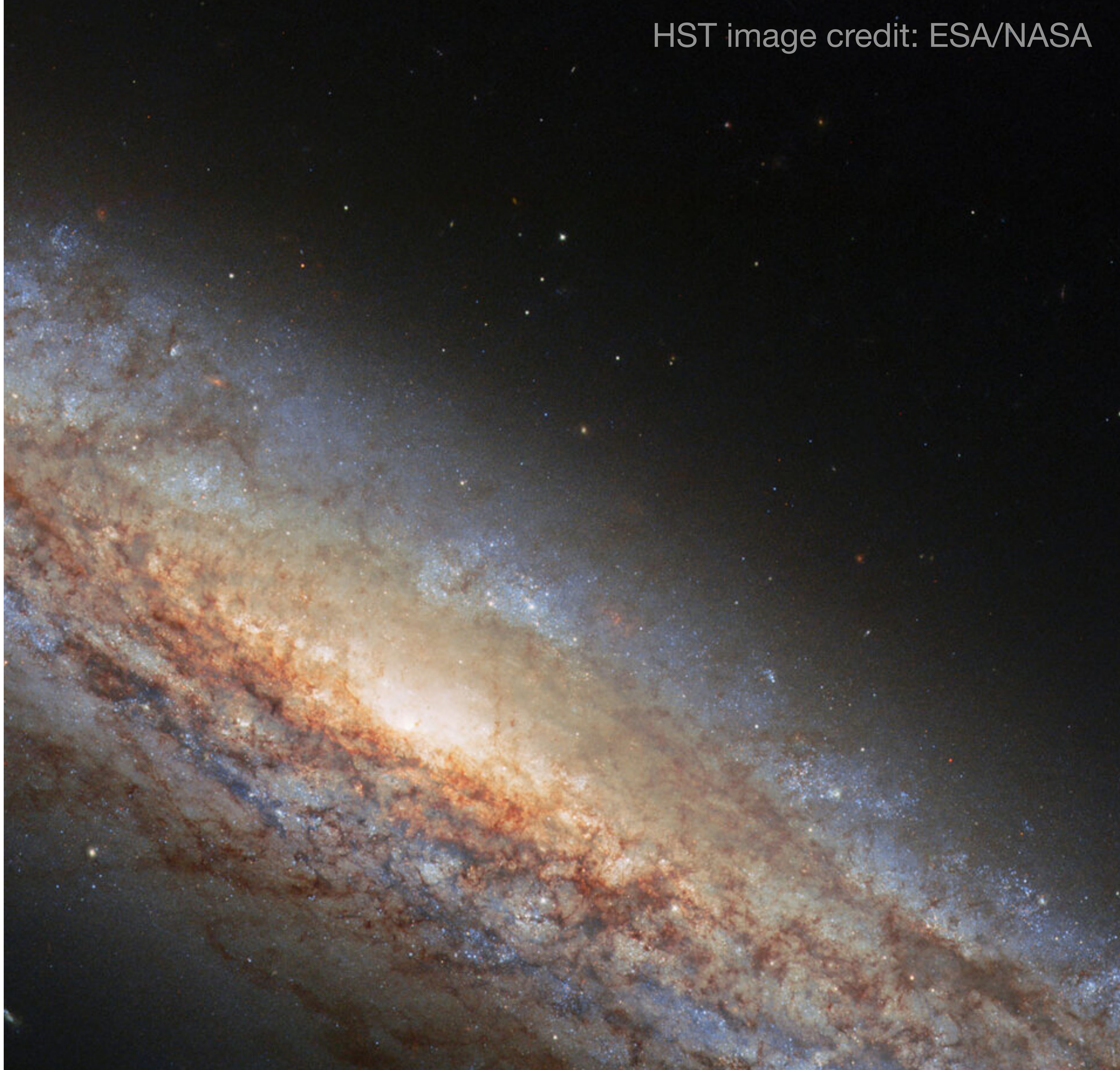
# Nuclear Transients in ZTF

**O4 Workshop**
**May 9, 2023**




**Simeon Reusch**

# I) ZTF 🔭

**It has been an exciting few years for the study of nuclear transients!**

# First ZTF TDE

van Velzen+ 2019

The Astrophysical Journal, 872:198 (11pp), 2019 February 20 https://doi.org/10.3847/1538-4357/aafe0c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## The First Tidal Disruption Flare in ZTF: From Photometric Selection to Multi-wavelength Characterization

Sjoert van Velzen[1,2], Suvi Gezari[1,3], S. Bradley Cenko[3,4], Erin Kara[1,3,5], James C. A. Miller-Jones[6], Tiara Hung[1], Joe Bright[7], Nathaniel Roth[1,3], Nadejda Blagorodnova[8], Daniela Huppenkothen[9], Lin Yan[10], Eran Ofek[11], Jesper Sollerman[12], Sara Frederick[1], Charlotte Ward[1], Matthew J. Graham[8], Rob Fender[7], Mansi M. Kasliwal[8], Chris Canella[8], Robert Stein[13], Matteo Giomi[14], Valery Brinnel[14], Jakob van Santen[13], Jakob Nordin[14], Eric C. Bellm[9], Richard Dekany[15], Christoffer Fremling[8], V. Zach Golkhou[9,16], Thomas Kupfer[8,17,18], Shrinivas R. Kulkarni[8], Russ R. Laher[19], Ashish Mahabal[8,20], Frank J. Masci[21], Adam A. Miller[22,23], James D. Neill[8], Reed Riddle[15], Mickael Rigault[24], Ben Rusholme[21], Maayane T. Soumagnac[25], and Yutaro Tachibana (優太朗橘)[26,27]

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# 29 more

THE ASTROPHYSICAL JOURNAL, 908:4 (26pp), 2021 February 10
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https://doi.org/10.3847/1538-4357/abc258

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**Seventeen Tidal Disruption Events from the First Half of ZTF Survey Observations: Entering a New Era of Population Studies**

Sjoert van Velzen[1,2], Suvi Gezari[1,3], Erica Hammerstein[1], Nathaniel Roth[1,3], Sara Frederick[1], Charlotte Ward[1], Tiara Hung[4], S. Bradley Cenko[3,5], Robert Stein[6], Daniel A. Perley[7], Kirsty Taggart[7], Ryan J. Foley[4], Jesper Sollerman[8], Nadejda Blagorodnova[9], Igor Andreoni[10], Eric C. Bellm[11], Valery Brinnel[12], Kishalay De[10], Richard Dekany[13], Michael Feeney[13], Christoffer Fremling[10], Matteo Giomi[14], V. Zach Golkhou[11,15], Matthew J. Graham[10], Anna. Y. Q. Ho[10], Mansi M. Kasliwal[10], Charles D. Kilpatrick[4], Shrinivas R. Kulkarni[10], Thomas Kupfer[15], Russ R. Laher[16], Ashish Mahabal[10,17], Frank J. Masci[16], Adam A. Miller[18,19], Jakob Nordin[12], Reed Riddle[13], Ben Rusholme[16], Jakob van Santen[6], Yashvi Sharma[10], David L. Shupe[16], and Maayane T. Soumagnac[20,21]

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February 20

https://doi.org/10.3847/1538-4357/aafe0c

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etric Selection to

Tiara Hung[1], Eran Ofek[11], Mansi M. Kasliwal[8], Eric C. Bellm[9], R. Kulkarni[8], Reed Riddle[15], 蔓太朗橘)[26,27]

van Velzen+ 2019

van Velzen+ 2021

# 29 more


van Velzen+ 2019

van Velzen+ 2021

Hammerstein+ 2021

# A jetted TDE


van Velzen+ 2019

van Velzen+ 2021

Hammerstein+ 2021

Andreoni+ 2022

# An extremely energetic TDE


van Velzen+ 2019

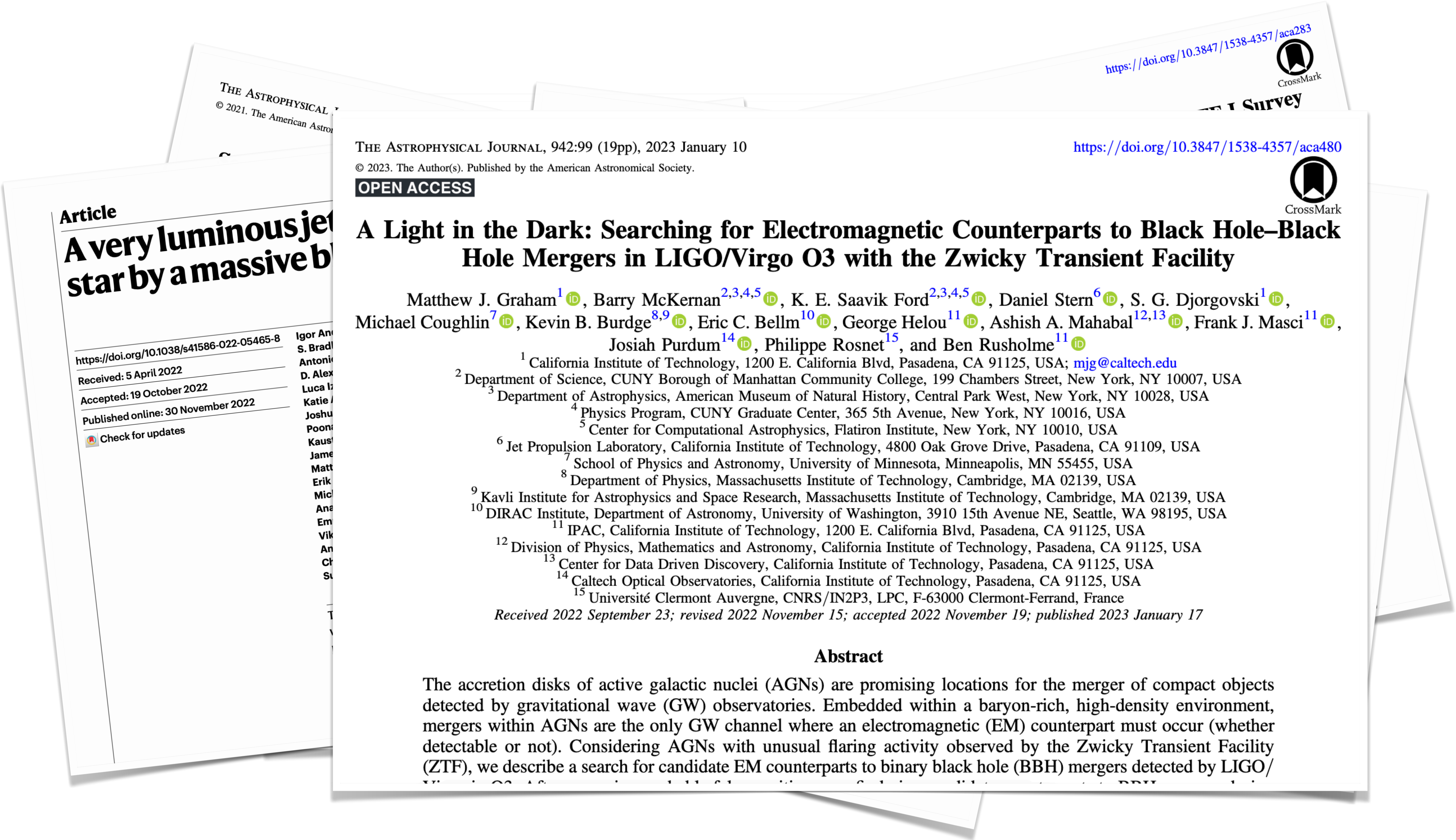
van Velzen+ 2021

Hammerstein+ 2021

Andreoni+ 2022

Subrayan+ 2023

# Possible EM counterparts to BH-BH mergers



The Astrophysical Journal, 942:99 (19pp), 2023 January 10 https://doi.org/10.3847/1538-4357/aca480


## A Light in the Dark: Searching for Electromagnetic Counterparts to Black Hole–Black Hole Mergers in LIGO/Virgo O3 with the Zwicky Transient Facility

Matthew J. Graham[1], Barry McKernan[2,3,4,5], K. E. Saavik Ford[2,3,4,5], Daniel Stern[6], S. G. Djorgovski[1], Michael Coughlin[7], Kevin B. Burdge[8,9], Eric C. Bellm[10], George Helou[11], Ashish A. Mahabal[12,13], Frank J. Masci[11], Josiah Purdum[14], Philippe Rosnet[15], and Ben Rusholme[11]
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**Abstract**

The accretion disks of active galactic nuclei (AGNs) are promising locations for the merger of compact objects detected by gravitational wave (GW) observatories. Embedded within a baryon-rich, high-density environment, mergers within AGNs are the only GW channel where an electromagnetic (EM) counterpart must occur (whether detectable or not). Considering AGNs with unusual flaring activity observed by the Zwicky Transient Facility (ZTF), we describe a search for candidate EM counterparts to binary black hole (BBH) mergers detected by LIGO/

van Velzen+ 2019

van Velzen+ 2021

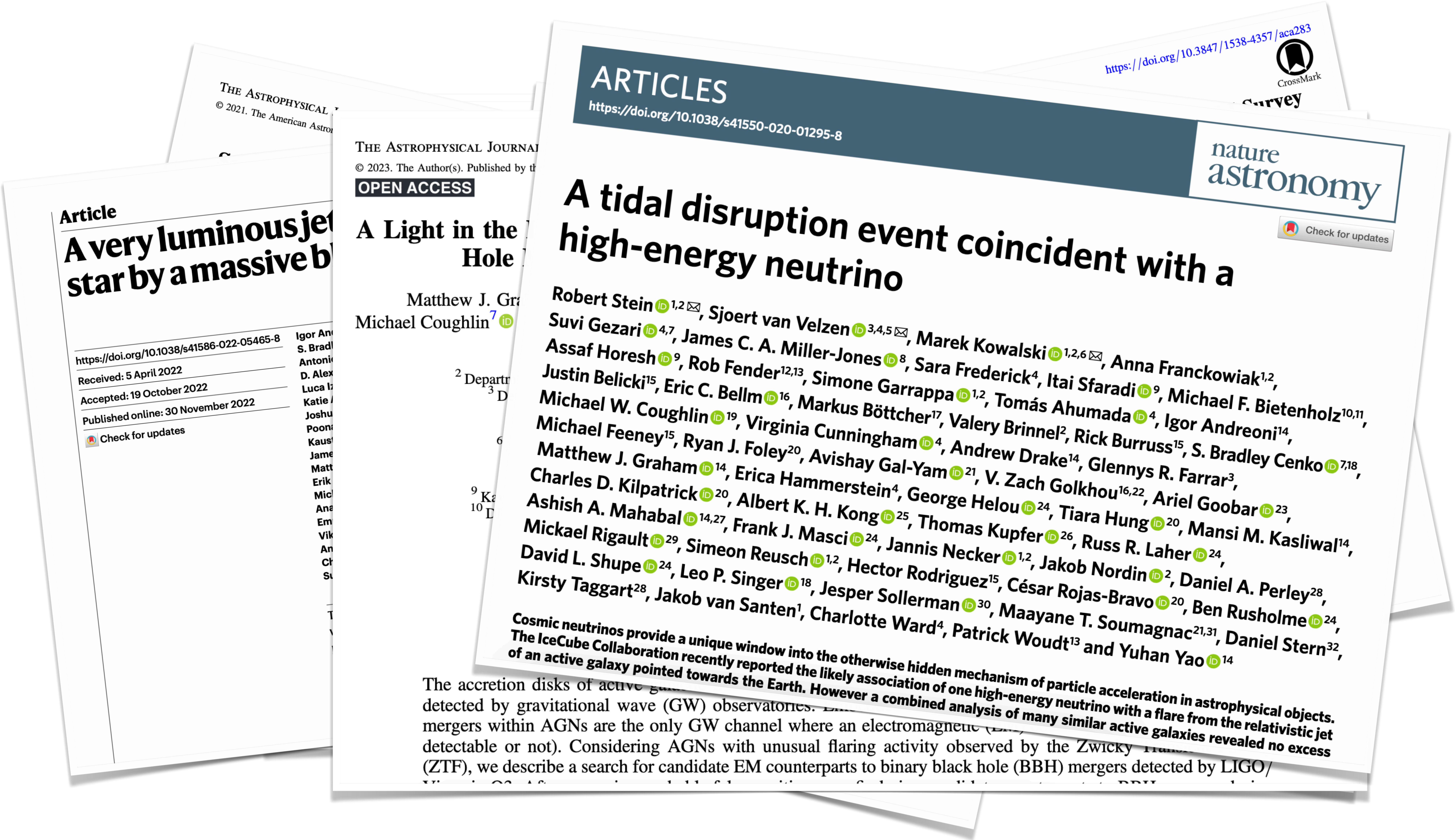
Hammerstein+ 2021

Andreoni+ 2022

Subrayan+ 2023

Graham+ 2023

# Three neutrino-associated TDE candidates


ARTICLES
https://doi.org/10.1038/s41550-020-01295-8

nature astronomy

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A tidal disruption event coincident with a high-energy neutrino

Robert Stein[1,2], Sjoert van Velzen[3,4,5], Marek Kowalski[1,2,6], Anna Franckowiak[1,2], Suvi Gezari[4,7], James C. A. Miller-Jones[8], Sara Frederick[4], Itai Sfaradi[9], Michael F. Bietenholz[10,11], Assaf Horesh[9], Rob Fender[12,13], Simone Garrappa[1,2], Tomás Ahumada[4], Igor Andreoni[14], Justin Belicki[15], Eric C. Bellm[16], Markus Böttcher[17], Valery Brinnel[2], Rick Burruss[15], S. Bradley Cenko[7,18], Michael W. Coughlin[19], Virginia Cunningham[4], Andrew Drake[14], Glennys R. Farrar[3], Michael Feeney[15], Ryan J. Foley[20], Avishay Gal-Yam[21], V. Zach Golkhou[16,22], Ariel Goobar[23], Matthew J. Graham[14], Erica Hammerstein[4], George Helou[24], Tiara Hung[20], Mansi M. Kasliwal[14], Charles D. Kilpatrick[20], Albert K. H. Kong[25], Thomas Kupfer[26], Russ R. Laher[24], Ashish A. Mahabal[14,27], Frank J. Masci[24], Jannis Necker[1,2], Jakob Nordin[2], Daniel A. Perley[28], Mickael Rigault[29], Simeon Reusch[1,2], Hector Rodriguez[15], César Rojas-Bravo[20], Ben Rusholme[24], David L. Shupe[24], Leo P. Singer[18], Jesper Sollerman[30], Maayane T. Soumagnac[21,31], Daniel Stern[32], Kirsty Taggart[28], Jakob van Santen[1], Charlotte Ward[4], Patrick Woudt[13] and Yuhan Yao[14]

Cosmic neutrinos provide a unique window into the otherwise hidden mechanism of particle acceleration in astrophysical objects. The IceCube Collaboration recently reported the likely association of one high-energy neutrino with a flare from the relativistic jet of an active galaxy pointed towards the Earth. However a combined analysis of many similar active galaxies revealed no excess

The Astrophysical Journal
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A Light in the ... Hole ...
Matthew J. Gra... Michael Coughlin[7]

The accretion disks of active ga... detected by gravitational wave (GW) observatories. ... mergers within AGNs are the only GW channel where an electromagnetic (EM... detectable or not). Considering AGNs with unusual flaring activity observed by the Zwicky Transi... (ZTF), we describe a search for candidate EM counterparts to binary black hole (BBH) mergers detected by LIGO/

Article
A very luminous jet ... star by a massive b...
https://doi.org/10.1038/s41586-022-05465-8
Received: 5 April 2022
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Published online: 30 November 2022
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...Survey

van Velzen+ 2019

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Stein+ 2021

# Three neutrino-associated TDE candidates


van Velzen+ 2019

van Velzen+ 2021

Hammerstein+ 2021

Andreoni+ 2022

Subrayan+ 2023

Graham+ 2023

Stein+ 2021

Reusch+ 2022

Image credit: DESY

# Three neutrino-associated TDE candidates

Image credit: DESY

# Three neutrino-associated TDE candidates

# All had a very luminous dust echo

Image credit: DESY

# Three neutrino-associated TDE candidates

# All had a very luminous dust echo

$3.6\sigma$ correlation of 63 accretion flares with **strong dust echo** with high-energy alerts

