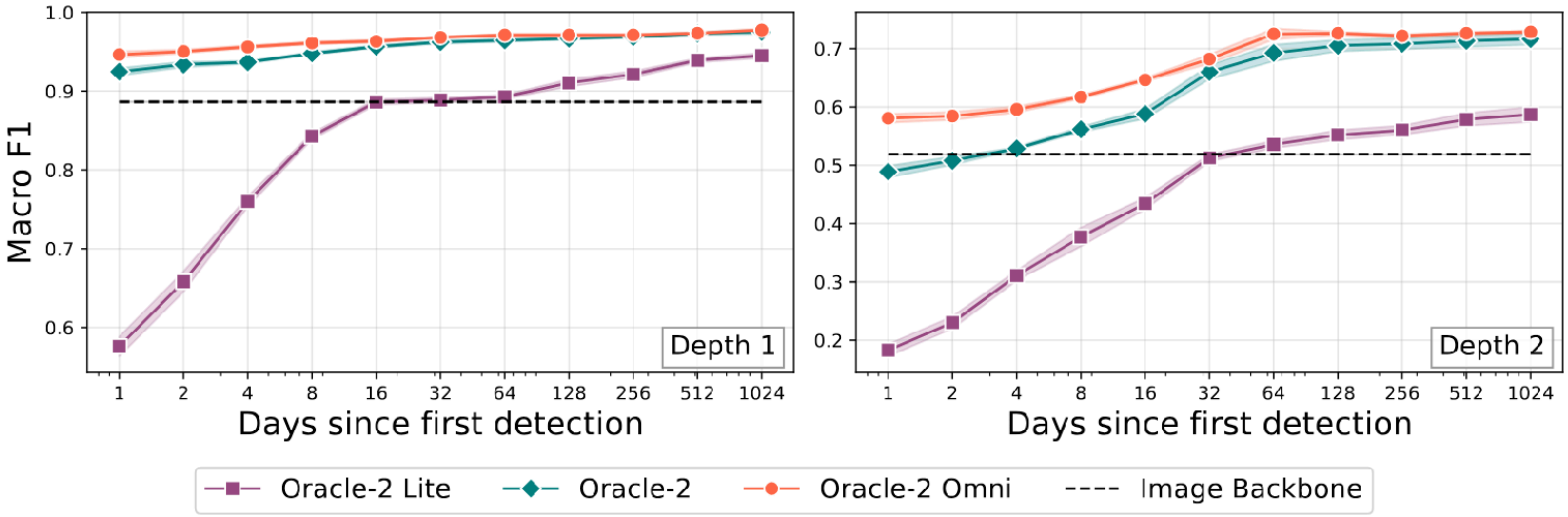

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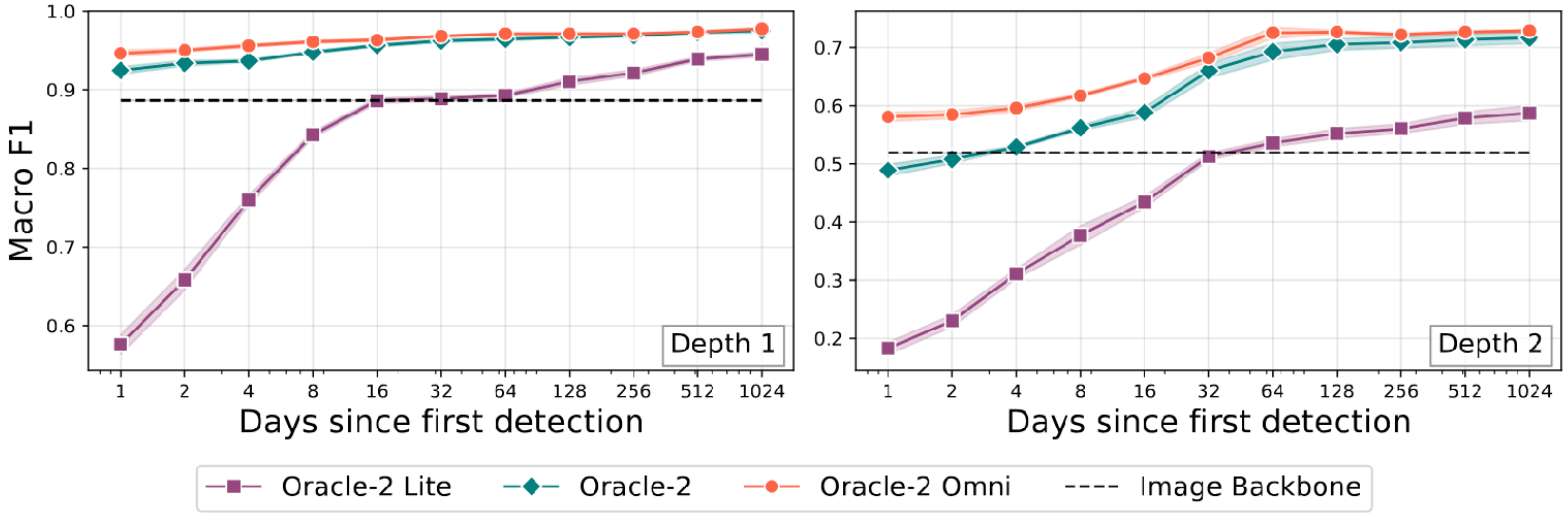
Real time performance for ZTF

Oracle-2 Omni > Oracle-2 > Oracle-2 Lite



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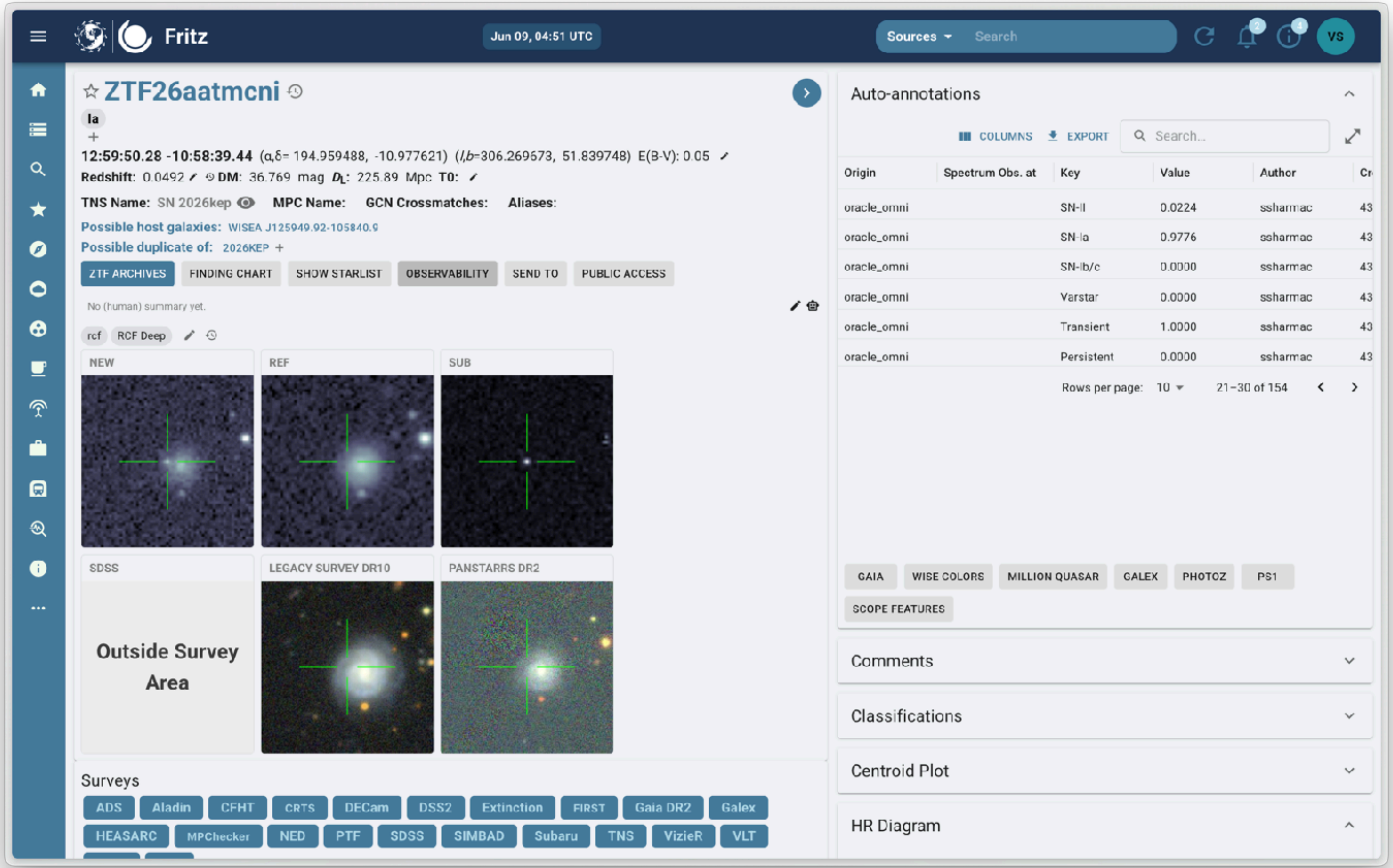
5. Real-time Deployment and Early Science