Image credit: DESY

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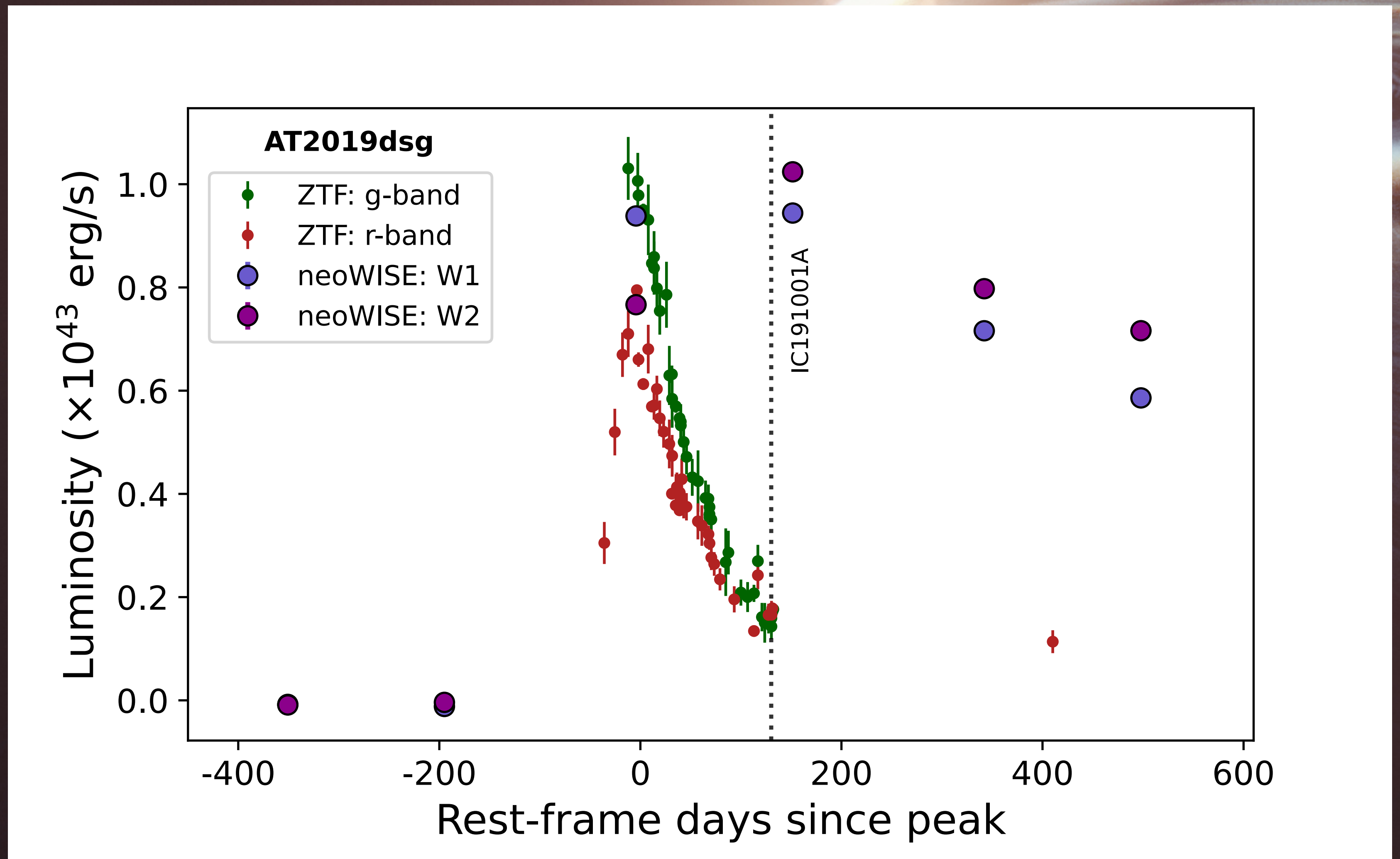
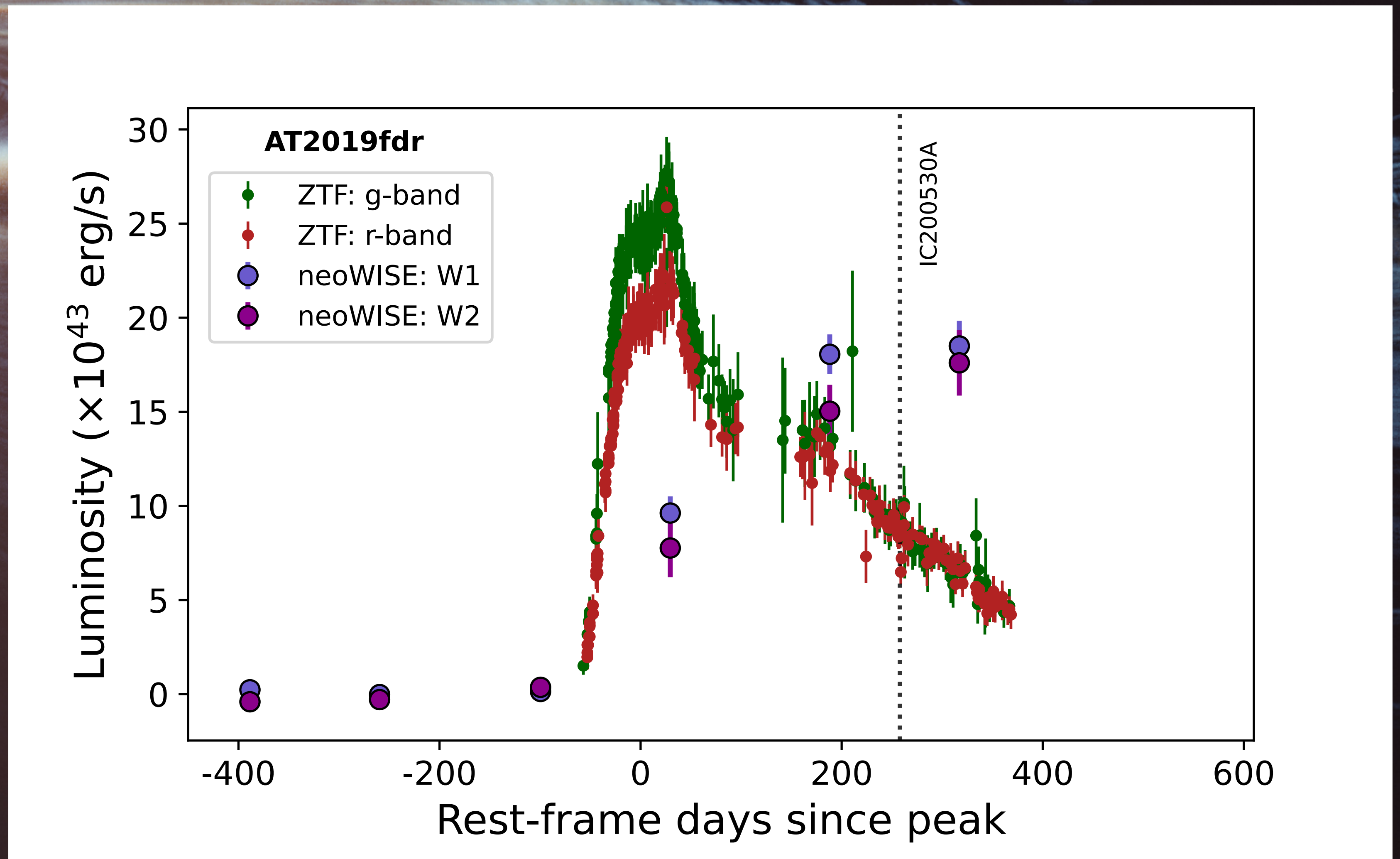
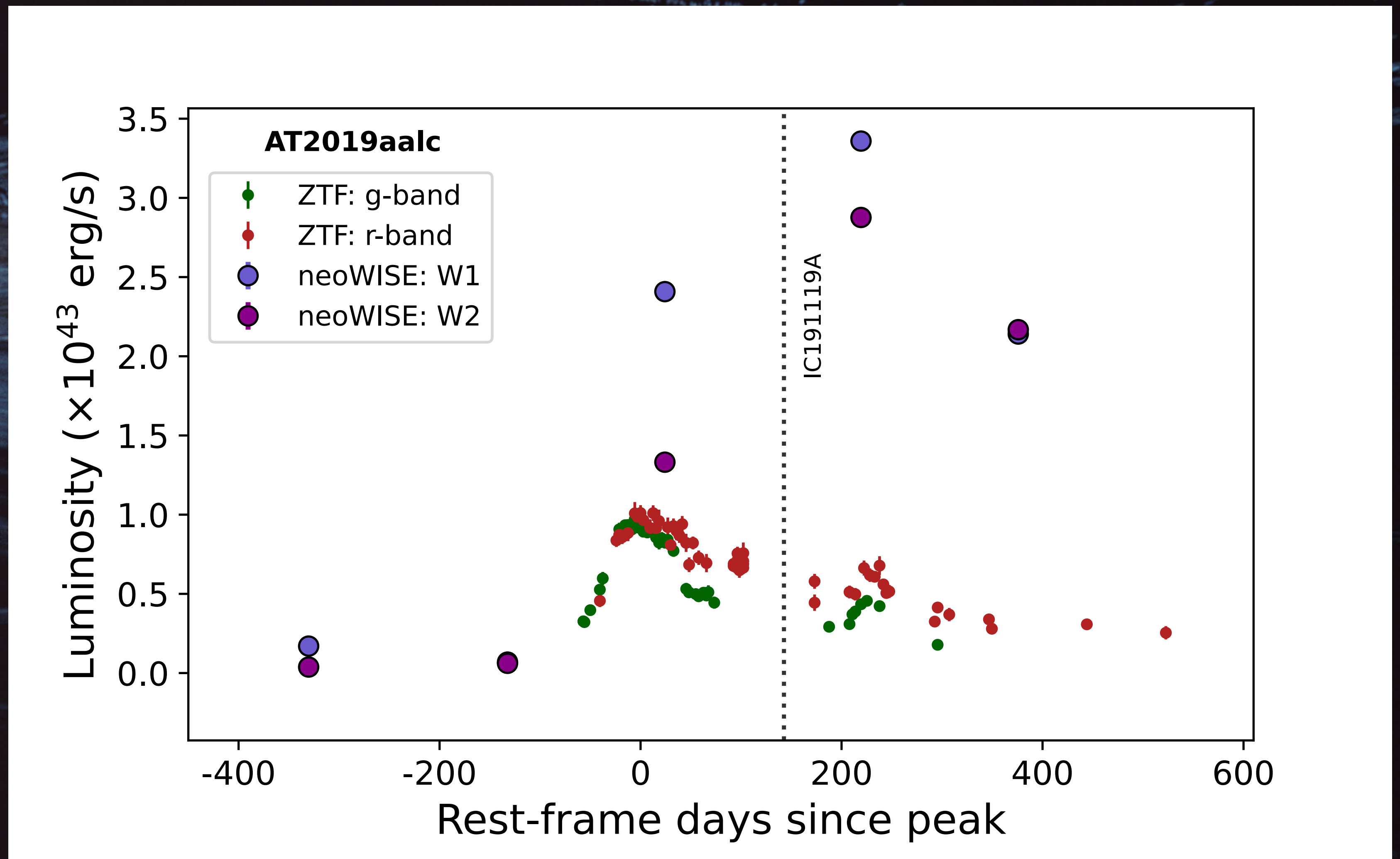
$3.6\sigma$ correlation of 63 accretion flares with **strong dust echo** with high-energy alerts



# Lots of interesting transients, but rather unstructured

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# What if we had a systematic sample of optical and IR lightcurves of the ZTF nuclear transients? 🤔

# II) A nuclear sample 💥

# Full Sample of all nuclear transients

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[2018.5, 2021] → 3.5 years worth of data

(400 million alerts)

# Full Sample of all nuclear transients

AMPEL nuclear filter

[2018.5, 2021] → 3.5 years worth of data

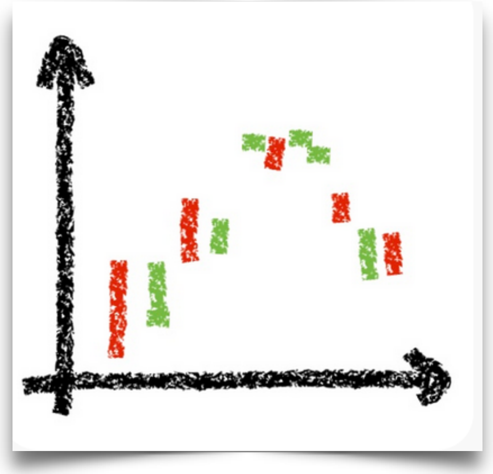
(400 million alerts)

Filtered by **host distance**, **PS1 star-galaxy score**, max. **brightness** and number of **detections**

**11687** transients in final selection

# Full Sample of all nuclear transients

**AMPEL nuclear filter**



**fpbot**

[2018.5, 2021] → 3.5 years worth of data

(400 million alerts)

Filtered by **host distance**, **PS1 star-galaxy score**, max. **brightness** and number of **detections**

**11687** transients in final selection

Obtained forced photometry with **fpbot**, applied baseline correction

# Crossmatch with WISE IR

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Vast majority has a WISE counterpart

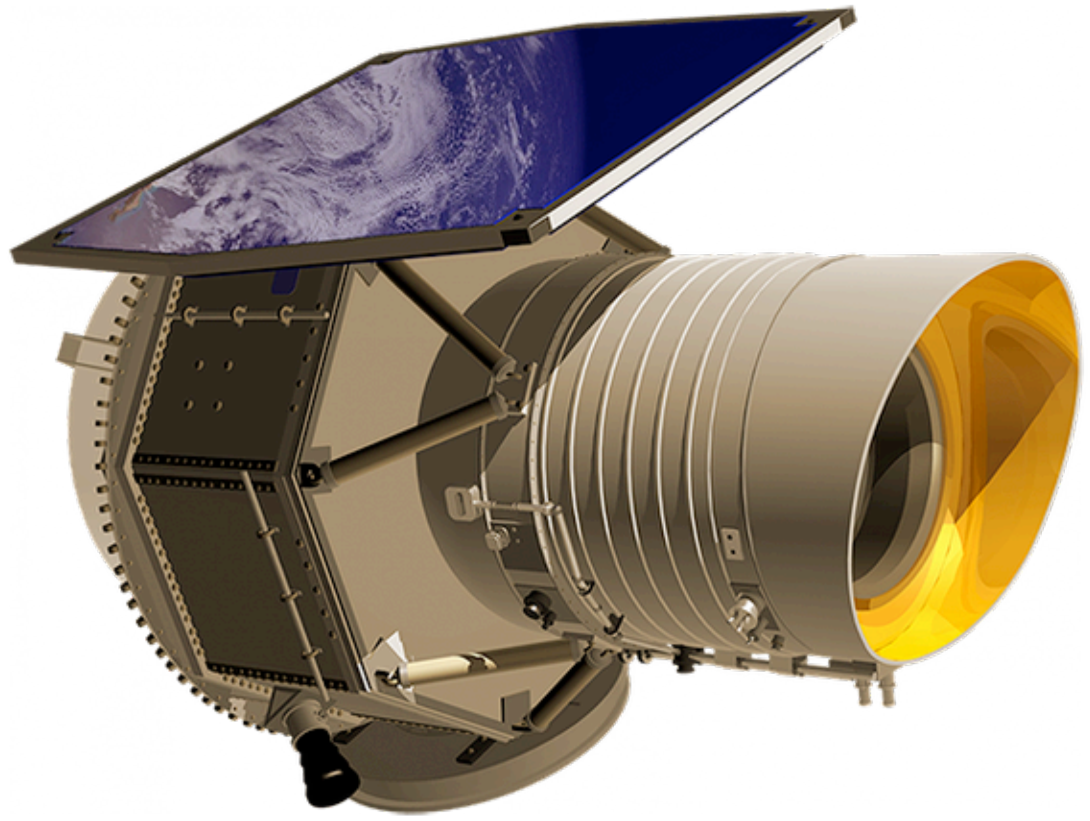


Image credit: NASA

# Crossmatch with WISE IR

Vast majority has a WISE counterpart

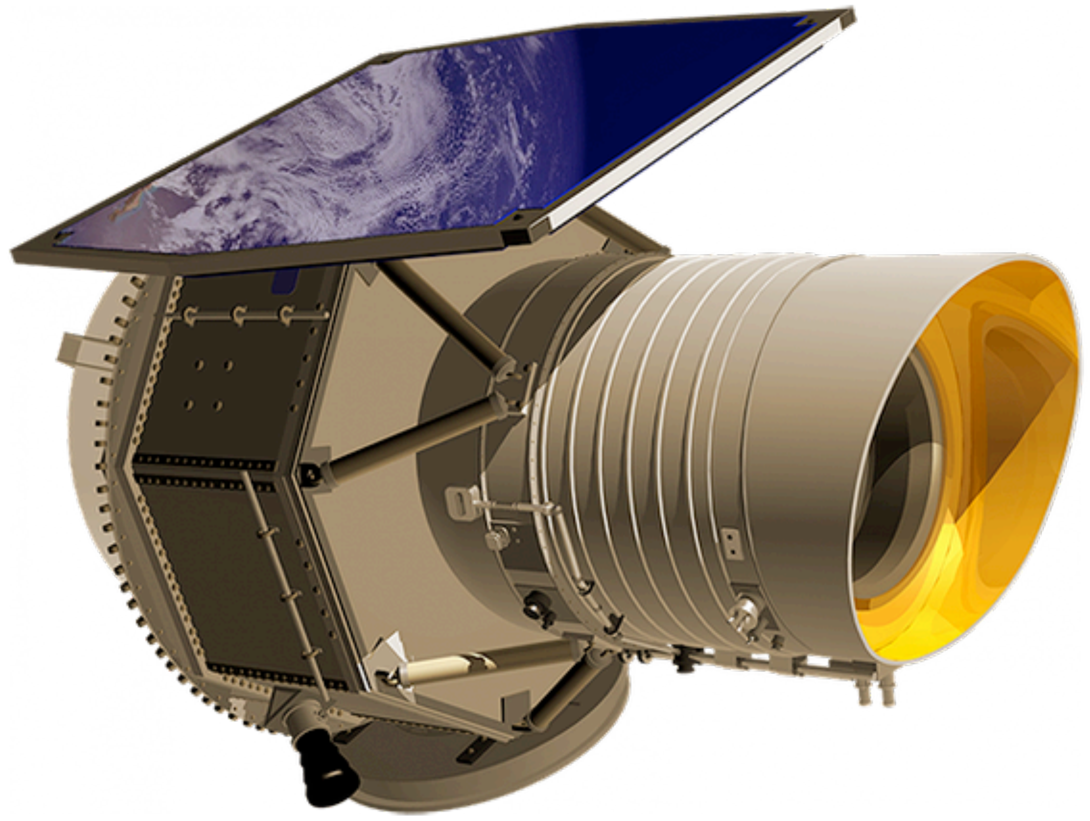
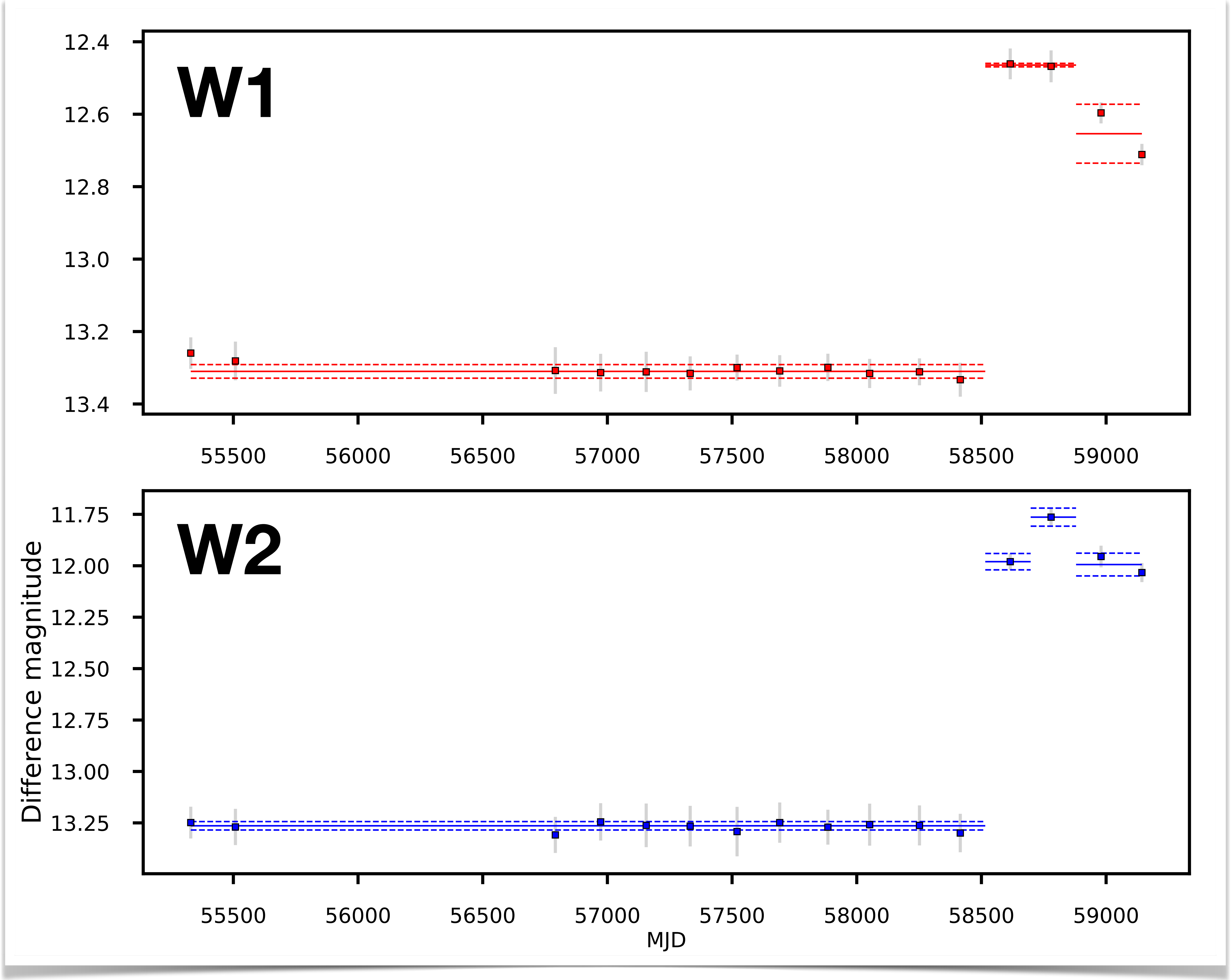


Image credit: NASA

Analyzed with a Bayesian block framework to find flares



# Crossmatch with WISE IR

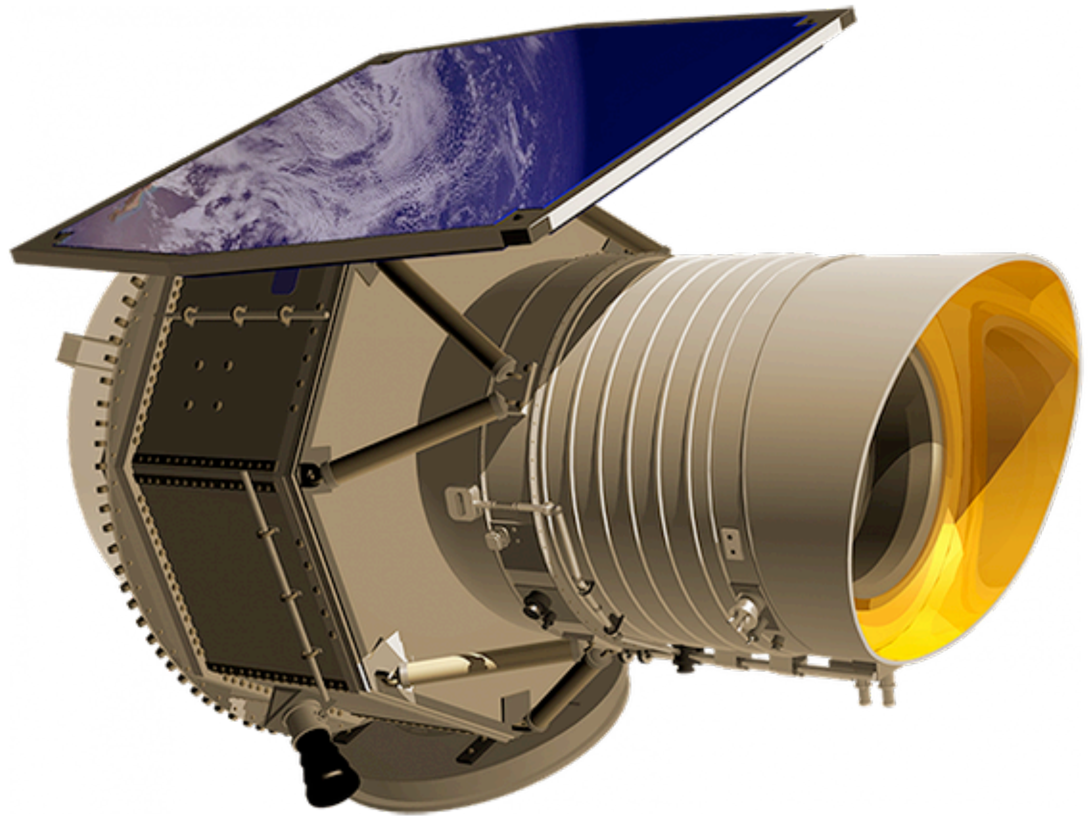


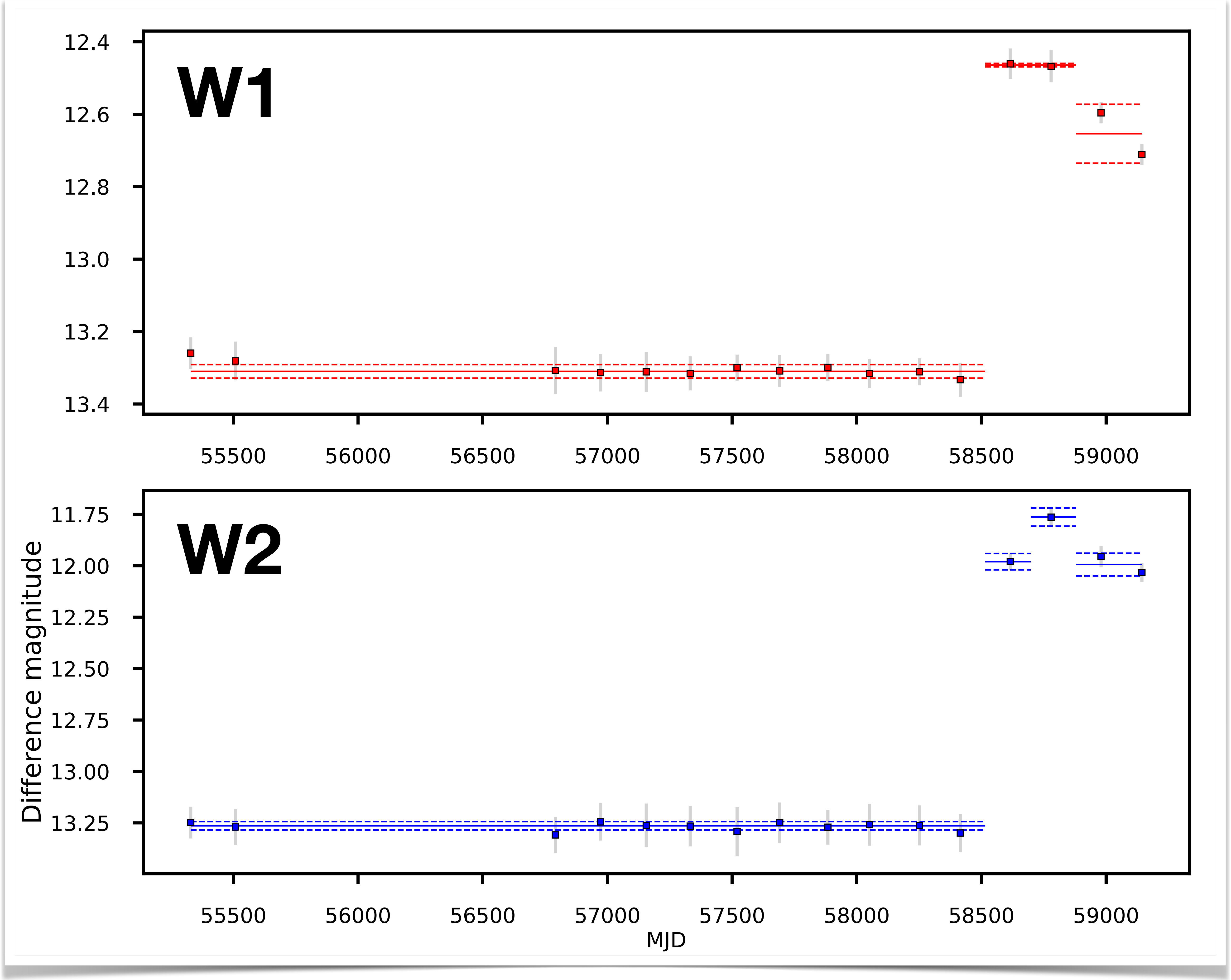
Image credit: NASA

Vast majority has a WISE counterpart

Analyzed with a Bayesian block framework to find flares

15% have a prominent IR flare

2% flare **after** the optical peak



# Trained BDT classifier with noisified lightcurves from Bright Transient Survey

see Dan Perley's talk

7284 ZTF transients

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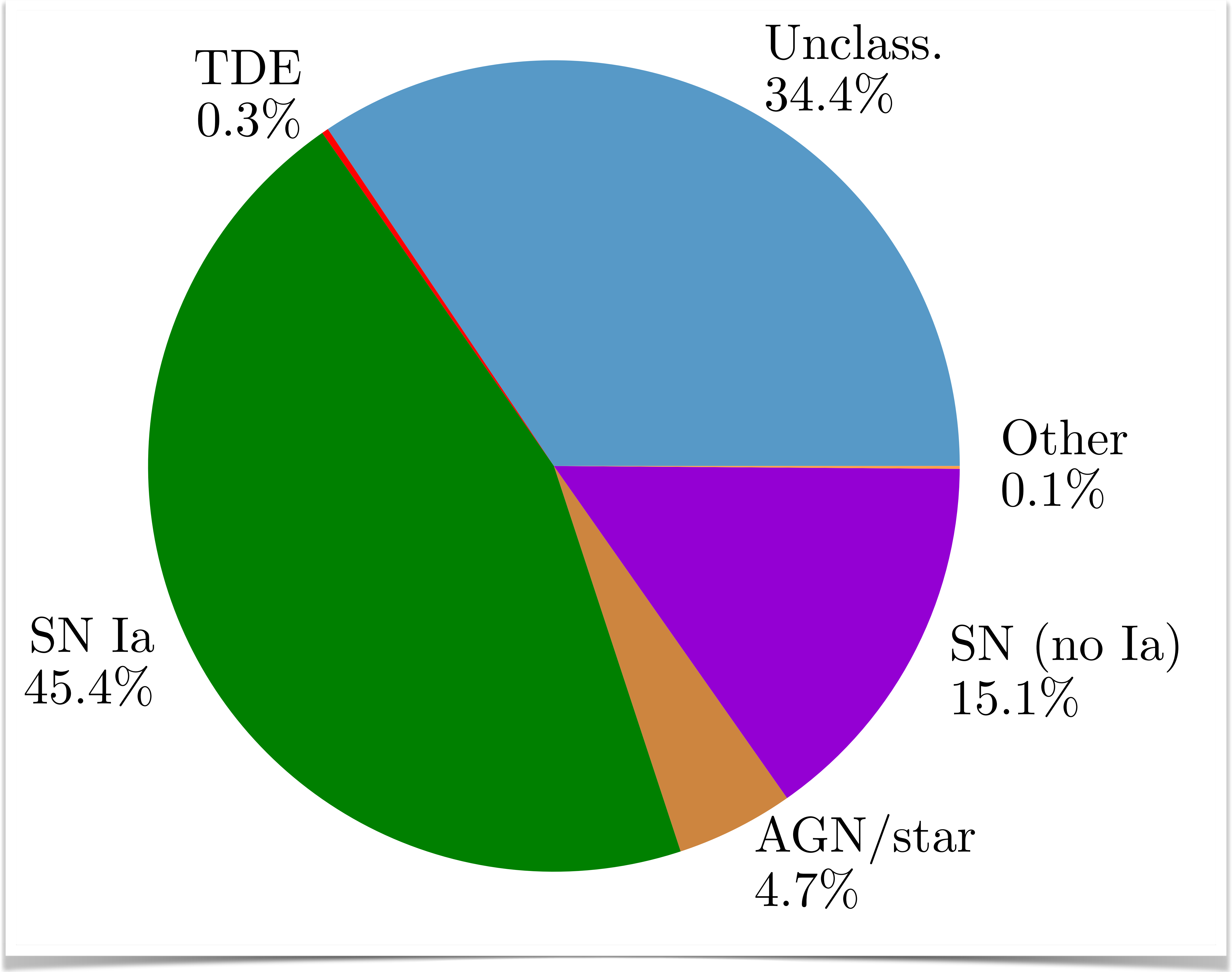
7284 ZTF transients

5315 of them classified (brighter than 18.5 mag)



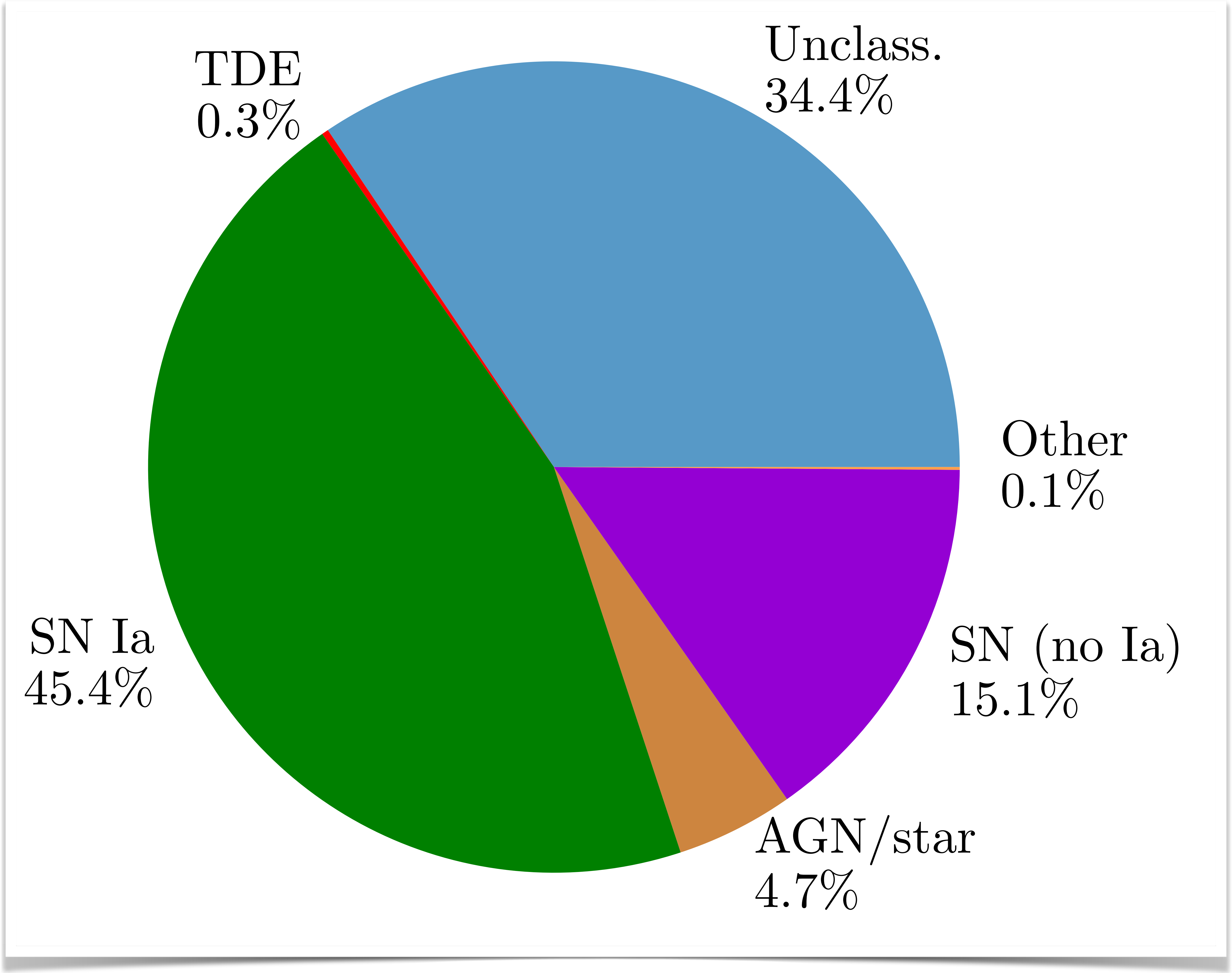
# Trained BDT classifier with noisified lightcurves from Bright Transient Survey

see Dan Perley's talk

7284 ZTF transients

5315 of them classified (brighter than 18.5 mag)

Problem: Brighter than nuclear selection, high class imbalance



# Trained BDT classifier with noisified lightcurves from the Bright Transient Survey

Noisification: Physically motivated remedy

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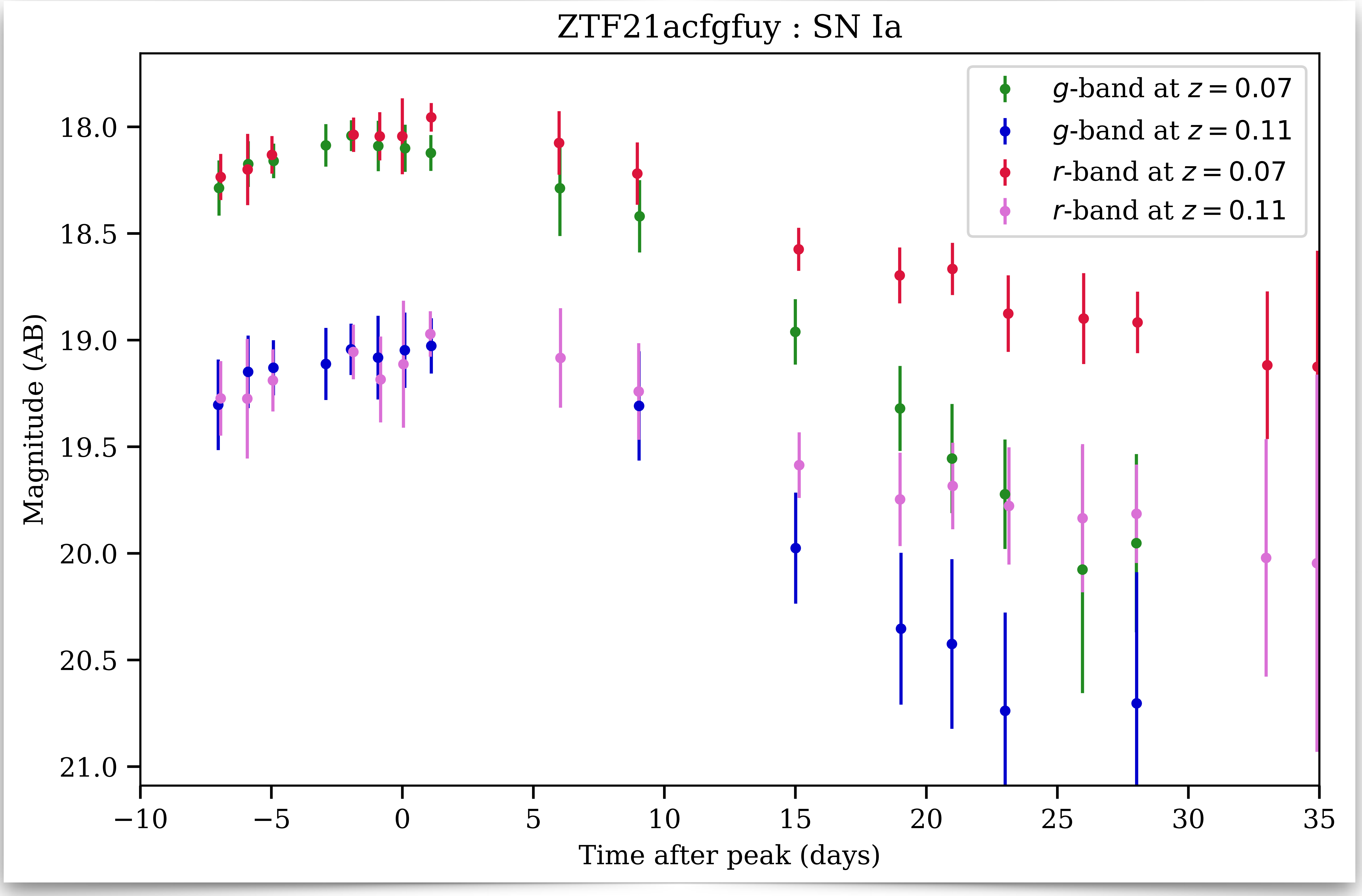
Noisification: Physically motivated remedy