Real-time Deployment



*In beta testing

Shah+26

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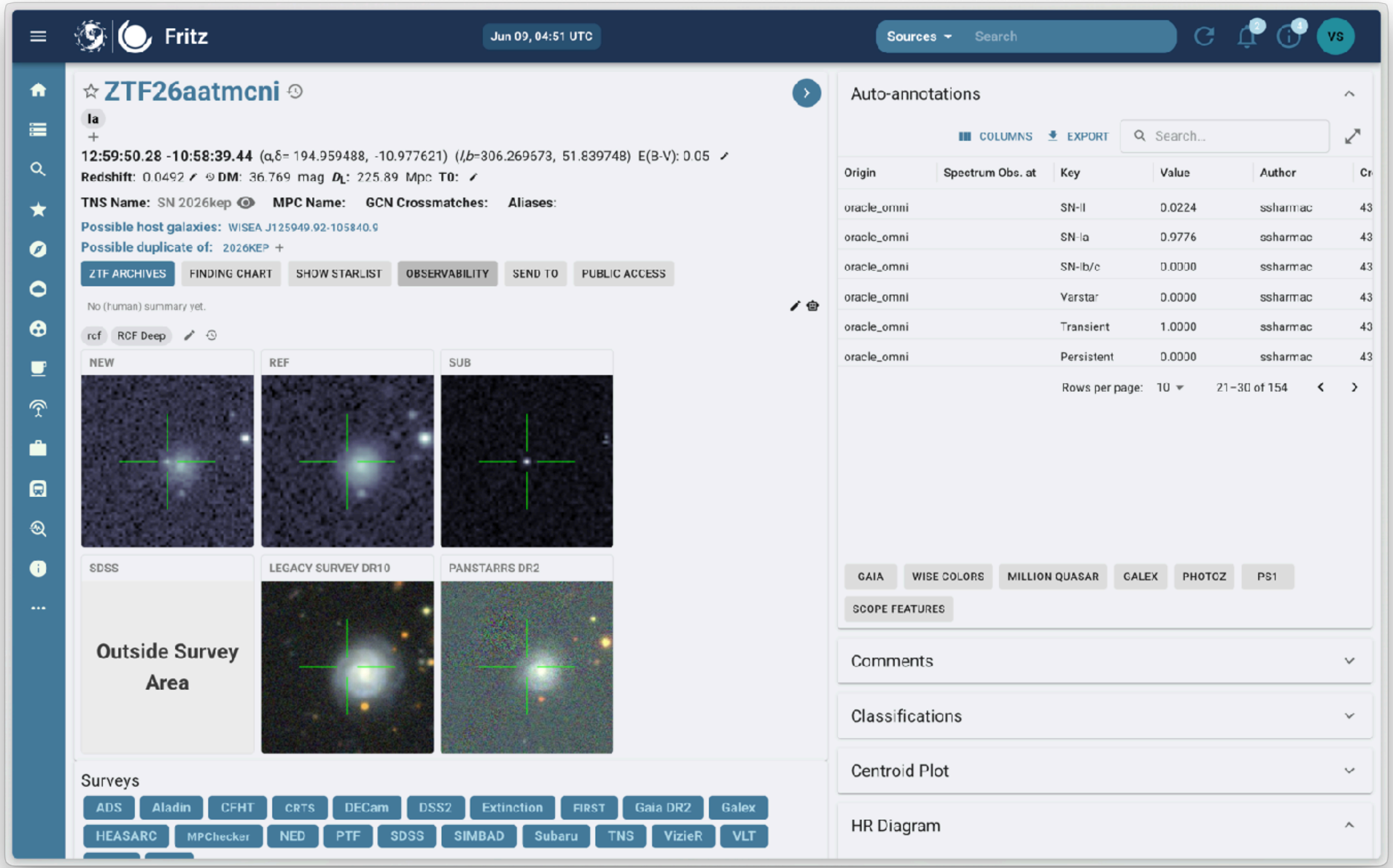

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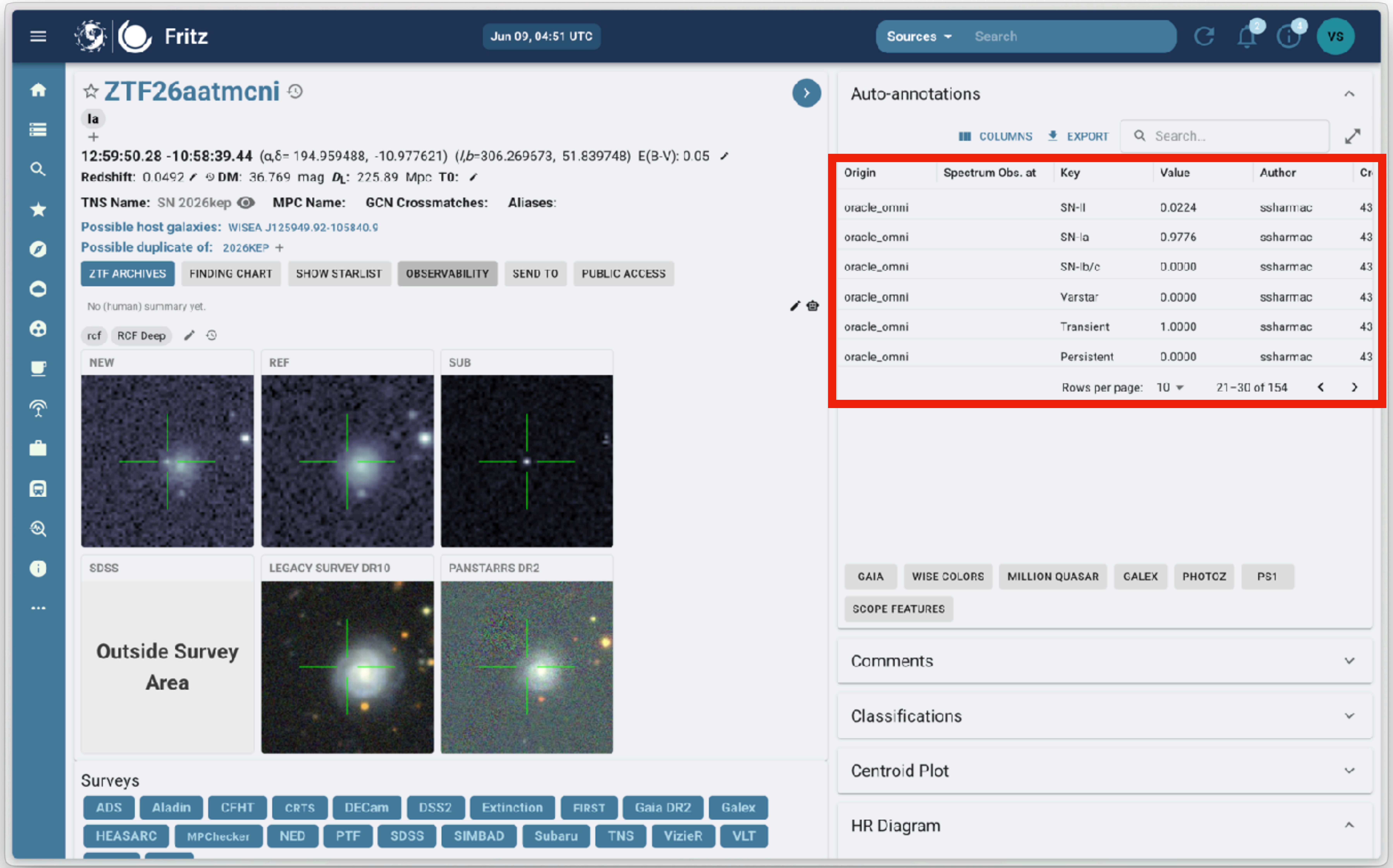