→ redshift
→ noisify
→ K-correct

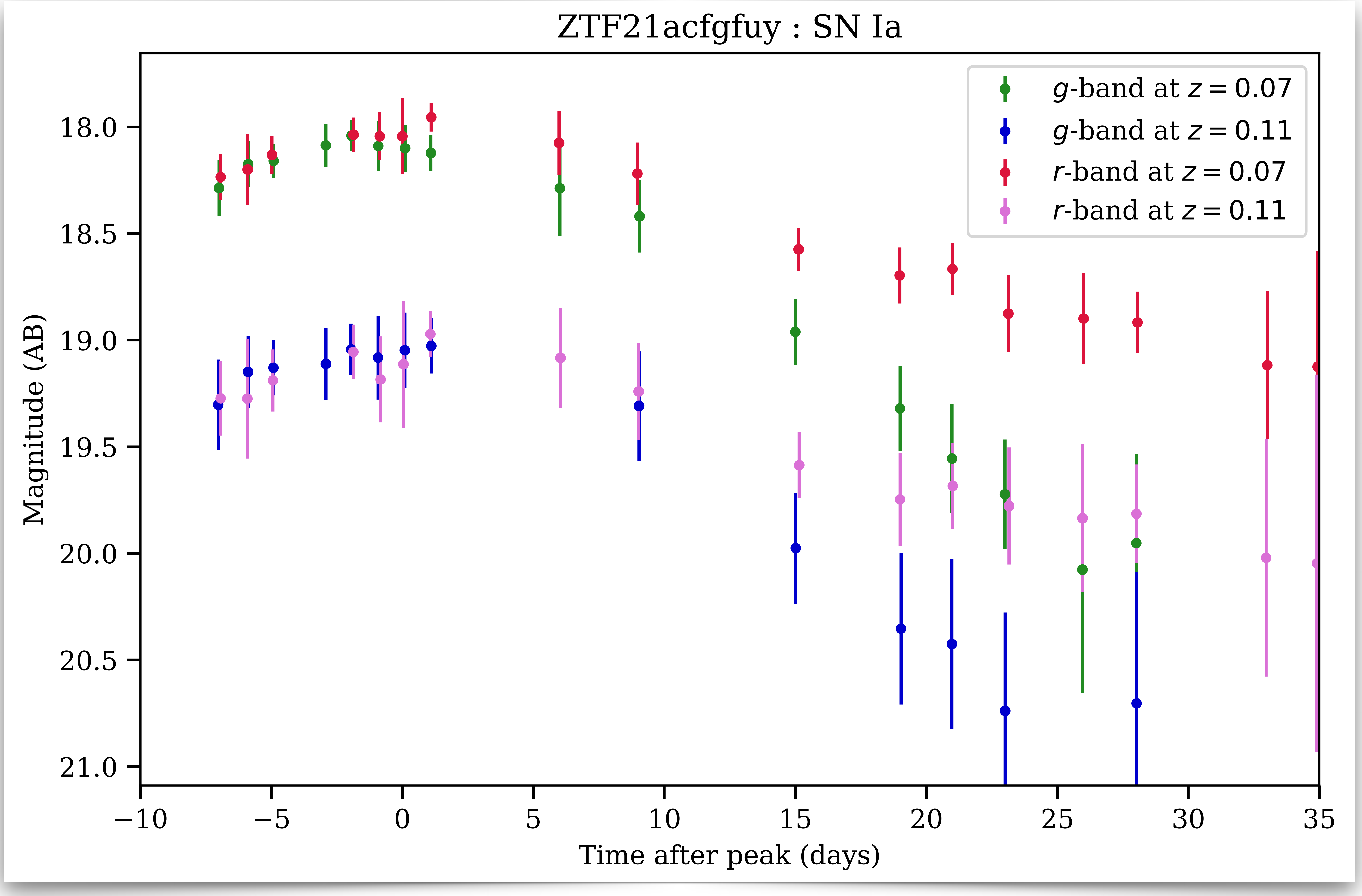


# Trained BDT classifier with noisified lightcurves from the Bright Transient Survey

Noisification: Physically motivated remedy

→ redshift
→ noisify
→ K-correct

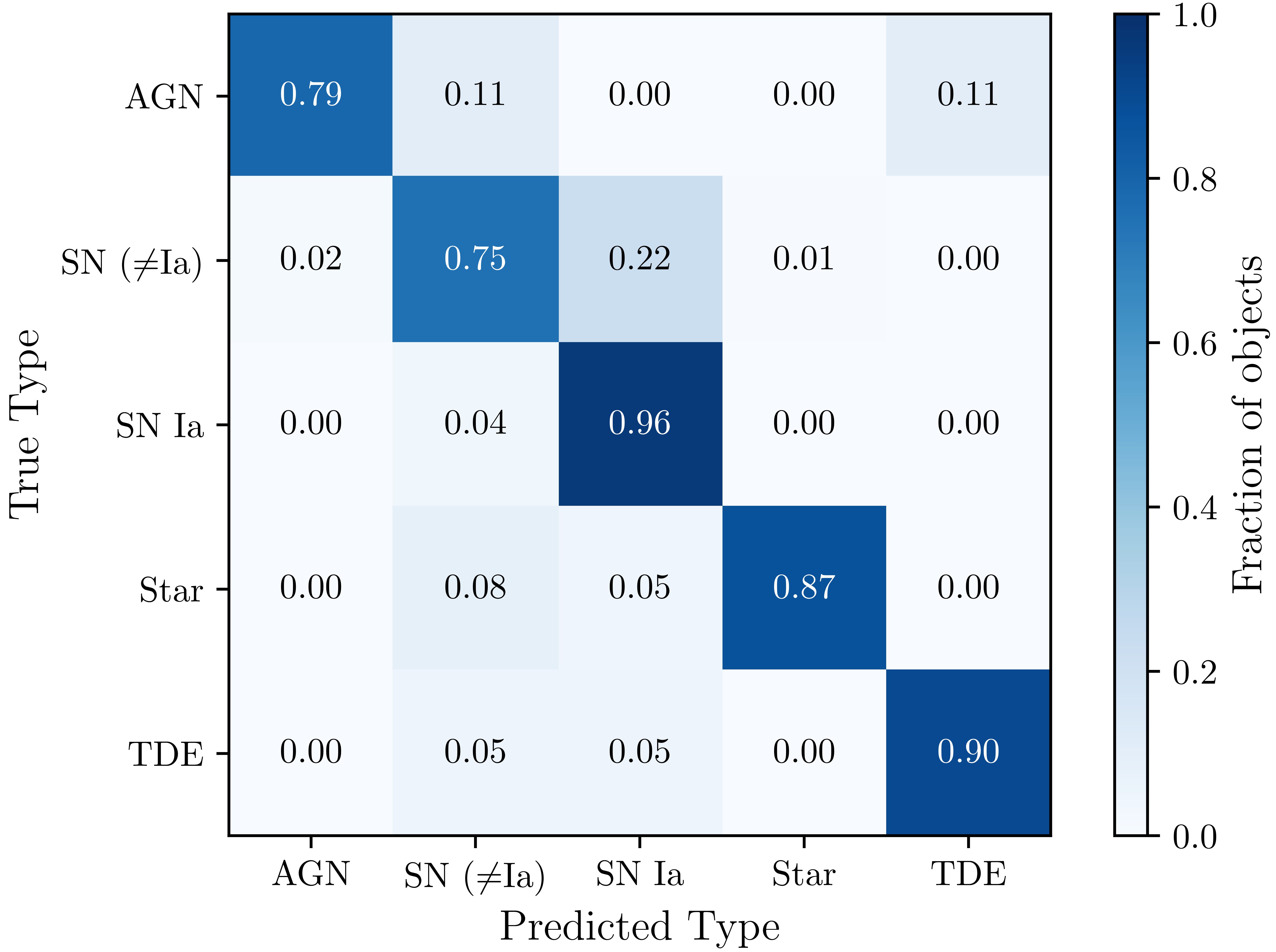
Feature extraction, currently only based on optical data



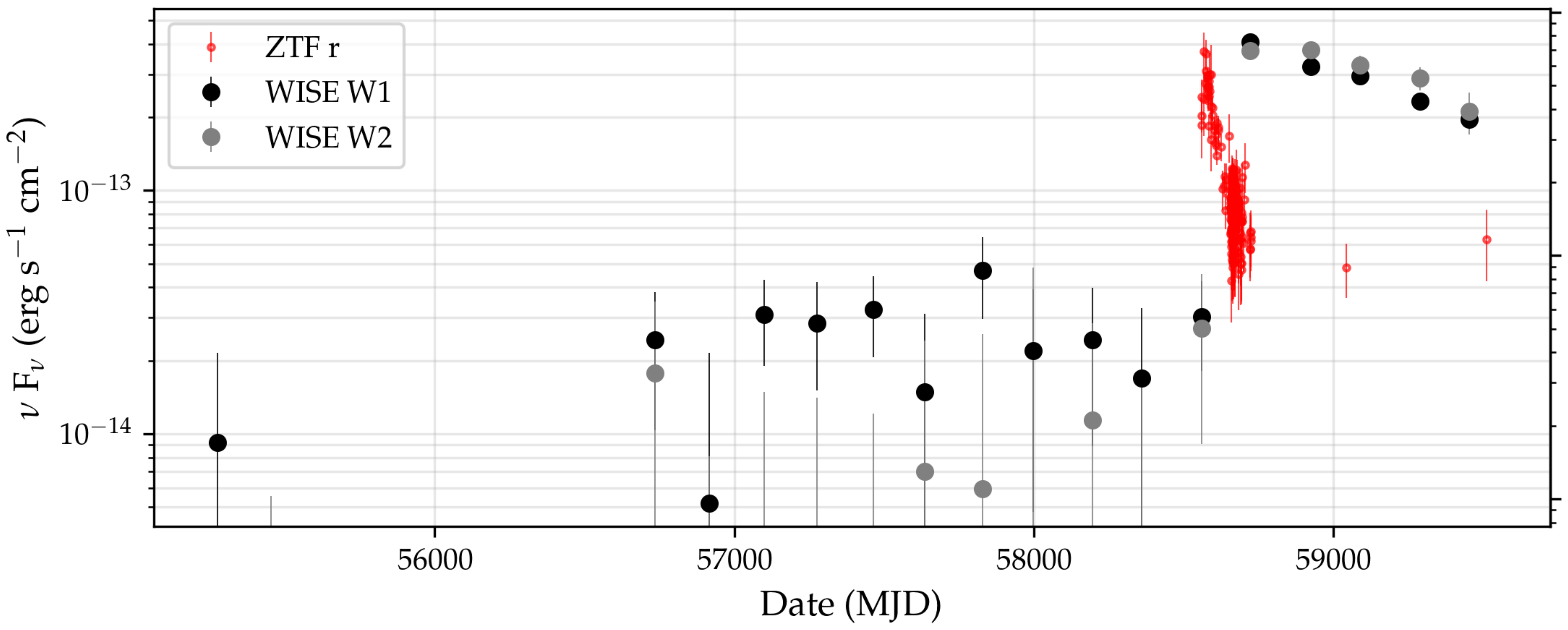
# Evaluation with test sample

preliminary

**Not including** noisified lightcurves in the test sample



# Identified some strong TDE candidates previously missed



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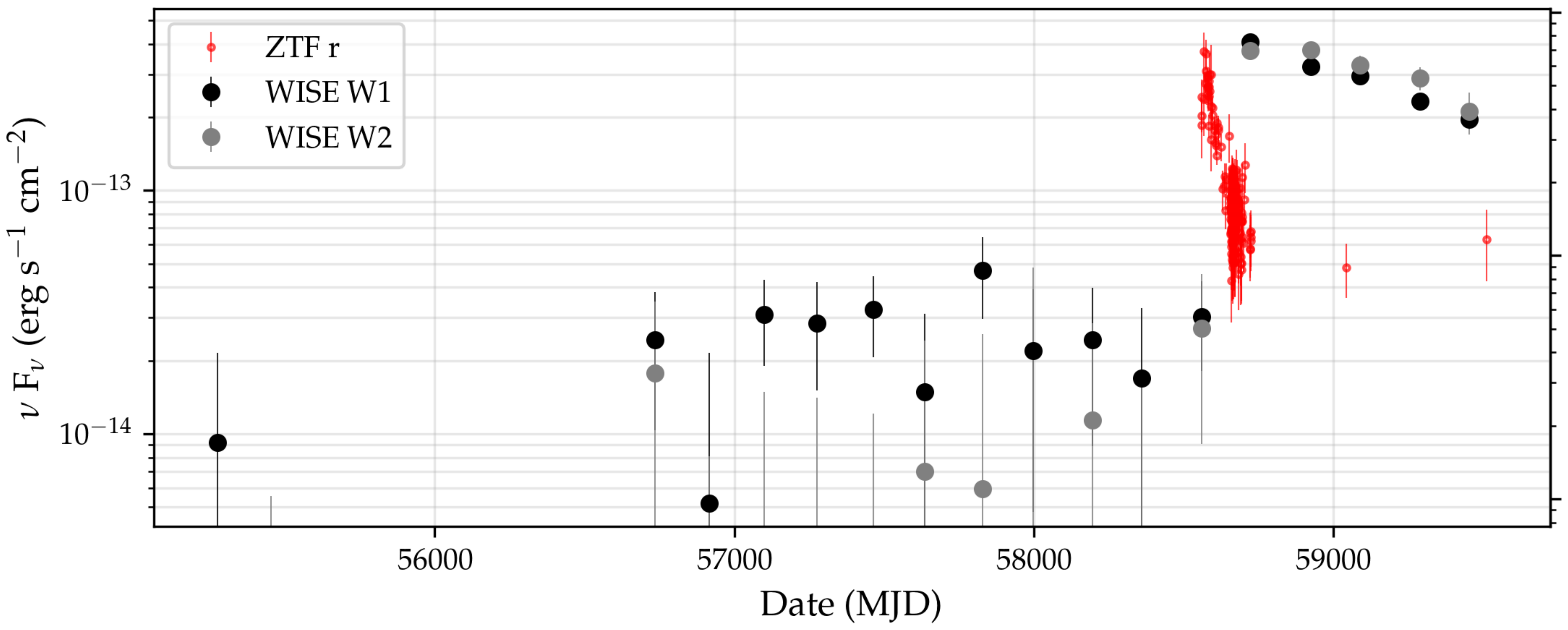


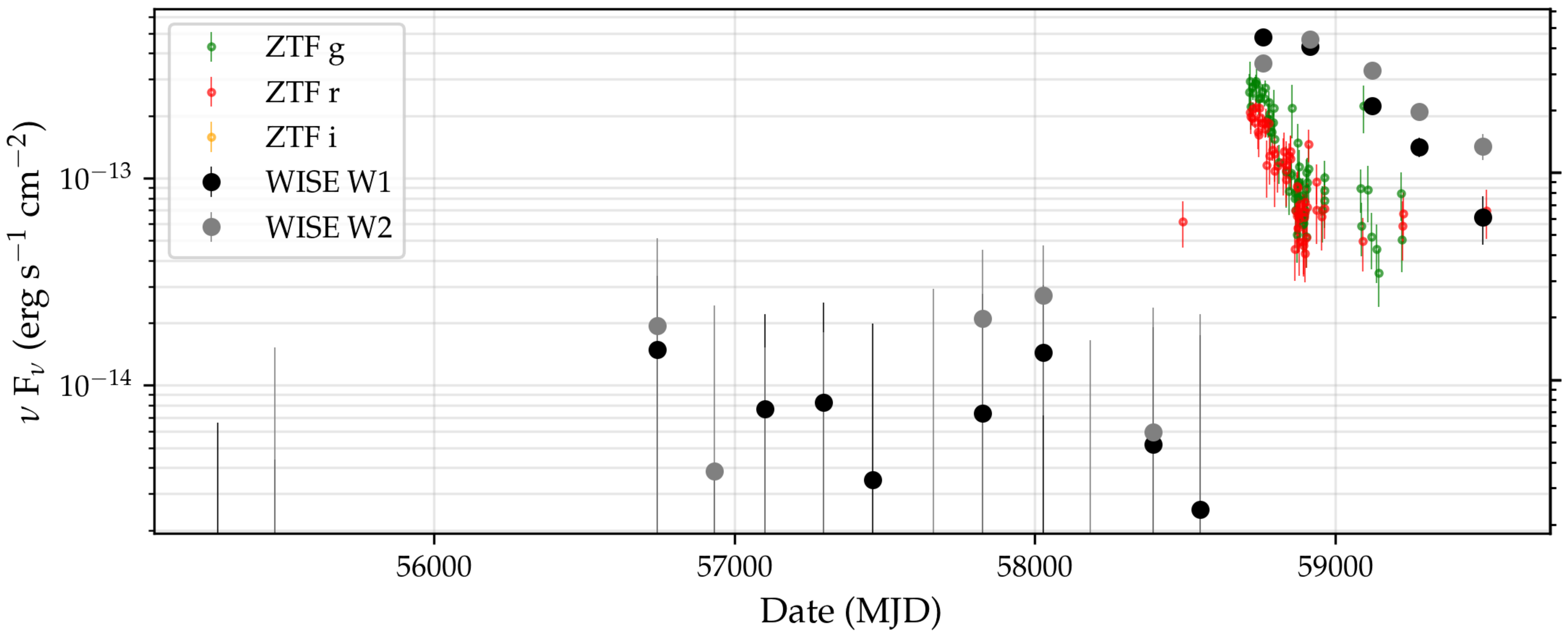

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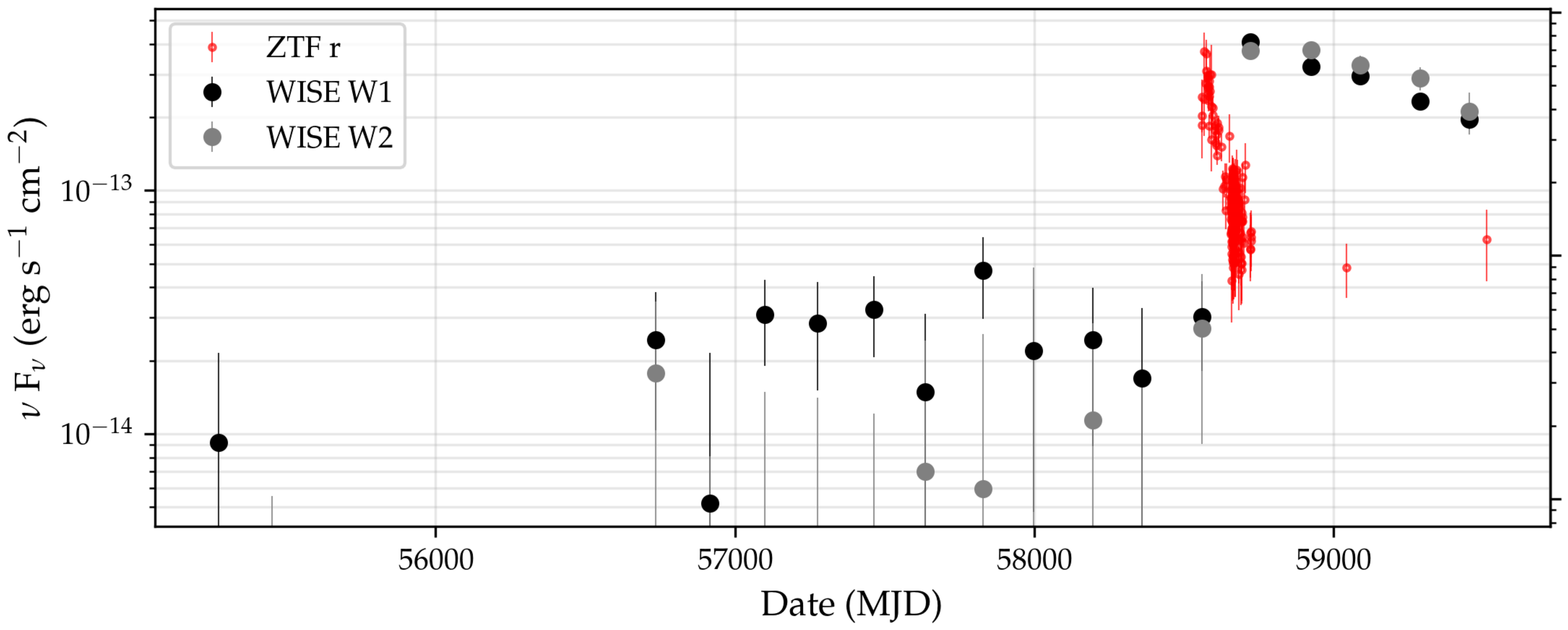


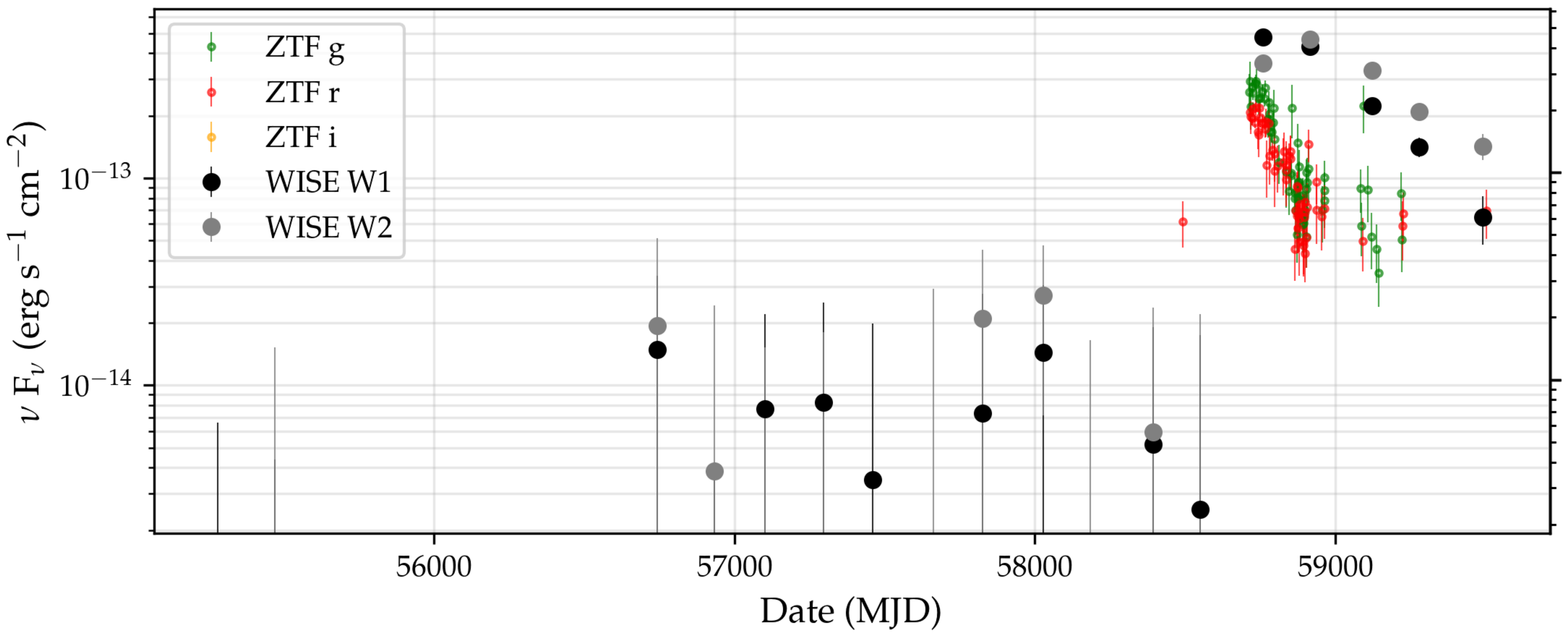


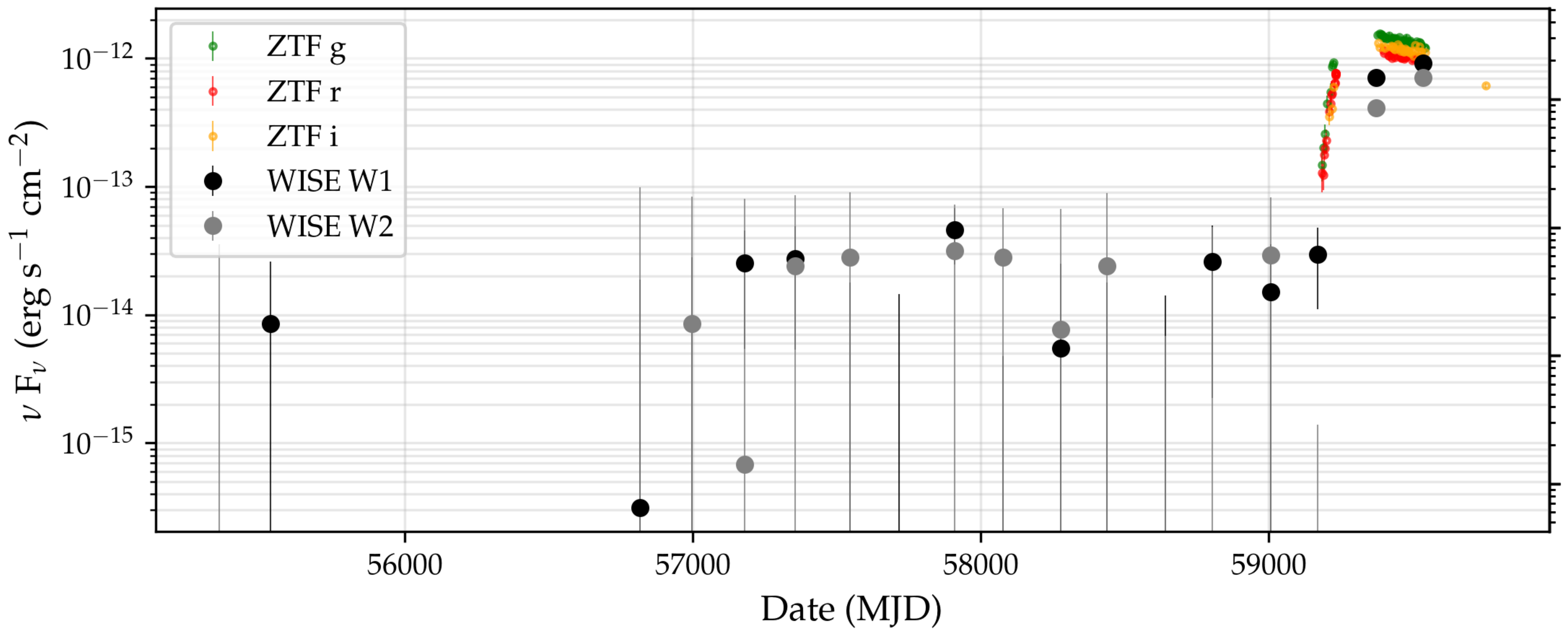

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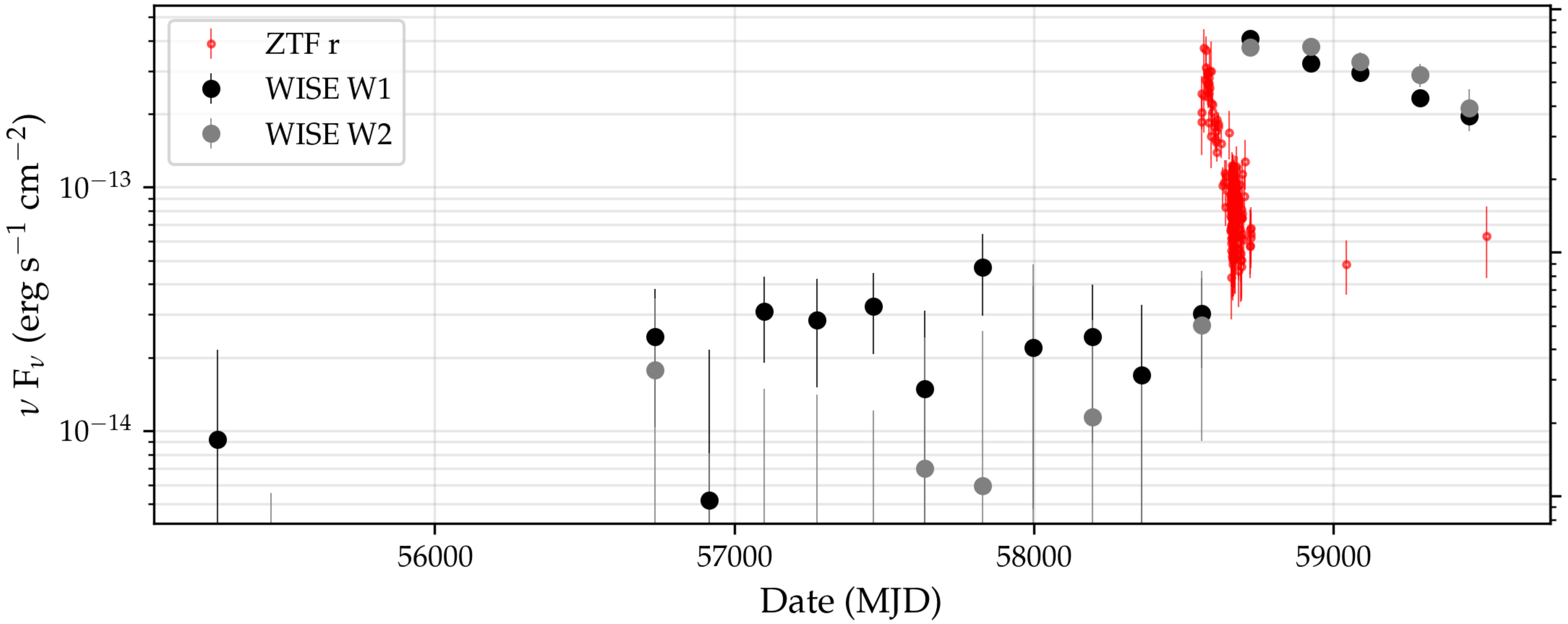
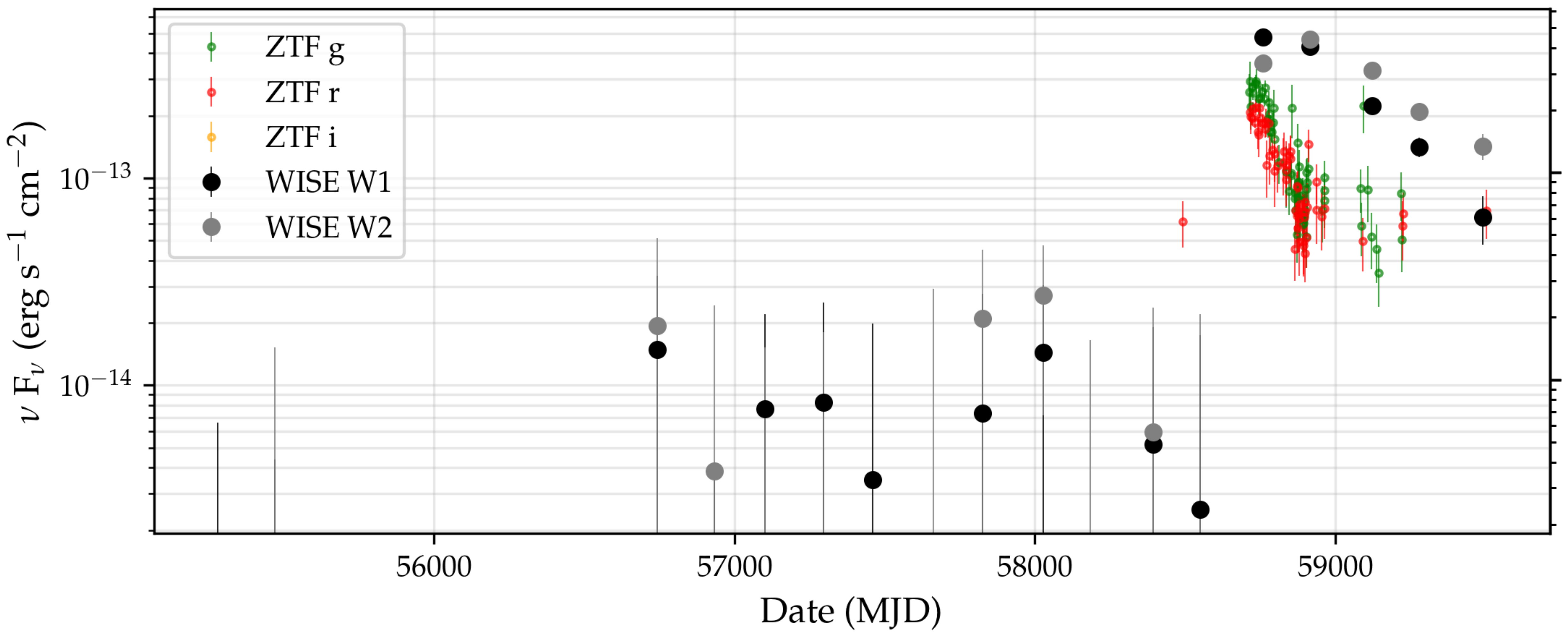
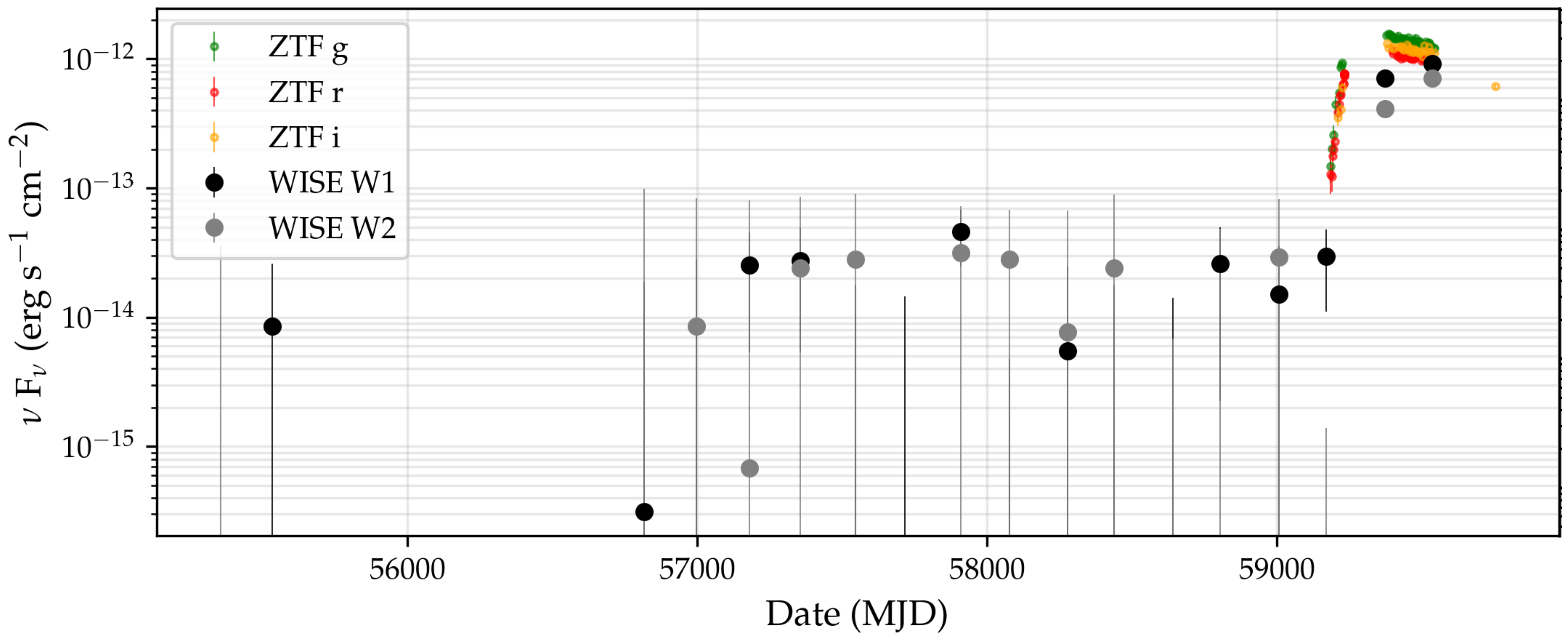
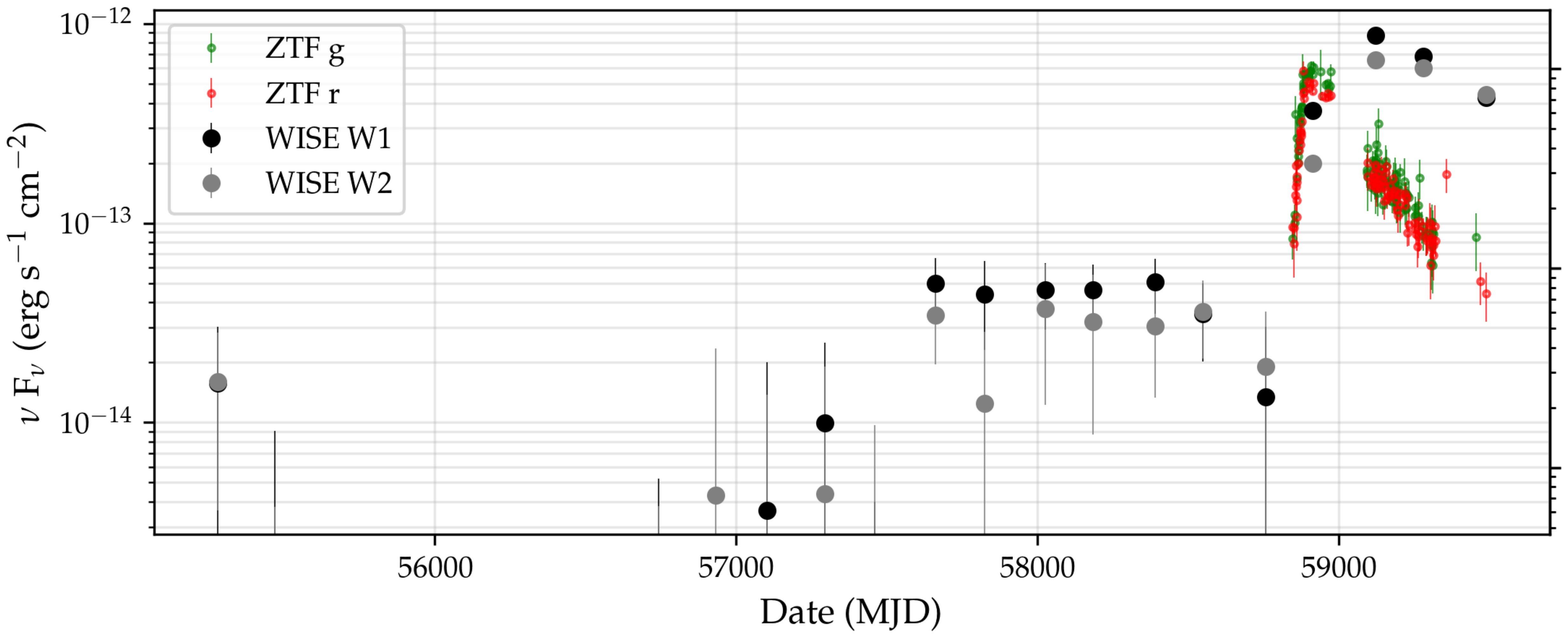


# Identified some strong TDE candidates previously missed


Live searches miss events

Combining data is potentially helpful

# III) What does this tell us about GW follow up?

# What can we learn from such a sample?

Photometric identification is still a challenge!

There might be types of events in the sample we missed so far

We know about SNe, stochastic AGN variability, AGN flares, CVs and TDEs. But what else?

Exclusively looking for KN signatures poses the danger of missing something

BBH counterparts (slowly evolving!)