*In beta testing

Shah+26

Real-time Deployment

Origin	Spectrum Obs. at	Key	Value	Author	Cr
oracle_omni		SN-II	0.0224	ssharmac	43
oracle_omni		SN-Ia	0.9776	ssharmac	43
oracle_omni		SN-Ib/c	0.0000	ssharmac	43
oracle_omni		Varstar	0.0000	ssharmac	43
oracle_omni		Transient	1.0000	ssharmac	43
oracle_omni		Persistent	0.0000	ssharmac	43

Rows per page: 10 21–30 of 154

***In beta testing**

Real-time Deployment

Origin	Spectrum Obs. at	Key	Value	Author	Cr
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Rows per page: 10 21–30 of 154

***In beta testing**

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Real-time Deployment

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- Deployed on the ZTF alert stream since May 15, 2026.

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Shah+26

Real-time Deployment

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- Astronote for AT25amdo within 10 days of model deployment!

Shah+26

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- Classified more than 1000 unique sources.
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AstroNote 2026-201

AstroNotes Stats

2026-06-20 18:02:35 Type: Object/s-Discovery/Classification Bibcode: 2026TNSAN.201....1S

Late-Time Re-brightening of AT 2025amdo Identified by ORACLE-2 Omni

Authors: V. G. Shah, C. Liu, N. Rehemtulla, A. A. Miller (Northwestern, CIERA), J. Sollerman, and A. Singh (Stockholm University) on behalf of ZTF

Source Group: ZTF

Keywords: Photometry , Spectroscopy , Supernova

Abstract: We report a late-time re-brightening of AT 2025amdo (~185 days after the initial peak) identified by ORACLE-2 Omni, a multimodal hierarchical classifier developed for real-time monitoring of the Zwicky Transient Facility (ZTF) alert stream.

AT 2025amdo (ZTF25acelynx) is a supernova candidate (z = 0.0800, DM ≈ 37.87; DESI) first discovered on 2025-11-23 22:19:12 UTC by the Wide Field Survey Telescope (WFST). In this AstroNote, we report the ORACLE-2 Omni (Shah et al. 2025) aided identification of a dramatic re-brightening event that appears to peak approximately 185 days after the primary maximum, reaching a brightness roughly 0.85 magnitudes brighter (ZTF r = 19.02 mag, M = −18.85 mag) than the initial peak (ZTF r = 19.86 mag, M = −18.01 mag). All magnitudes have been corrected for Milky Way extinction but **do not** account for host extinction. We also report forced-photometry 3-sigma detections (Masci et al. 2023) throughout the interval (ZTF r ≈ 21.5 mag, M ≈ −16.5 mag) between the decline of the first peak and the onset of the secondary brightening, indicating persistent emission over this period.

The light curve bears notable similarities to previously reported double-peaked stripped-envelope supernovae, such as SN 2023aew (Sharma et al. 2024 ; Kangas et al. 2024), although the delay between the two peaks in AT 2025amdo is approximately twice as long.

We obtained a spectrum of the transient using the Alhambra Faint Object Spectrograph and Camera (ALFOSC) on the Nordic Optical Telescope (NOT) following the re-brightening. Spectral template matching using SNID-Sage (Stoppa et al. 2026) shows reasonable agreement with late-time Type Ia/c templates and, in particular, similarity to the peculiar double-peaked SN 2023aew around its second peak.

Given the unusual photometric evolution and the ambiguity in the current spectroscopic classification, we encourage additional follow-up observations.

This AstroNote is based on observations obtained with the Samuel Oschin 48-inch Telescope and the 60-inch Telescope at Palomar Observatory as part of the Zwicky Transient Facility

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6. Summary

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- Adding **multi-modal inputs** can **significantly improve performance, especially at early times,** without adding any labelling cost
- Hierarchical classification gives us a way to build in **astrophysical structure and taxonomies into the classification problem** and can replace an entire ecosystem of classifiers with a single model

Thank you!

Hierarchical Classification

Shah et al. (2025b)

Multimodality

Shah et al (2026)

GitHub https://github.com/dev-ved30/Oracle

https://huggingface.co/collections/vedshah30/oracle

SkAI
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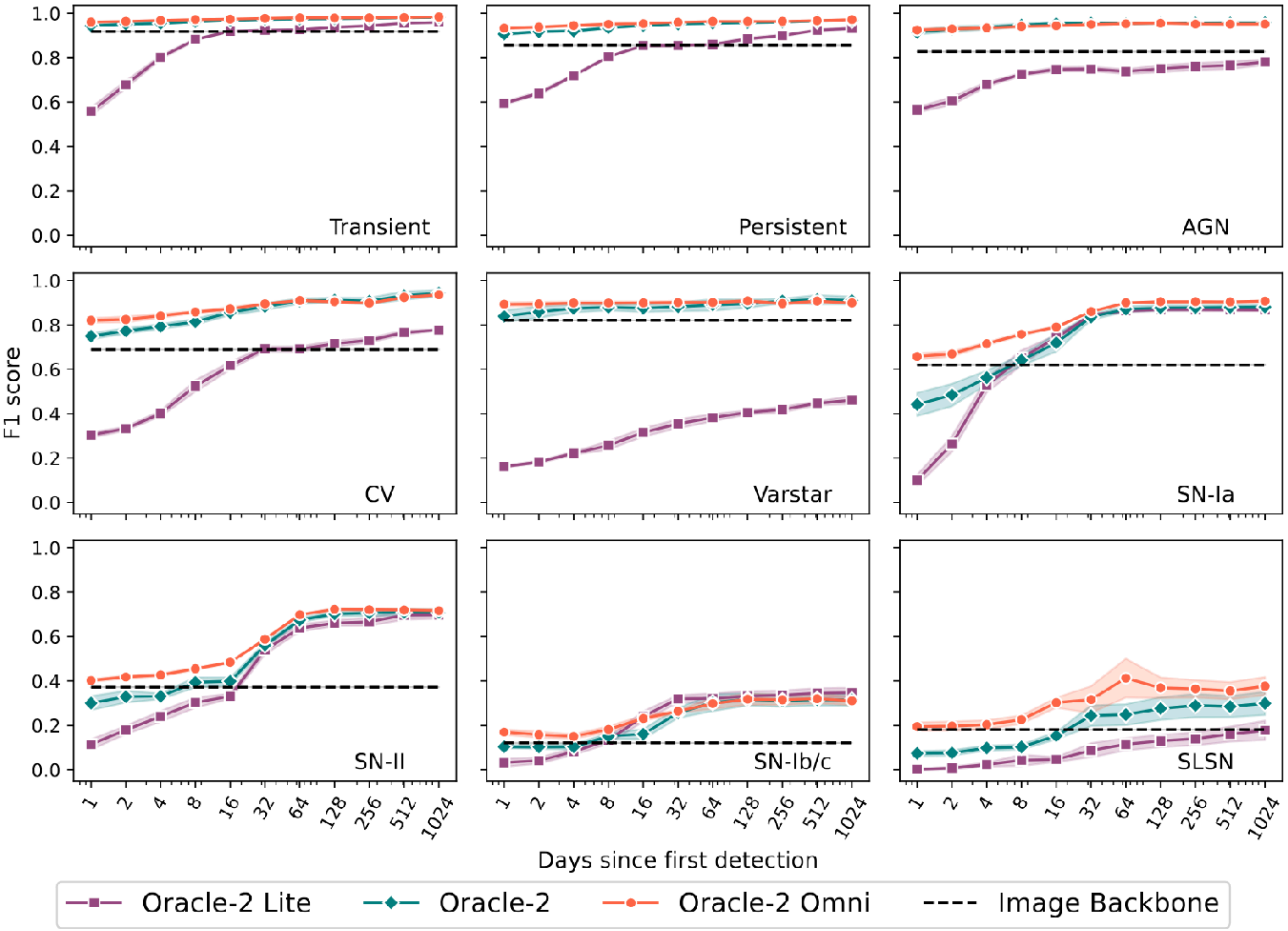
Northwestern University

Northwestern CIERA
CENTER FOR INTERDISCIPLINARY EXPLORATION AND RESEARCH IN ASTROPHYSICS

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Questions?


F1 score
Transient
Persistent
AGN
CV
Varstar
SN-Ia
SN-II
SN-Ib/c
SLSN
1.0
0.8
0.6
0.4
0.2
0.0
1
2
4
8
16
32
64
128
256
512
1024
Days since first detection
Oracle-2 Lite
Oracle-2
Oracle-2 Omni
Image Backbone

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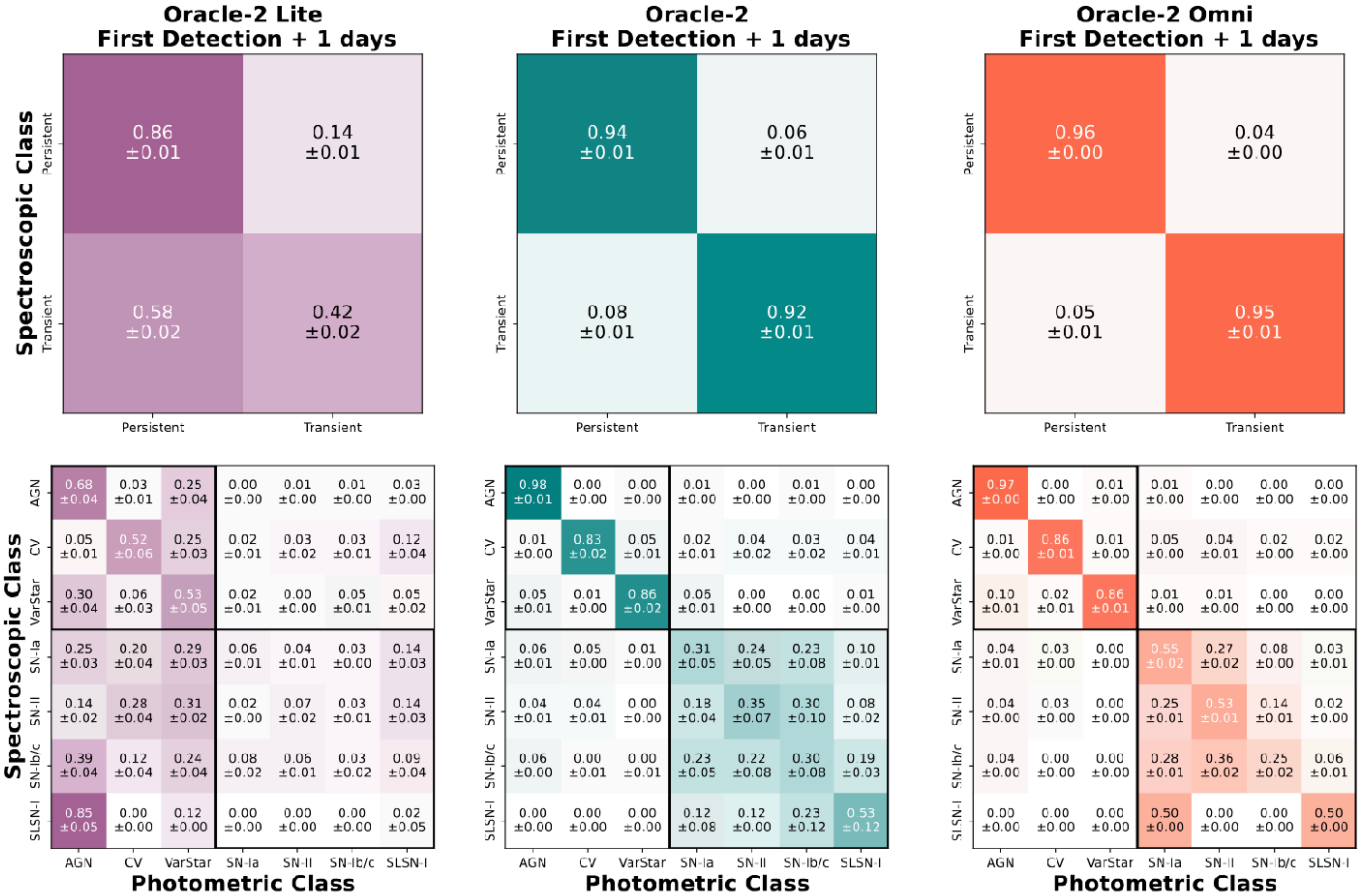
Confusion matrices at 1 day