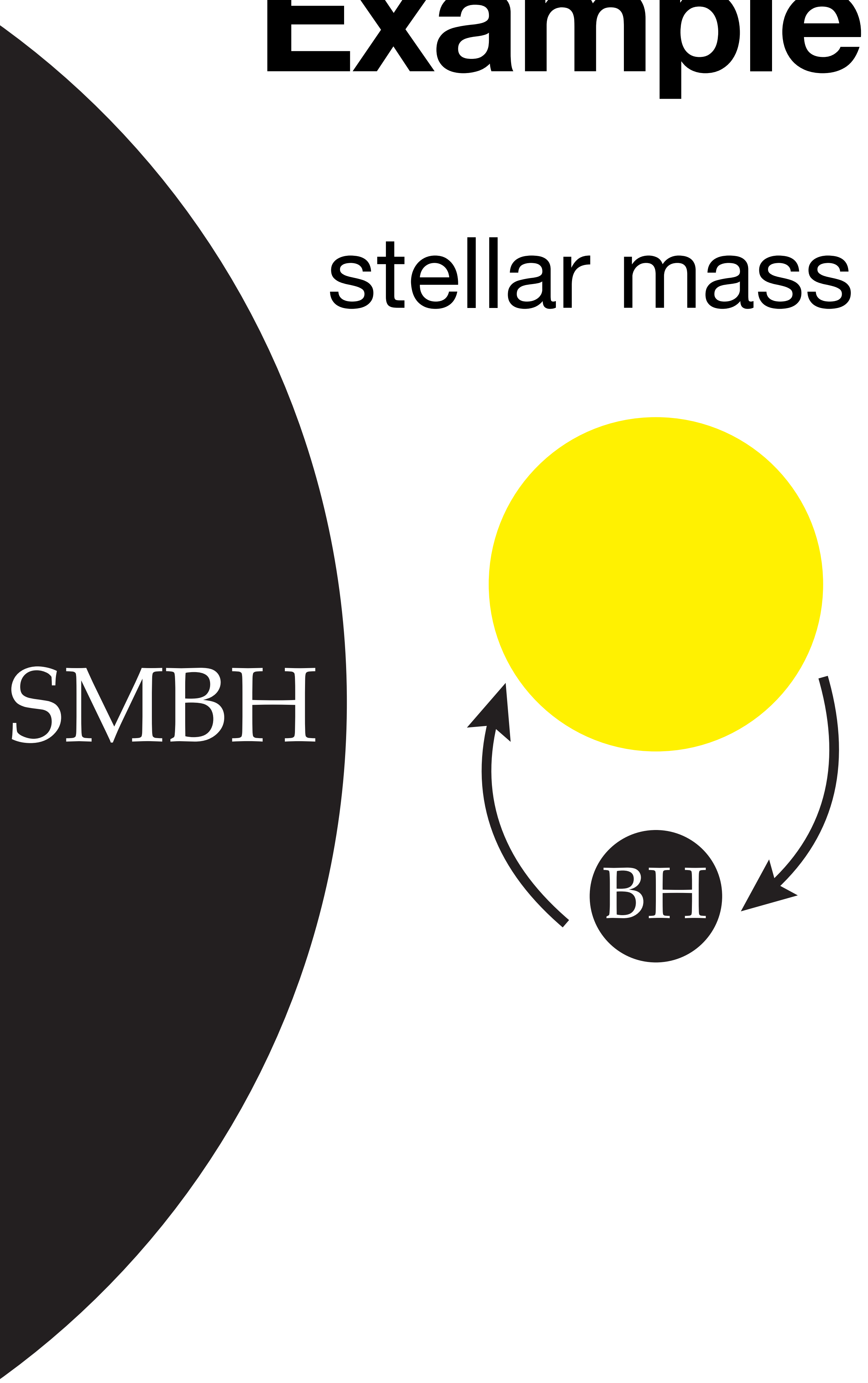
See Matthew Graham's talk

# Example: What about micro-TDEs?

Y. Yang+ 2022

# Example: What about micro-TDEs?

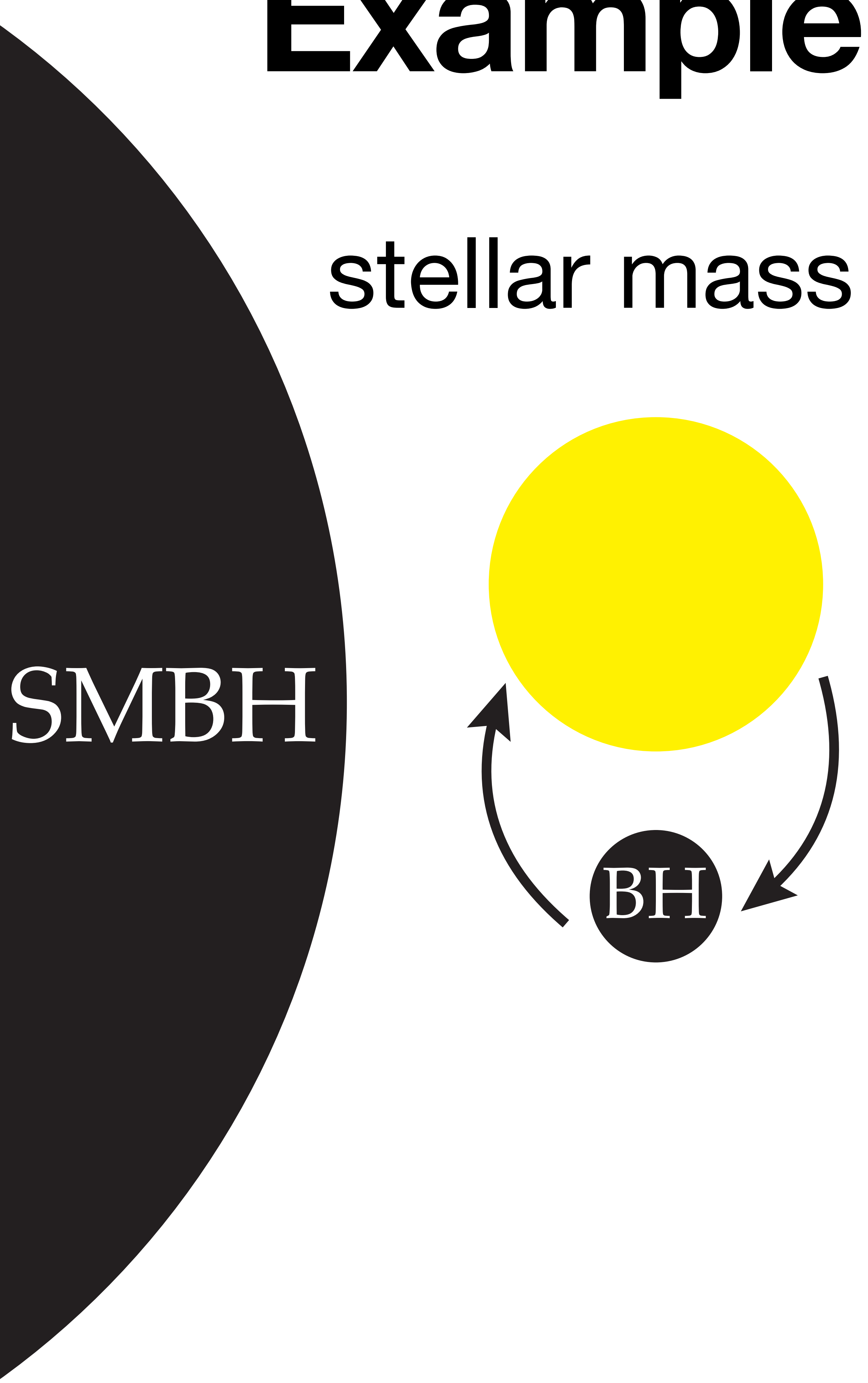
stellar mass BH tidally disrupting a star




Y. Yang+ 2022

# Example: What about micro-TDEs?

stellar mass BH tidally disrupting a star




Maybe enhanced rate close to the SMBH due to pre-existing accretion disk

Y. Yang+ 2022

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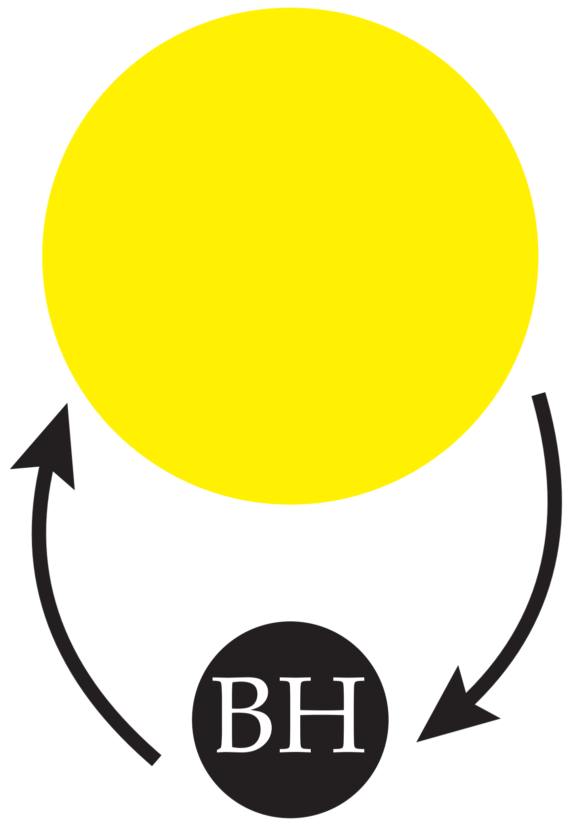
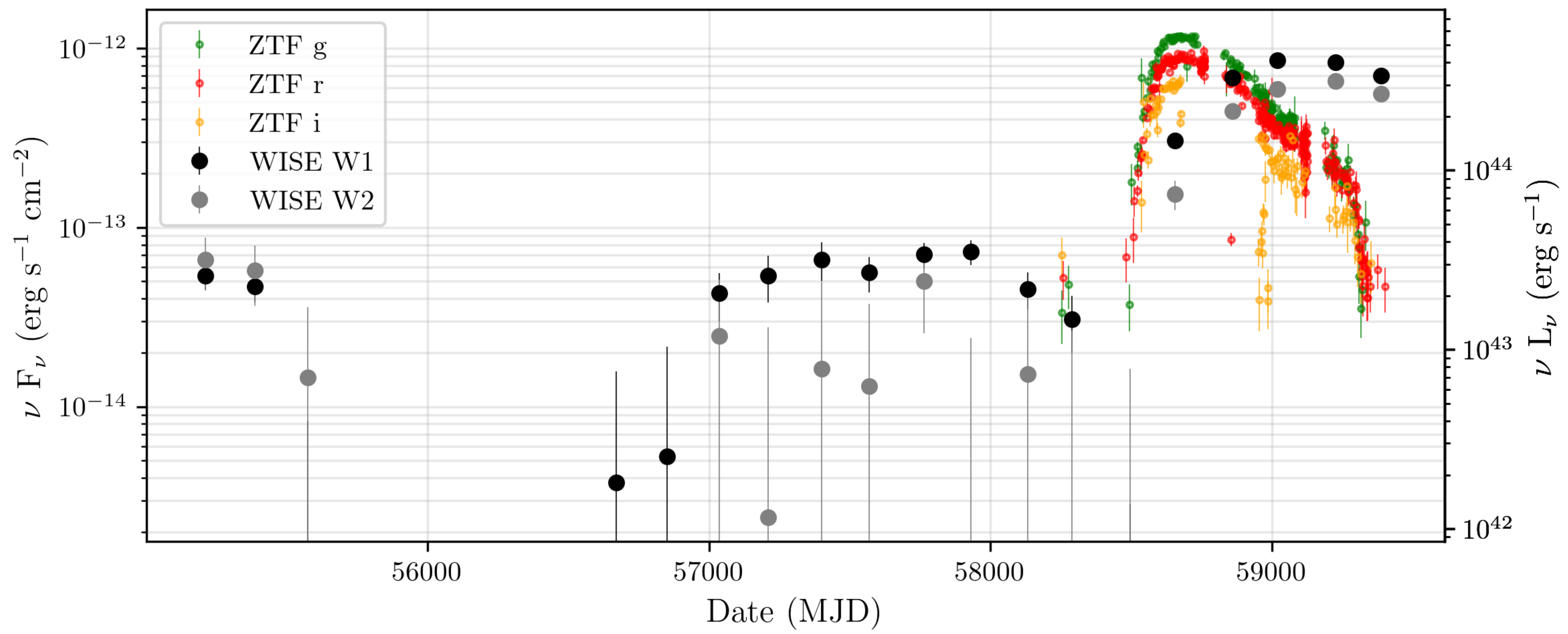



Maybe enhanced rate close to the SMBH due to pre-existing accretion disk

EM signature: Similar to TDEs, but SMBH mass above Hills mass for **bright** $\mu$TDEs

**Faint** $\mu$TDEs: unusual flaring in the AGN light curve




Literature candidate $\mu$TDE

**ZTF19aailpwl** (part of the sample)

Y. Yang+ 2022

# Event type possibly observable as EM transients

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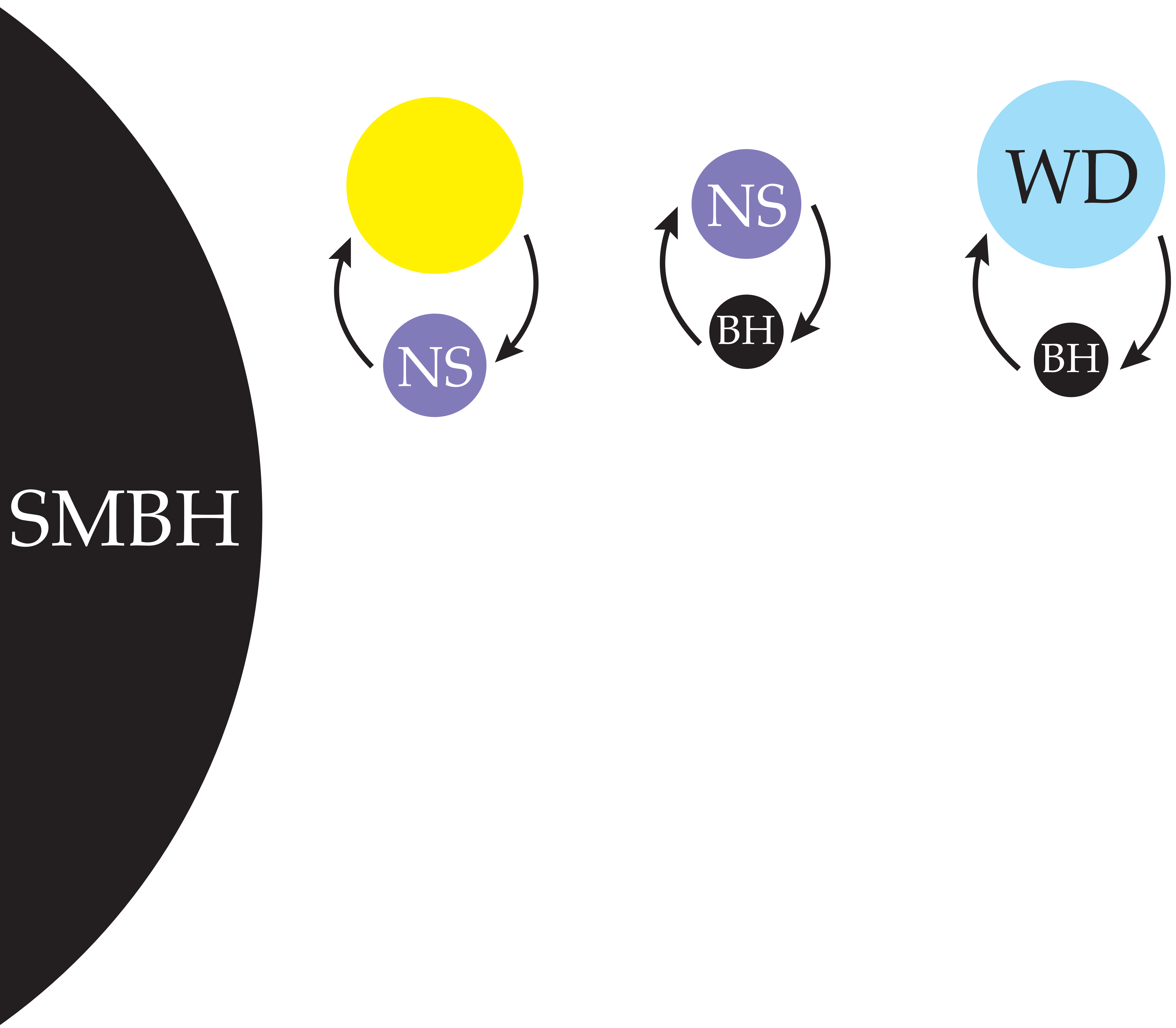
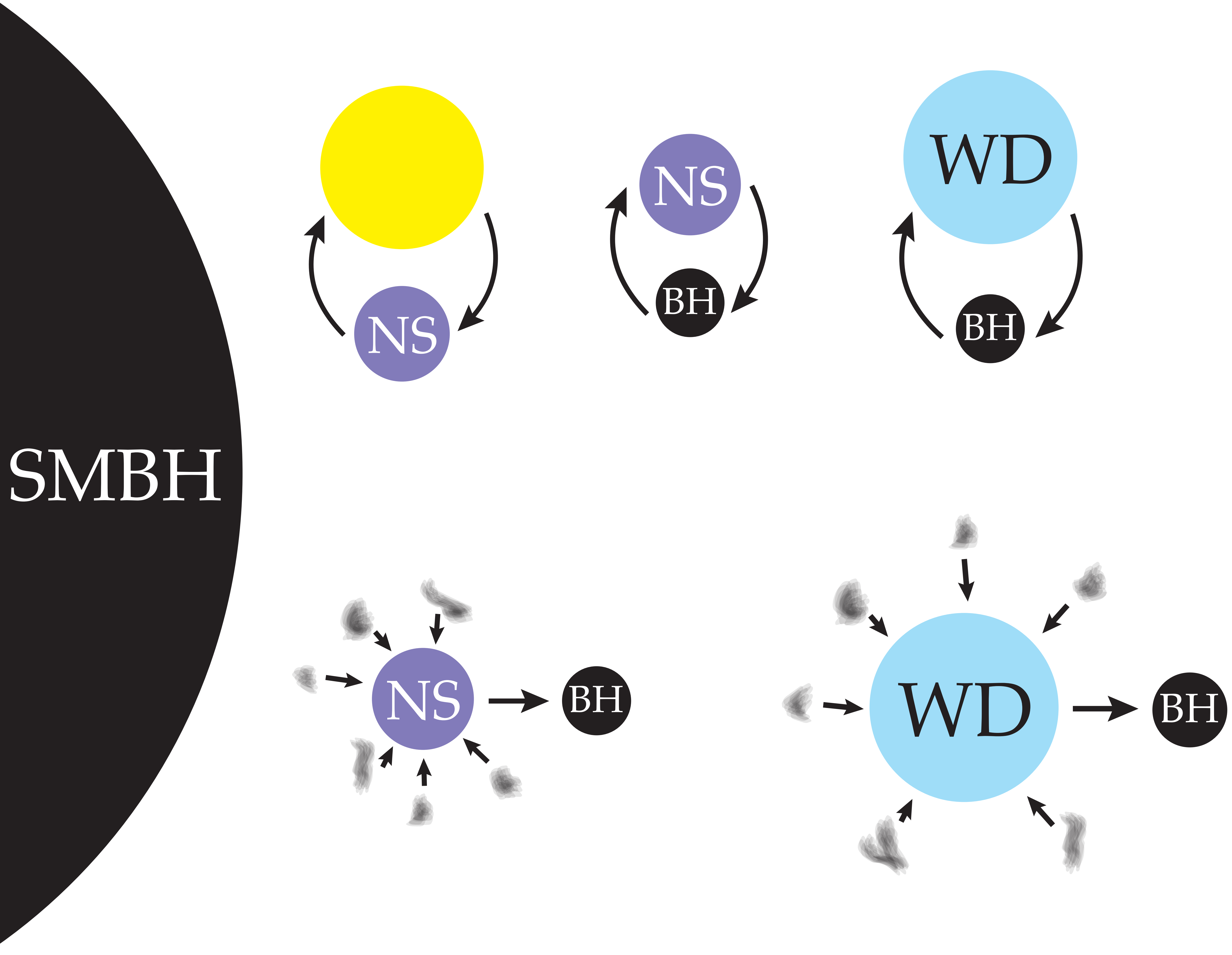