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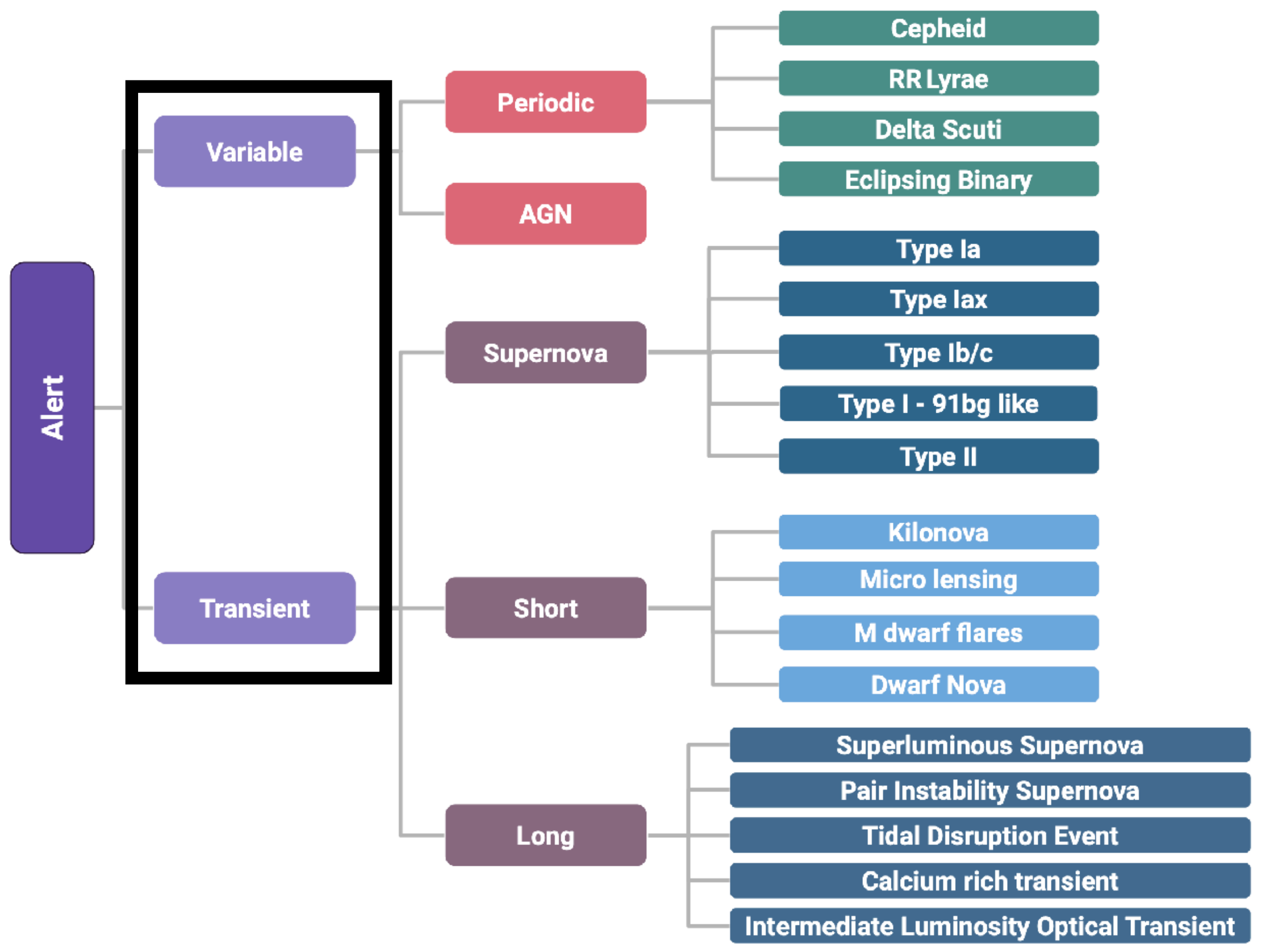
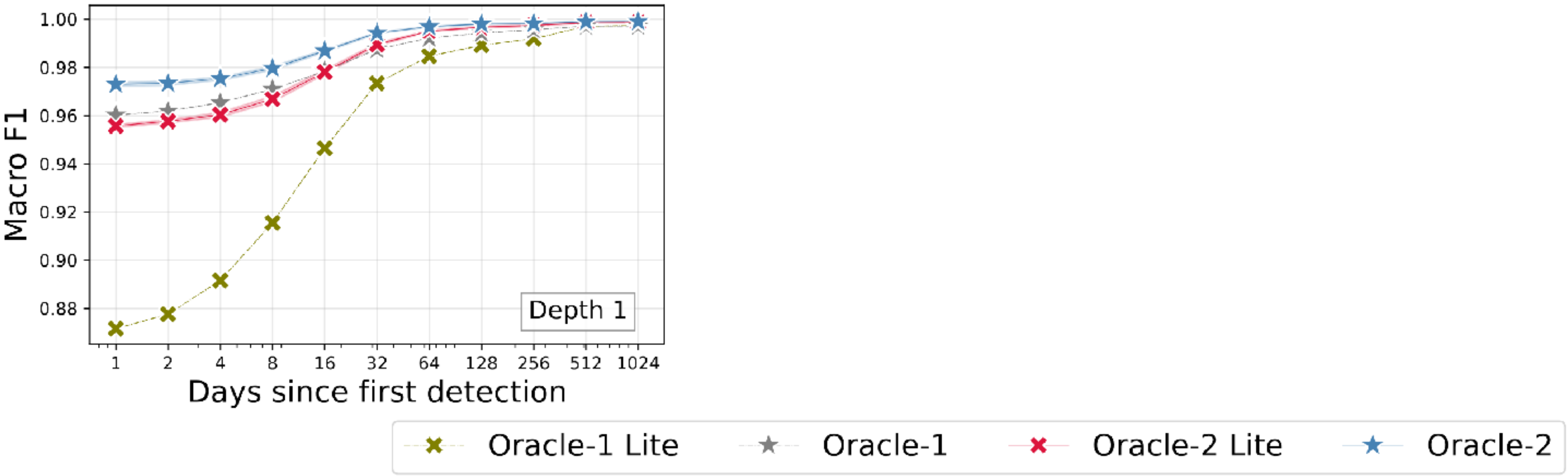
Multi-modal Architecture

4. Results for LSST (using ELAsTiCC)

Real time performance on ELAsTiCC





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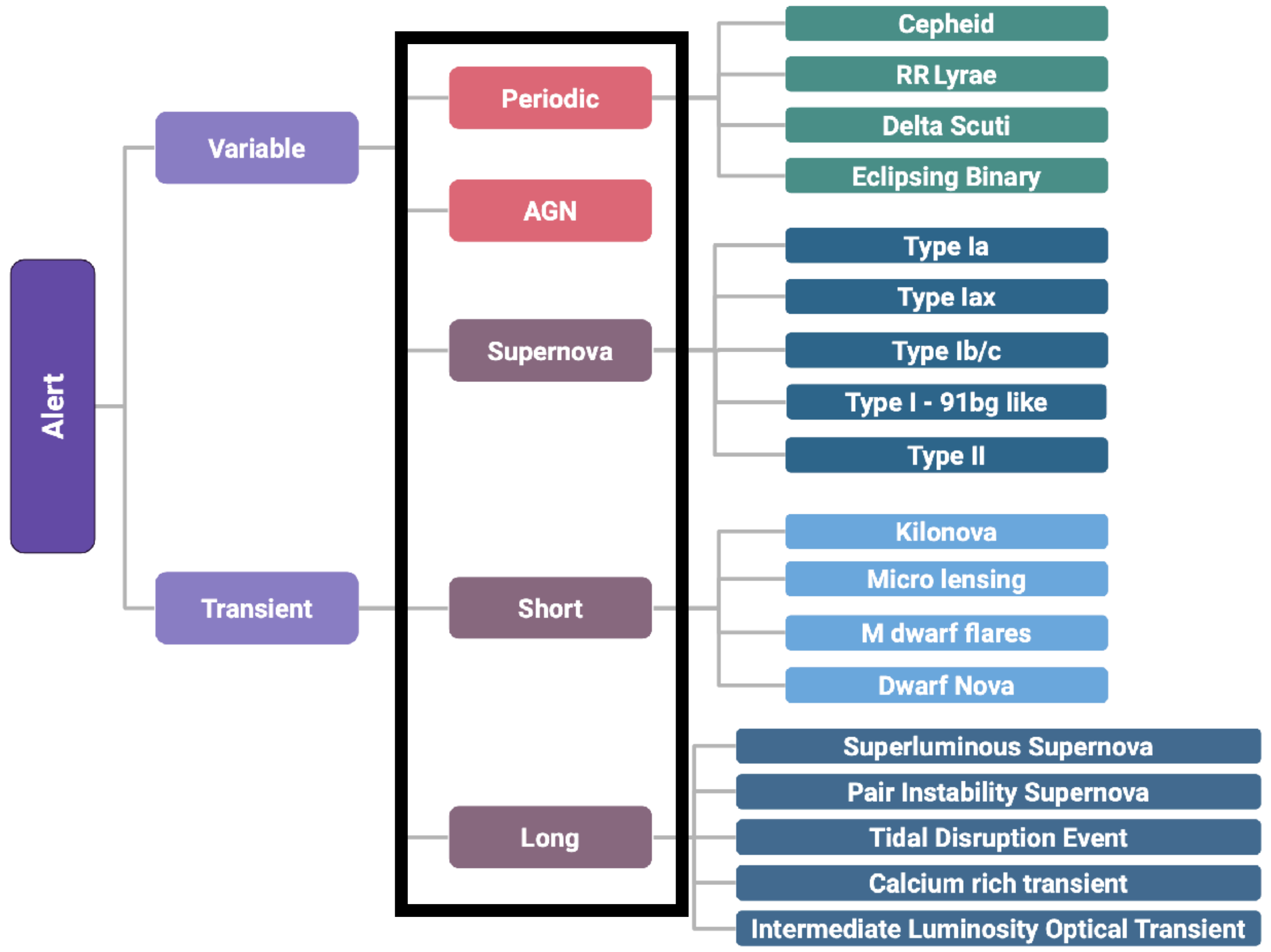
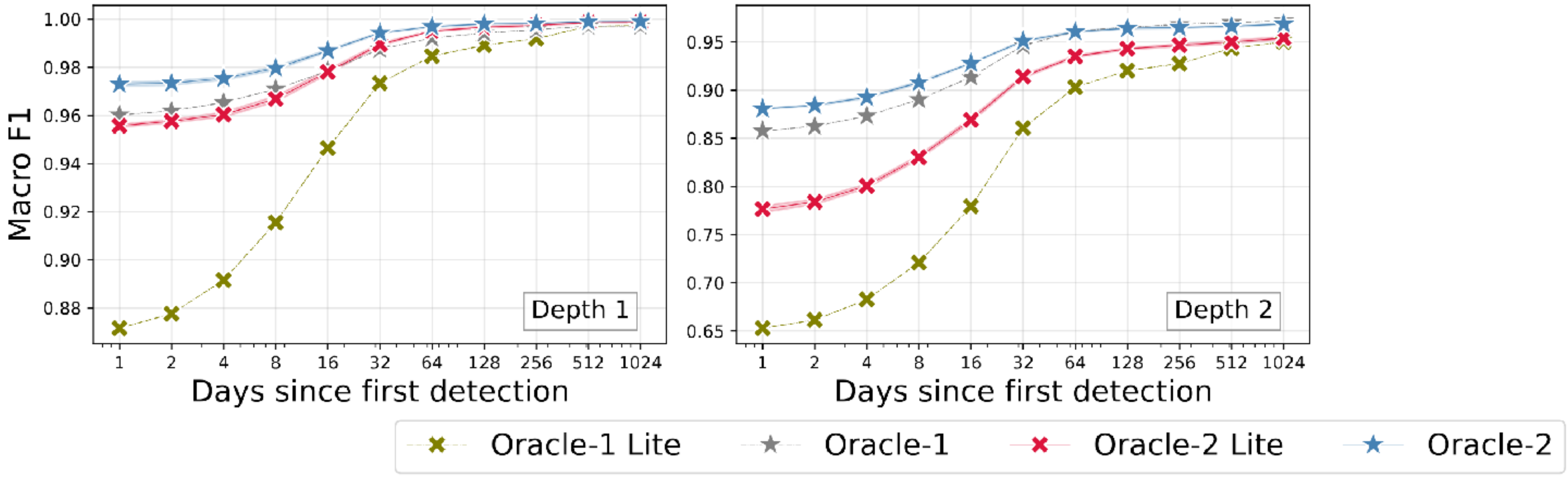
Real time performance on ELAsTiCC





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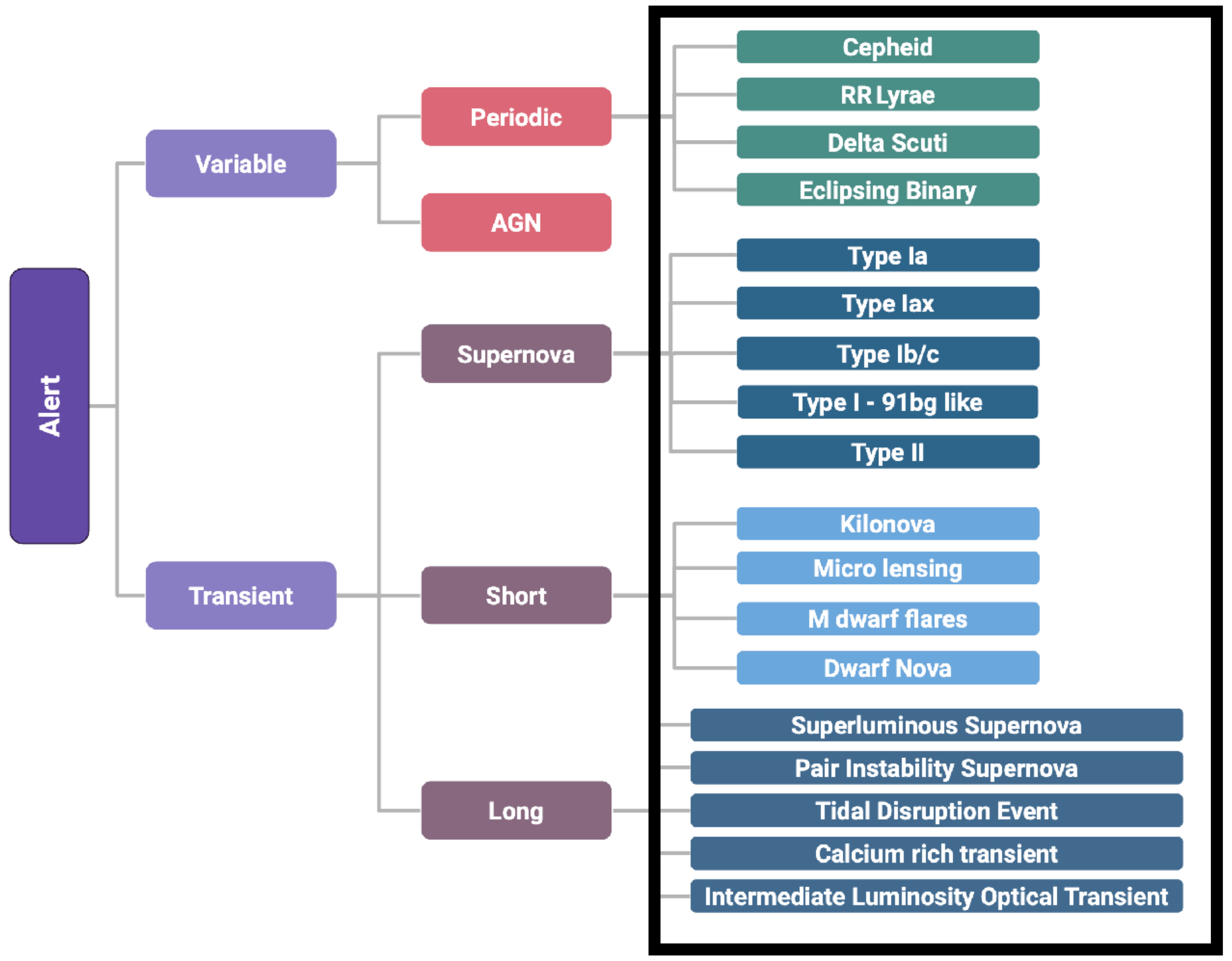
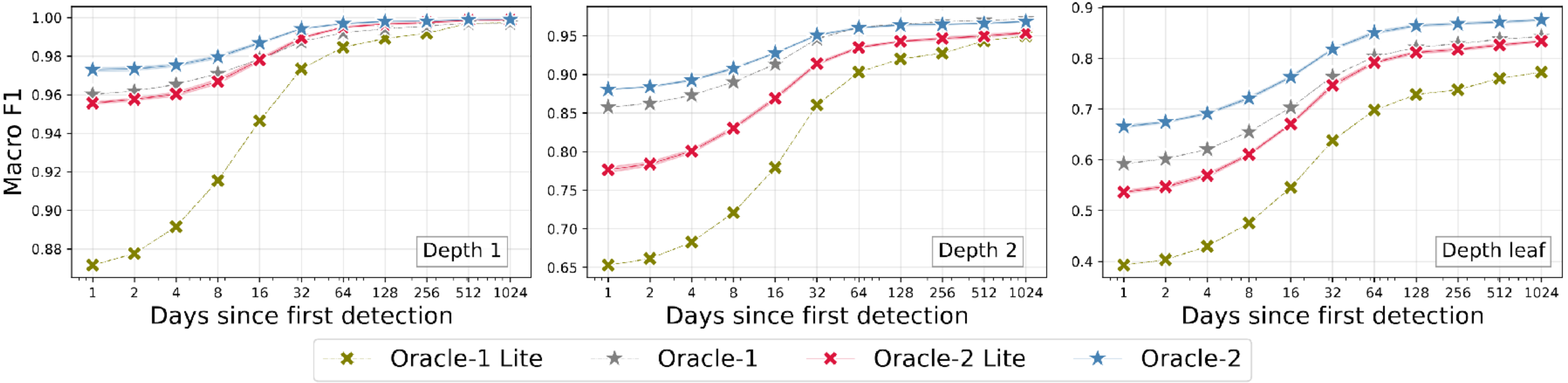
Real time performance on ELAsTiCC





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Dataset

ELAsTiCC for LSST:

- Used ~500,000 simulated sources from the ELAsTiCC data set across 19 classes.
- 70:30% split for training/testing. 5% of the training data for left aside for validation.
- Combination of light curves and metadata.