**Other $\mu$TDE channels**

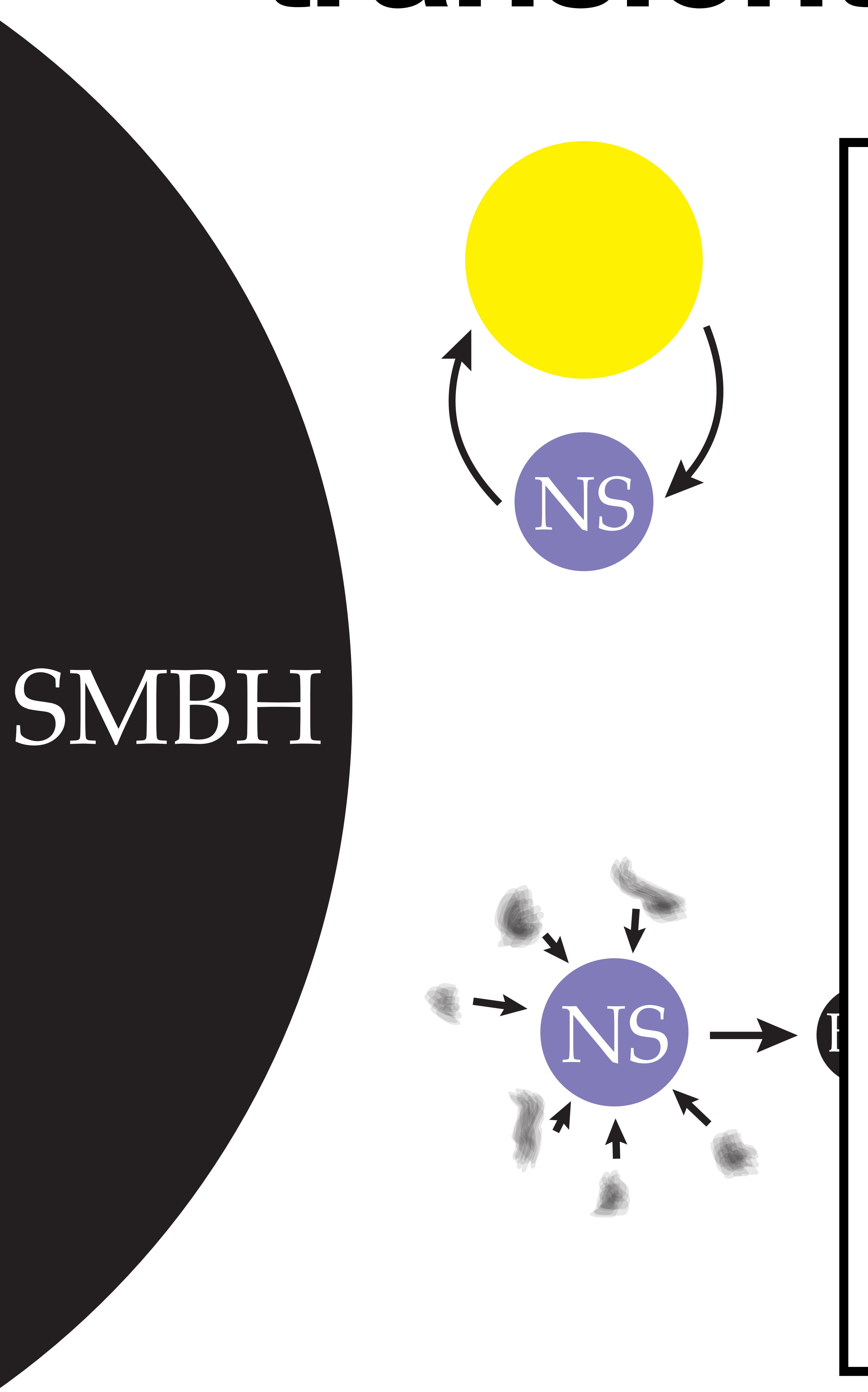
# Event type possibly observable as EM transients




**Other $\mu$TDE channels**

**Accretion induced collapse**

# Event type possibly observable as EM transients

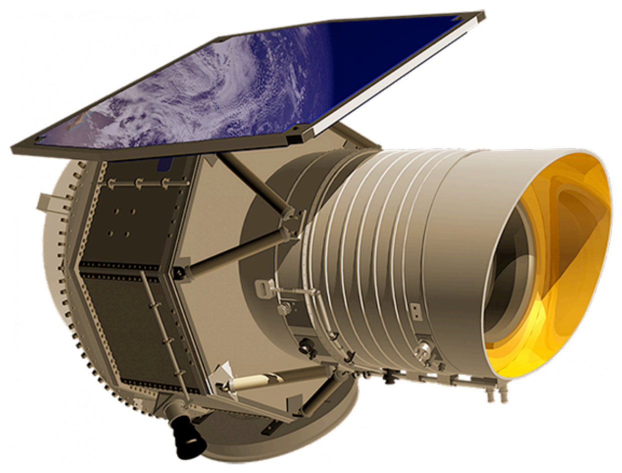



There should be some of these contained in the nuclear sample

GW signals unlikely to be accessible to LVK

But one can potentially learn about BH evolution and binary formation in AGN disks

# Nuclear sample: Created with AMPEL



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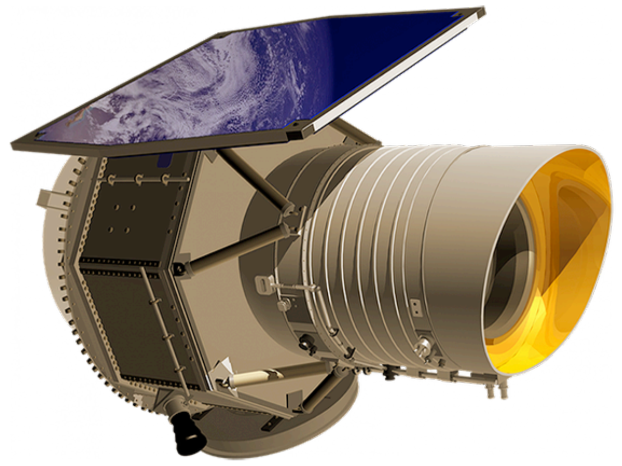
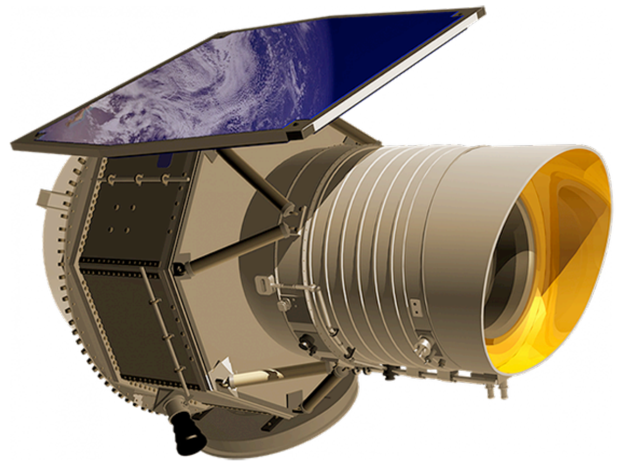


**User-specified pipeline**

# Nuclear sample: Created with AMPEL

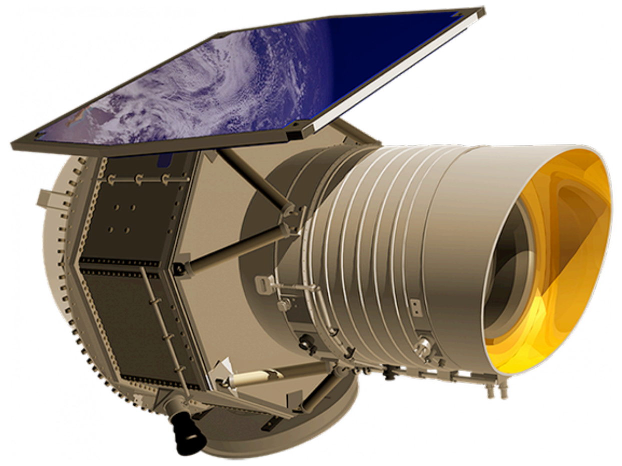


User-specified pipeline

Science

# Nuclear sample: Created with AMPEL

See Jakob Nordin's talk



User-specified pipeline

Science

# There is so much more data to be combined

**See Jakob Nordin's talk**

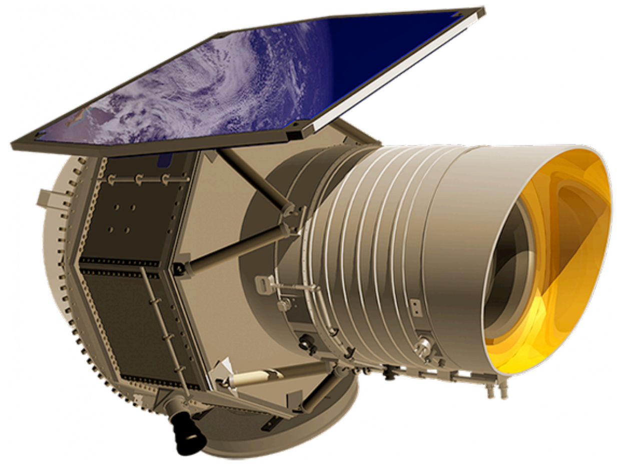
cta cherenkov telescope array

VERA C. RUBIN OBSERVATORY

IceCube

ZTF

LIGO VIRGO



ULTRASAT Ultraviolet Transient Astronomy Satellite

→

**User-specified pipeline**

→

**Science**

# To ponder

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➡ But only if we have the right tools for it!

Rapid follow up is great! But maybe there is something to be gained from archival studies

How about automatic coincidence searches for **all** O4 alerts?

🕵️Background studies using the normal survey ("blind")

# Summary

Image credit: Palomar Observatory

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**ZTF has vastly increased the TDE sample**

Image credit: Palomar Observatory

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**Created a flux-limited, unbiased sample of nuclear events**

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**🚦AMPEL enables all this**

# Summary

Image credit: Palomar Observatory

**ZTF has vastly increased the TDE sample**

**Created a flux-limited, unbiased sample of nuclear events**

**Classification effort ongoing**

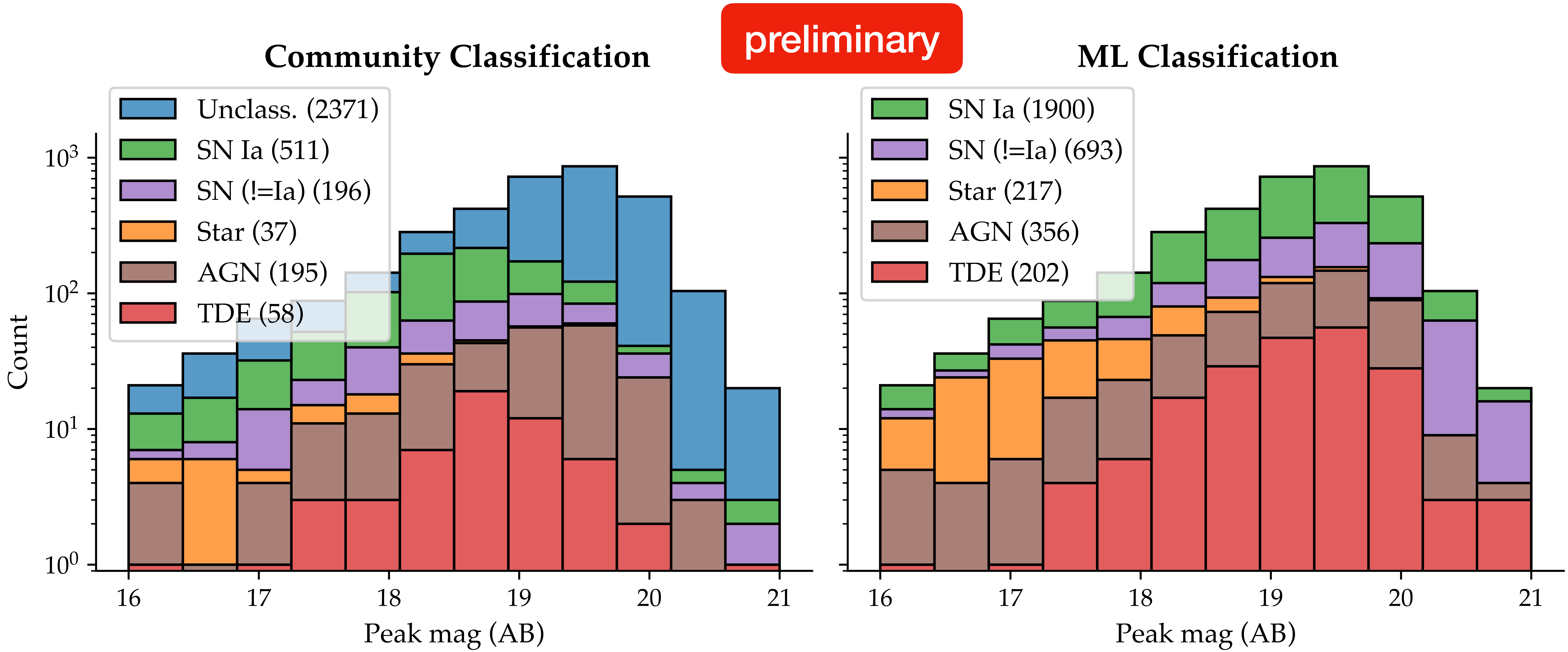
**Explore the wealth of transients contained in the sample**