ZTF:

- Used ~15,000 transients and variables from ZTF organized across 7 classes.
- 80%/10%/10% split for train/test/validation.
- Combination of light curves, metadata, and images.

Data Augmentation

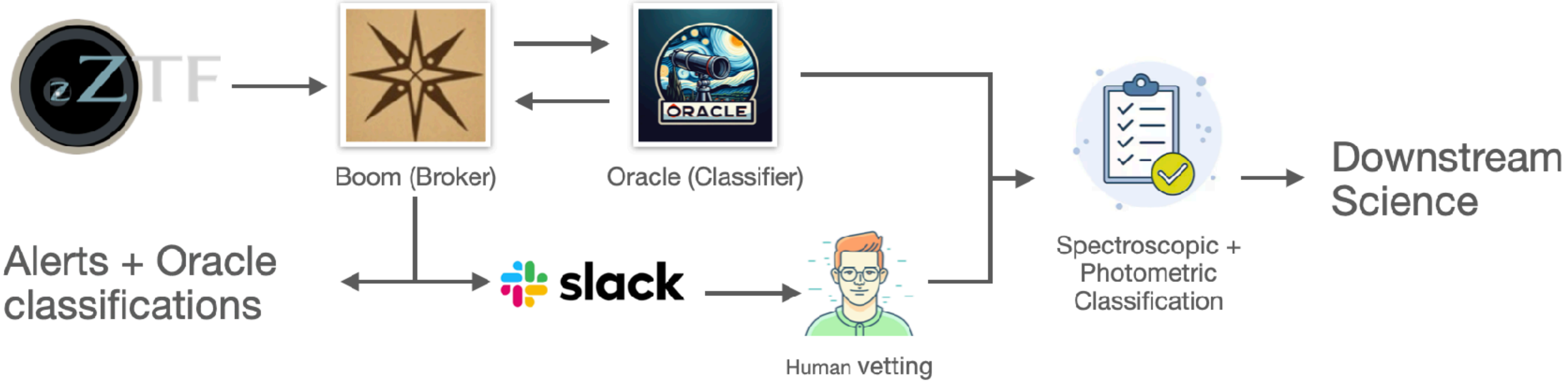
- Since we want **Oracle** to classify observations in real time, we explicitly trained the model to classify partial light curves.
- For the omni models, we add random rotations and flips to the images in order to promote rotational invariance and prevent overfitting.

Hyperparameters

Parameter	Value
Epochs	1000
Batch Size	1024
Learning rate	2e-4
Non linearity	tanh, ReLU
Optimizer	Adam
Alpha (For loss function)	0.5

Table 4. Hyper-parameters used for training ORACLE.

Real-time Deployment



*In beta testing

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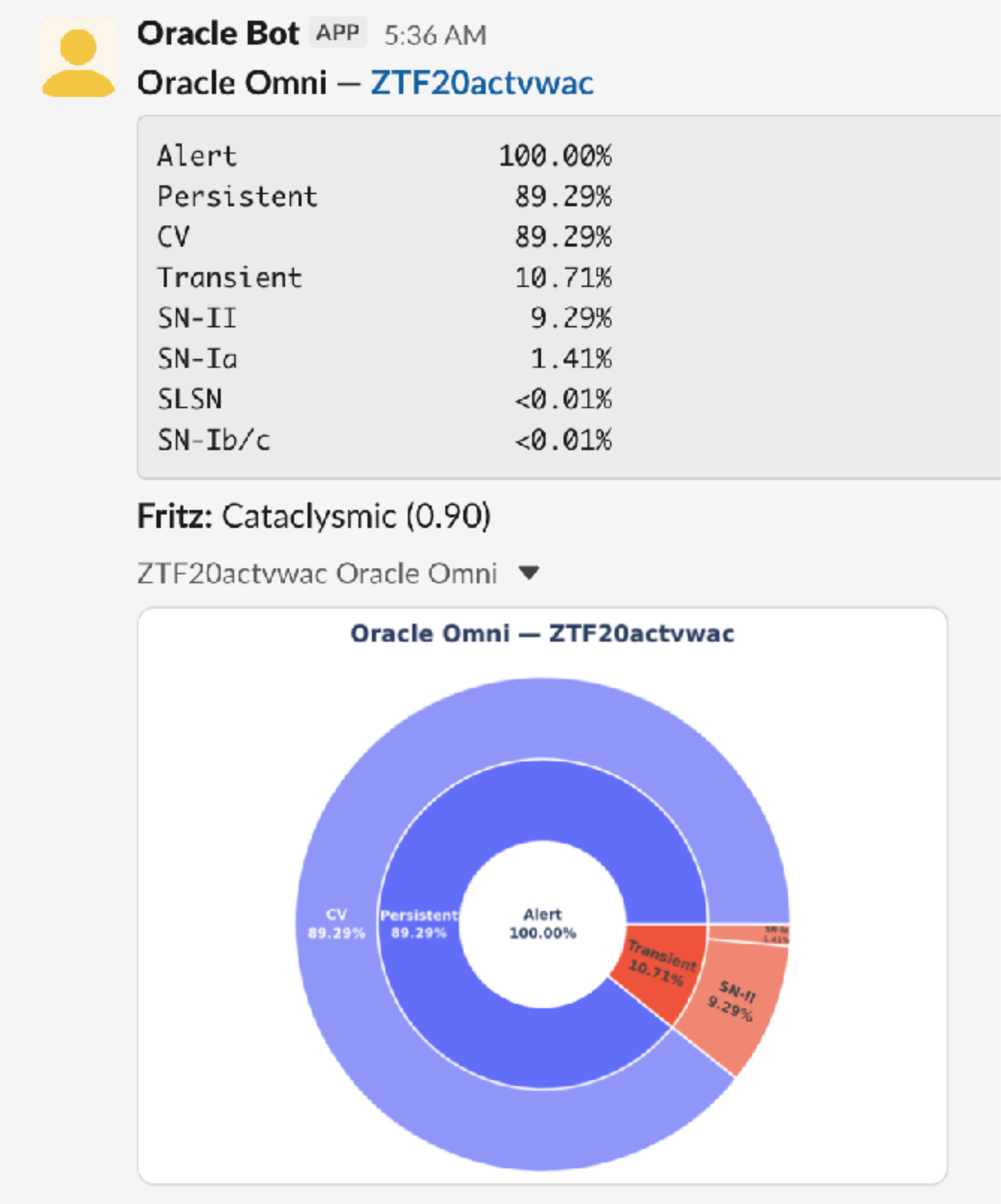
Real-time Deployment



***In beta testing**

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Real-time Deployment

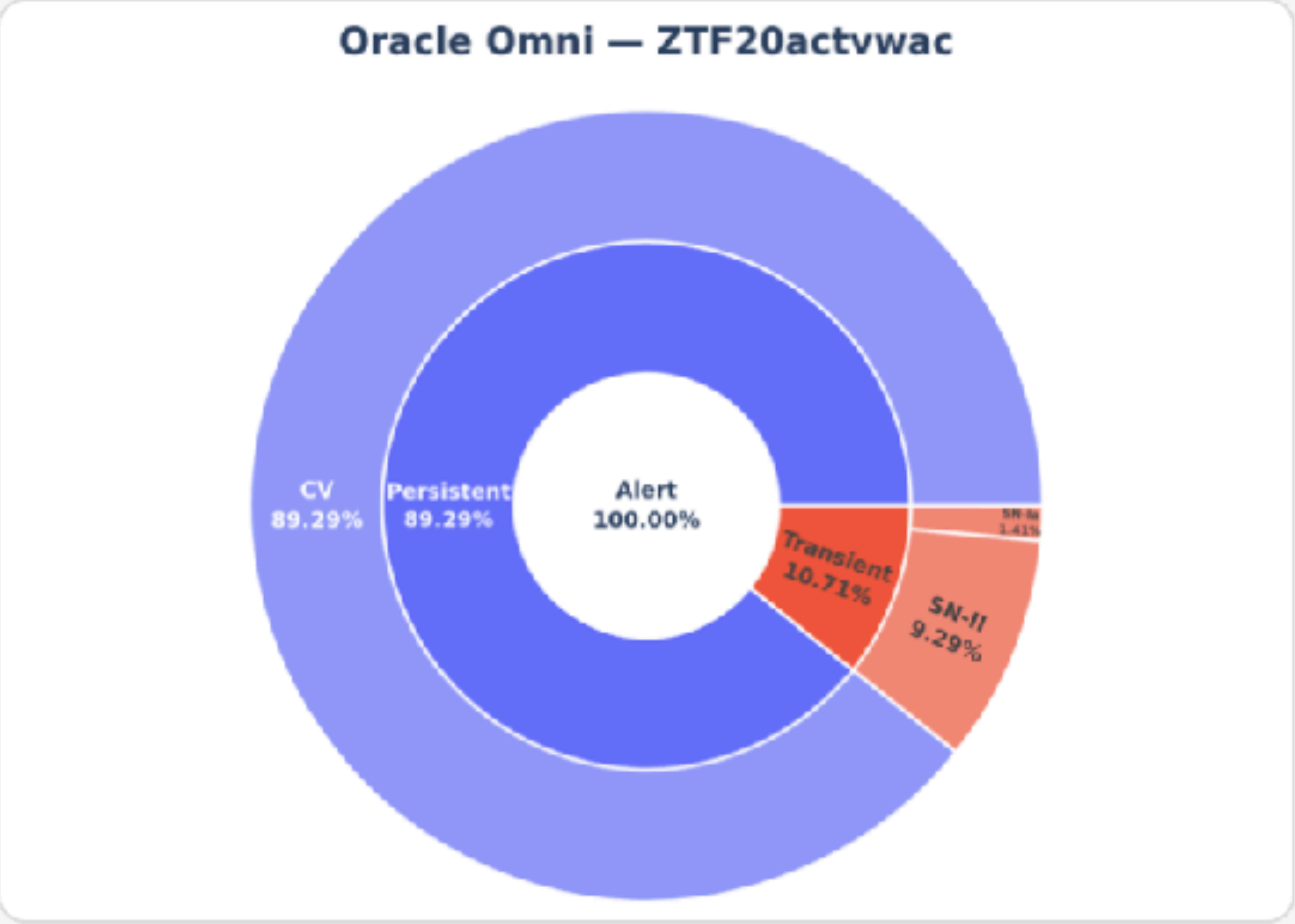
Oracle Bot APP 5:36 AM

Oracle Omni — ZTF20actvwac

Alert	100.00%
Persistent	89.29%
CV	89.29%
Transient	10.71%
SN-II	9.29%
SN-Ia	1.41%
SLSN	<0.01%
SN-Ib/c	<0.01%

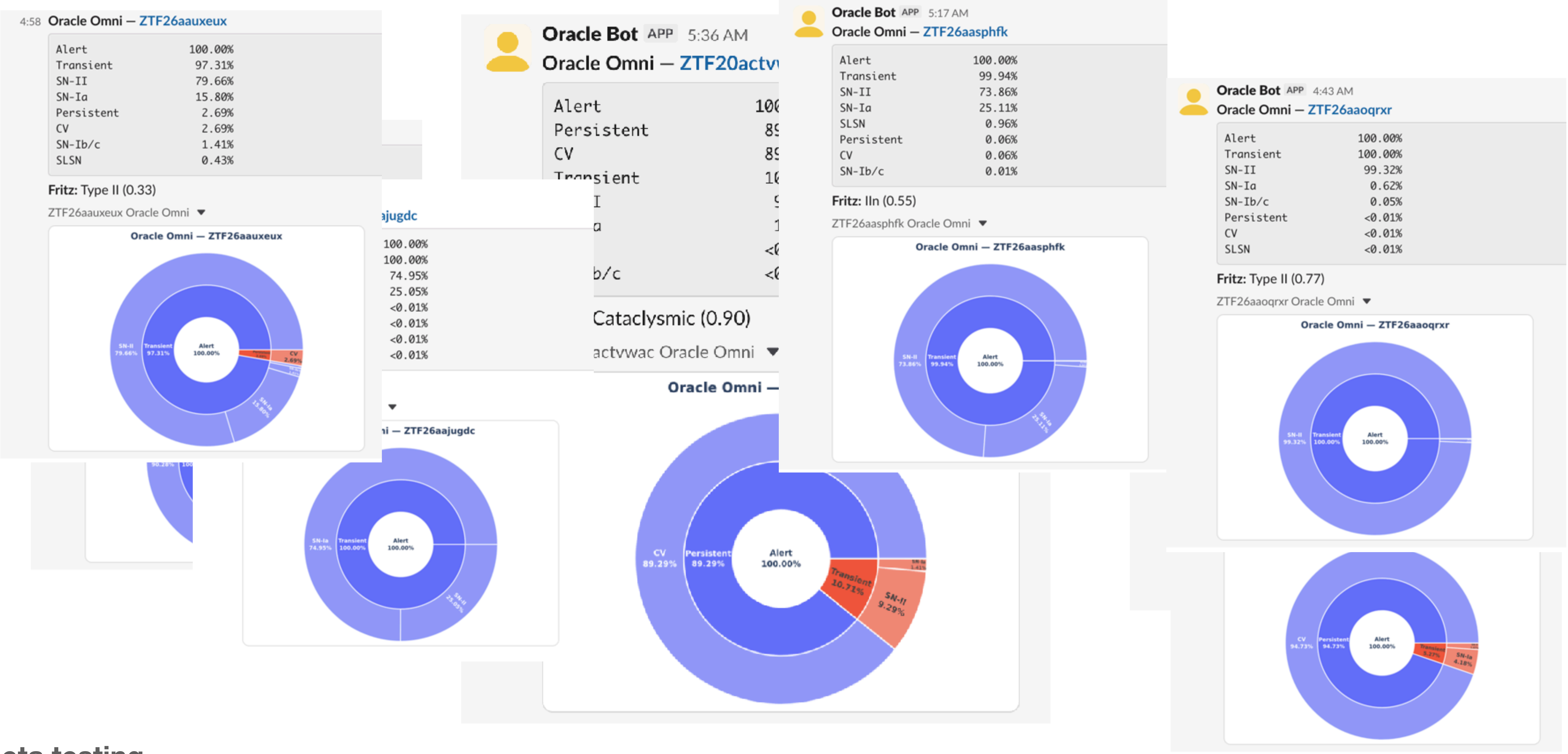
Fritz: Cataclysmic (0.90)

ZTF20actvwac Oracle Omni ▼



*In beta testing

Real-time Deployment



*In beta testing