**🚦AMPEL enables all this**

**Archival analyses have their own merits**

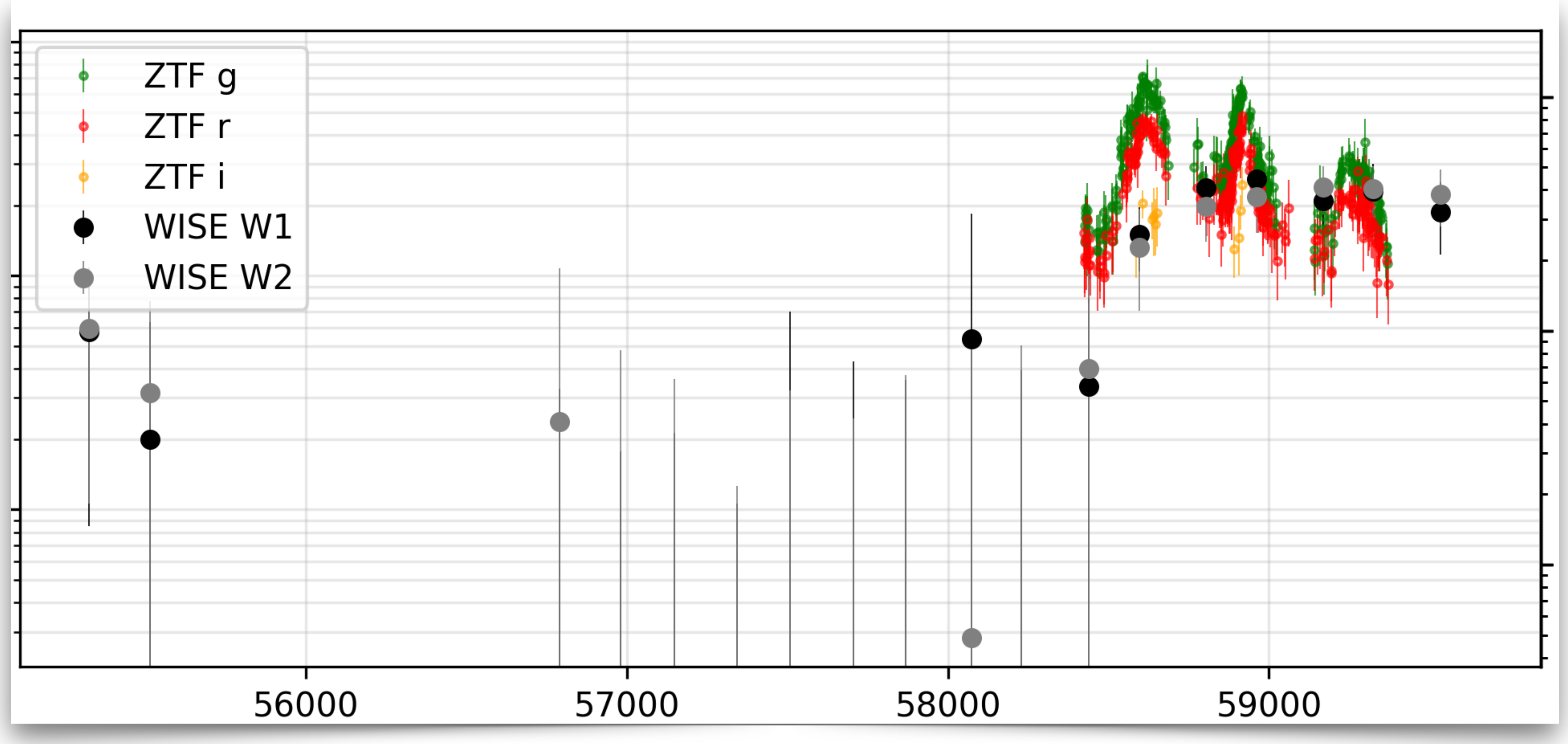
# Bonus

# Classification results

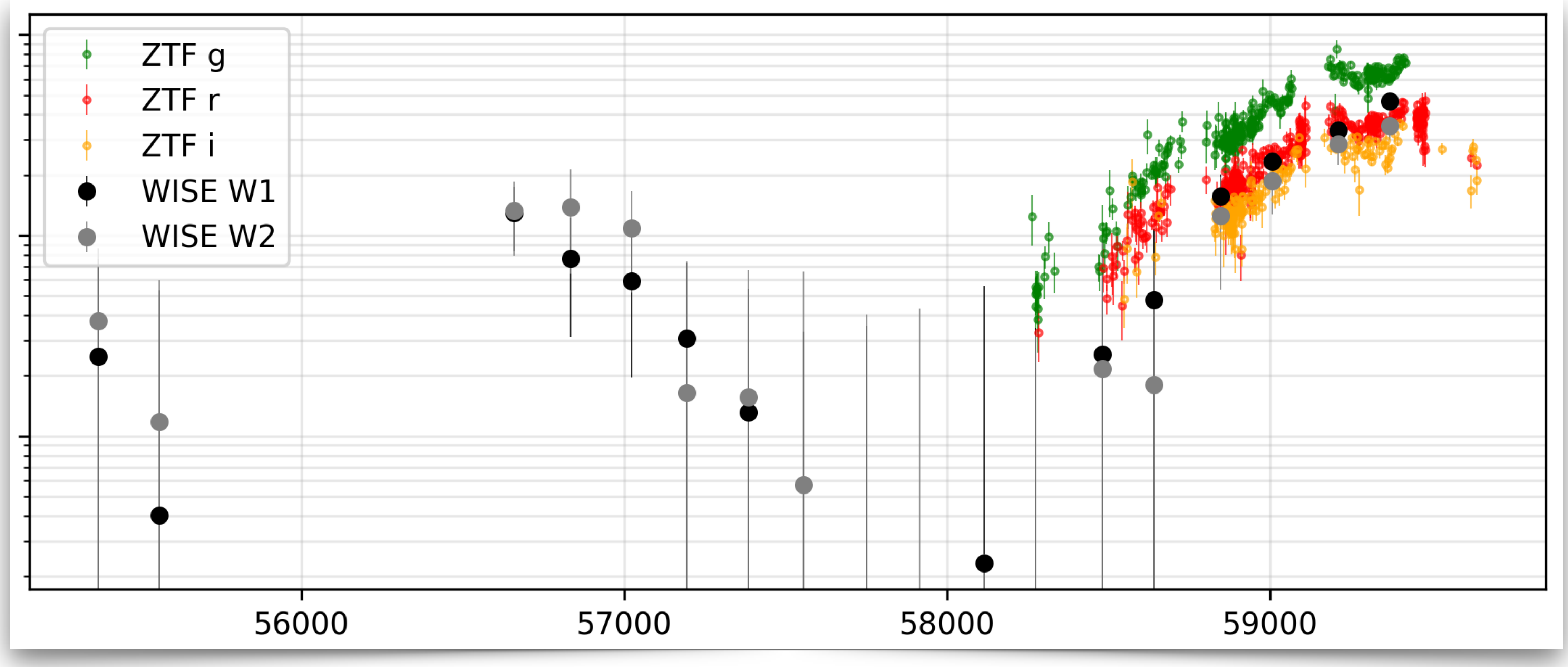


# IR transients: Filtered by IR

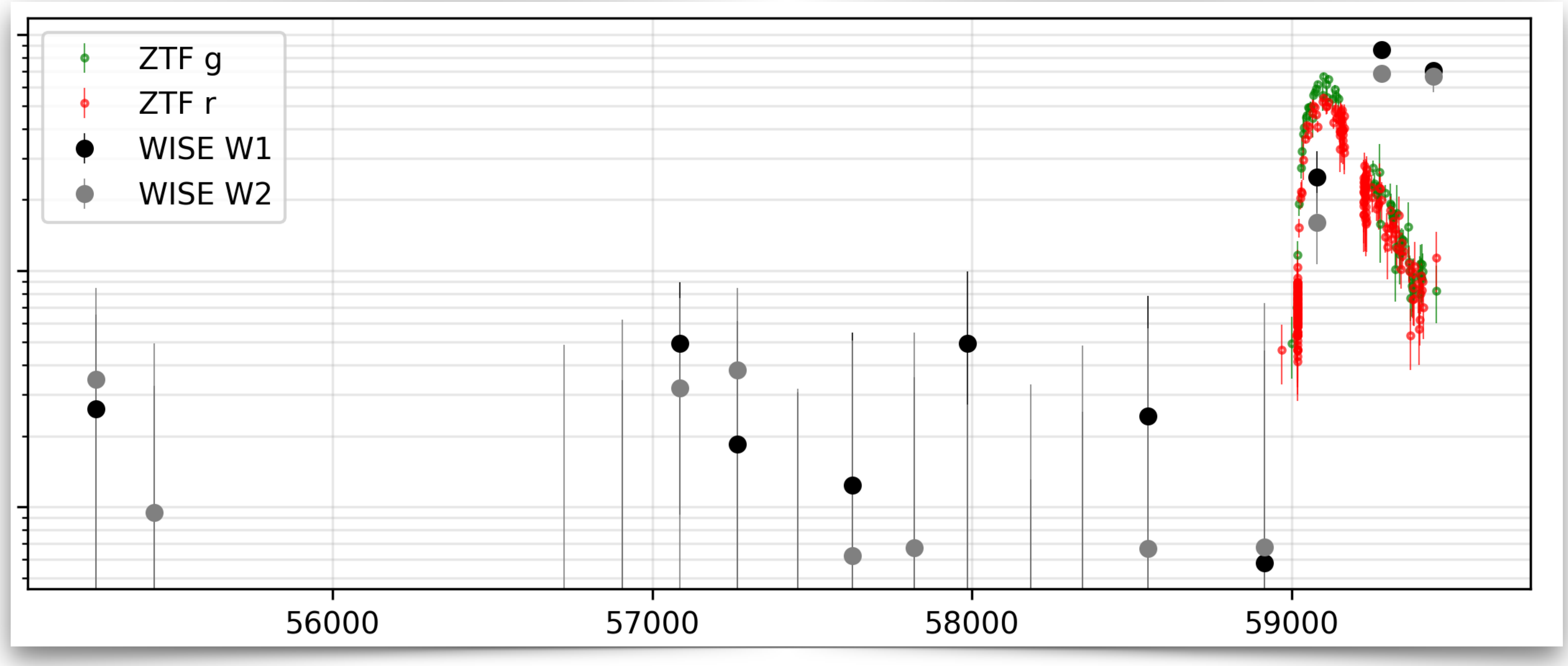
## Blazar candidates



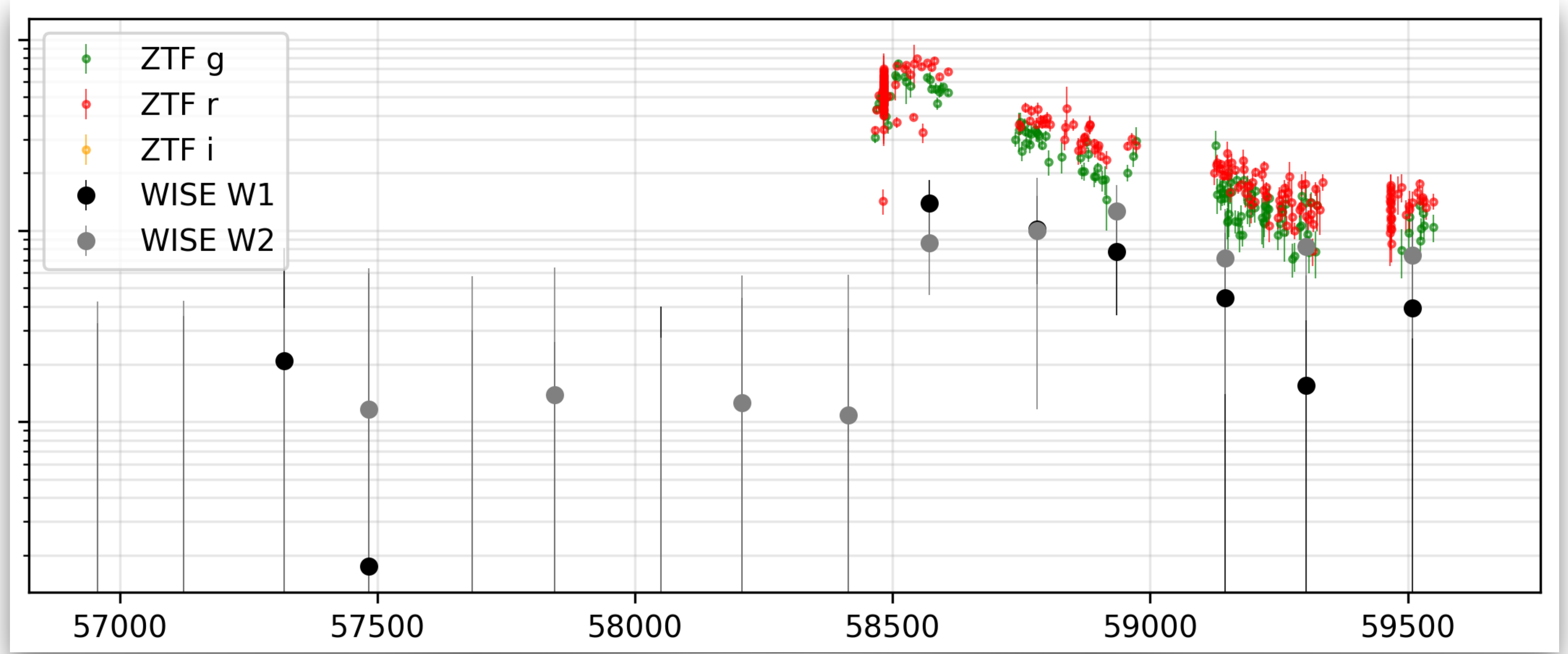

## slow rise, simultaneous IR rise



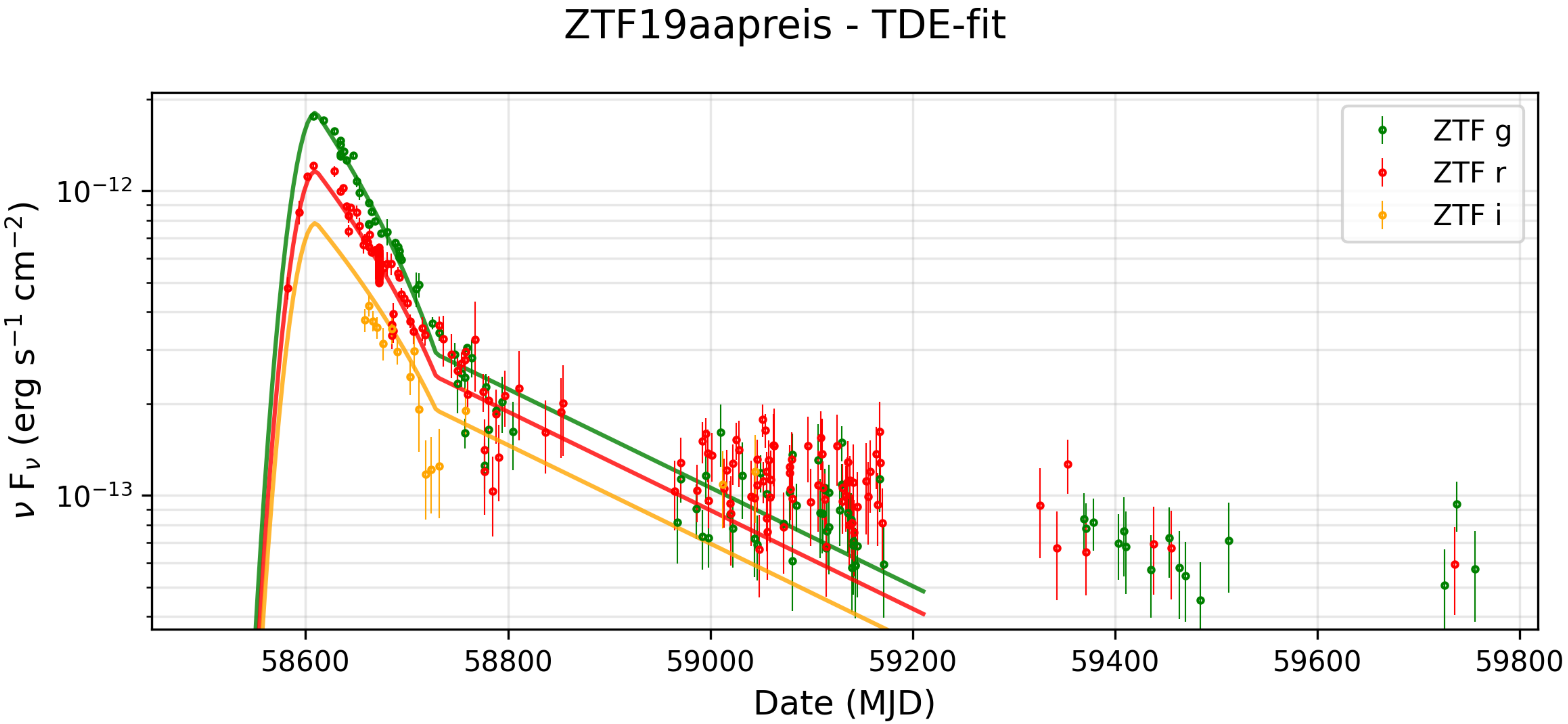

## TDE candidate




## Tywin-like



# Feature extraction: TDE Fit



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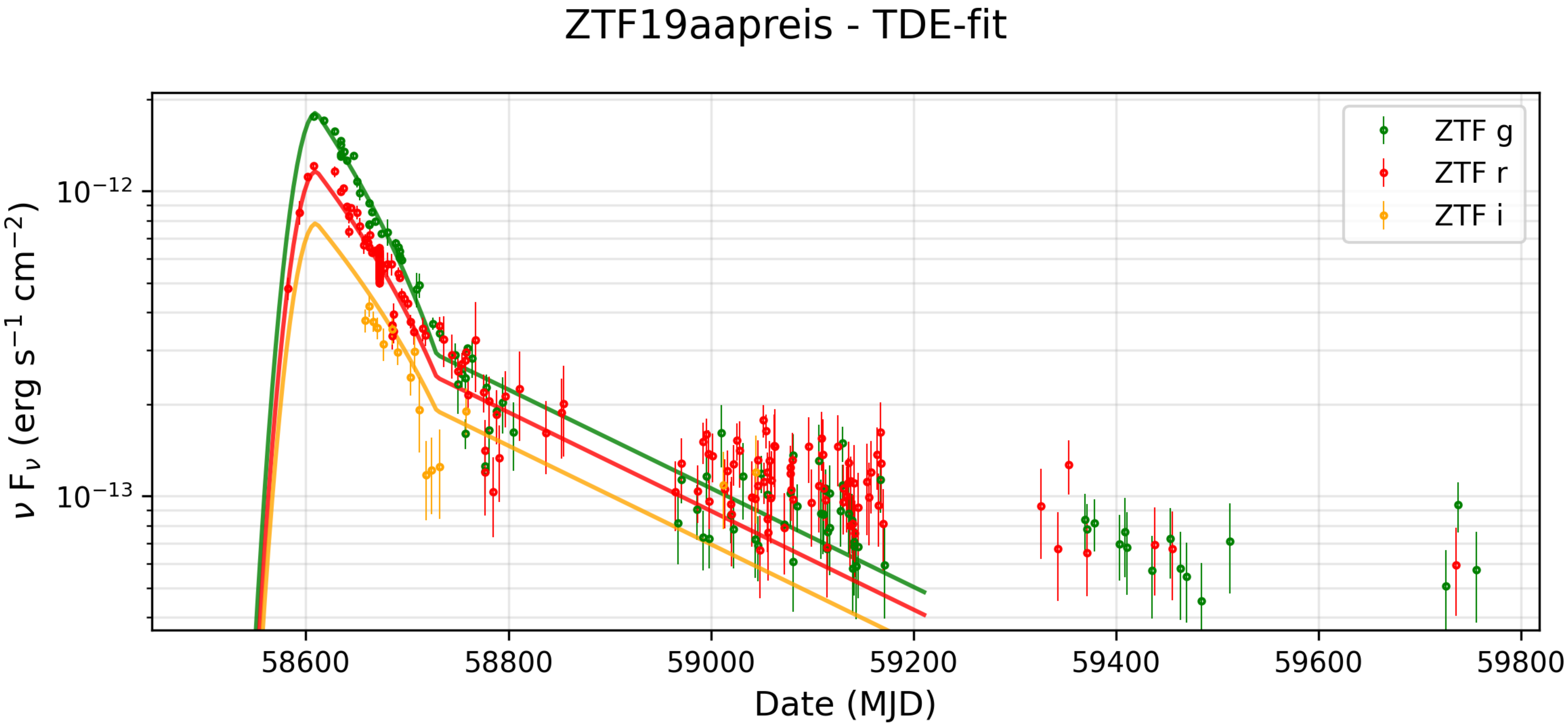
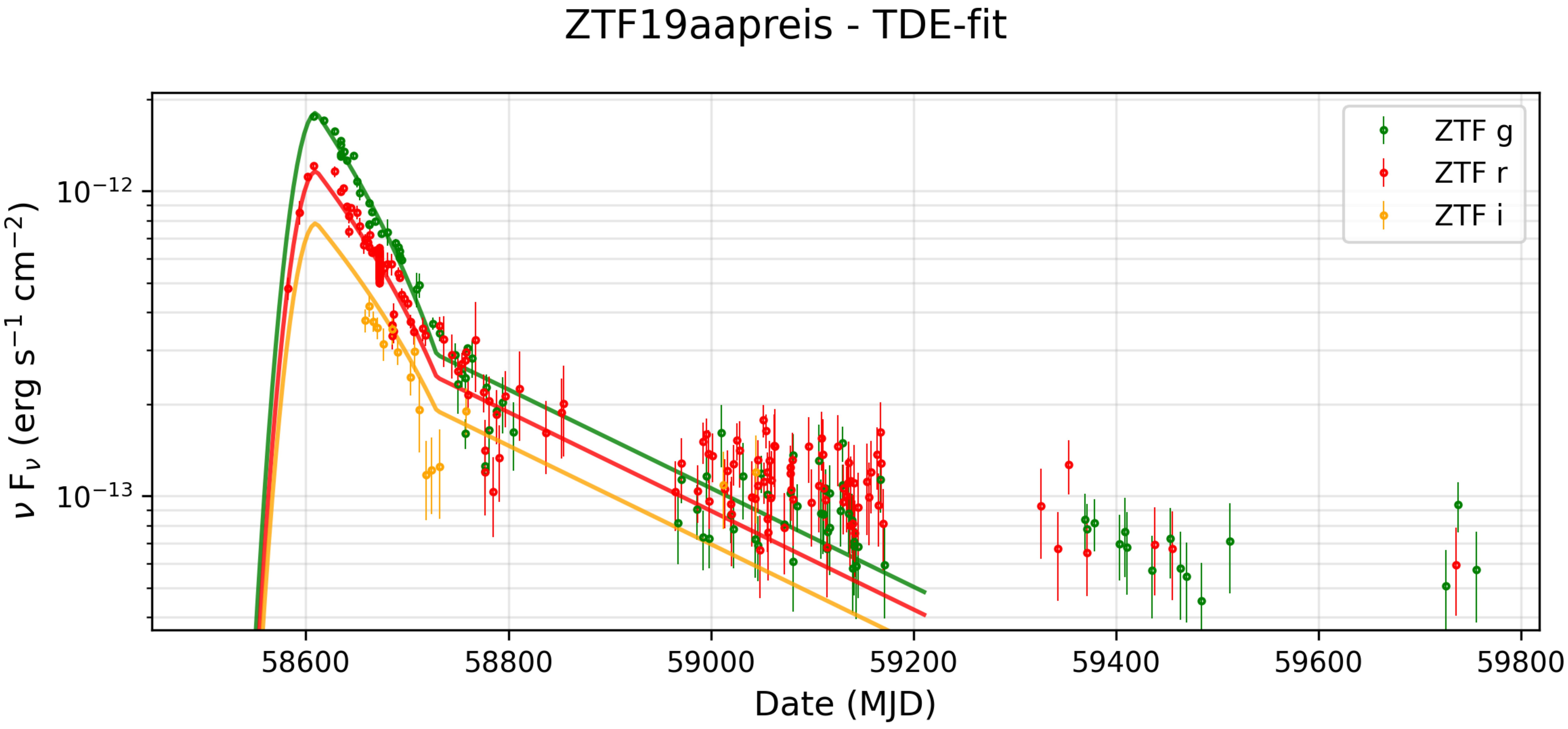



**Fit parameters:**

**risetime**
**decaytime**
**BB temp**
**BB d_temp**
**t_evo time**

# Feature extraction: TDE Fit




**Fit parameters:**

**risetime**
**decaytime**
**BB temp**
**BB d_temp**
**t_evo time**

**Fitted twice (stability)**

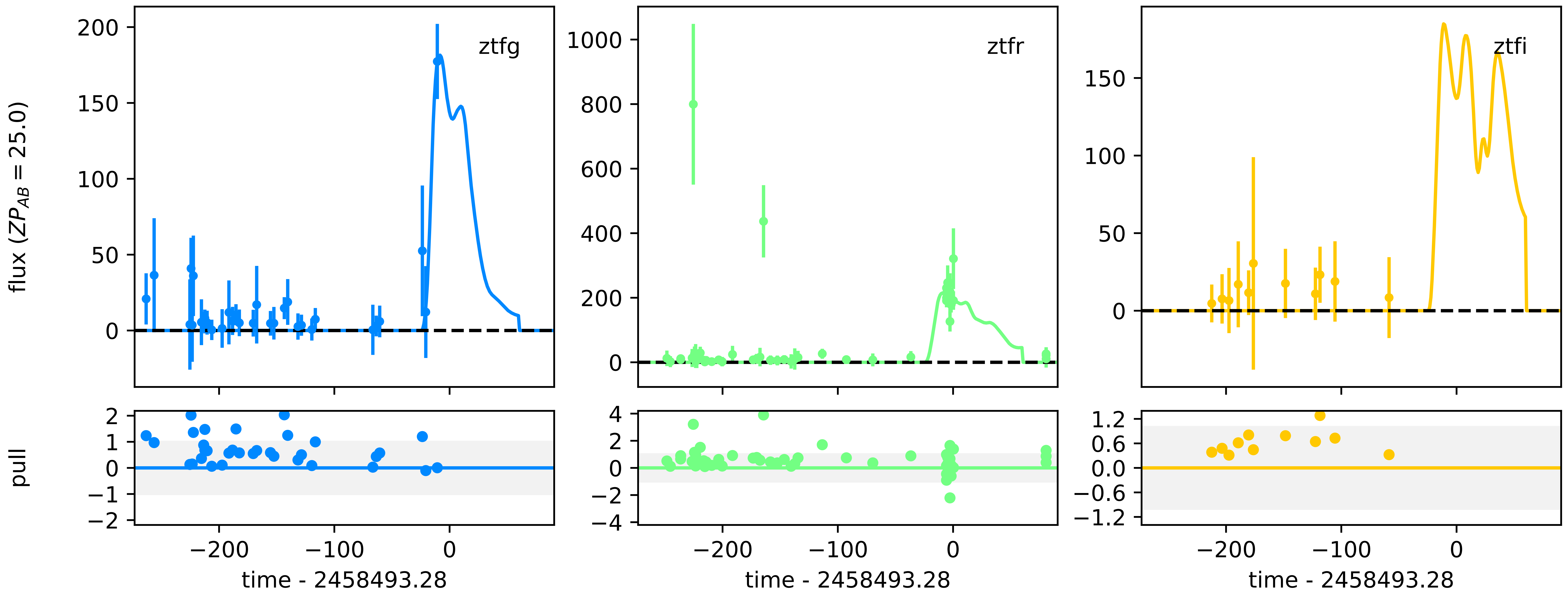
**Problem: T runaway (no UV)**

# Feature extraction: SALT Fit (SN Ia)

ZTF19aaafvzy salt2 None
chisq 87.77
ndof 90

$z = 0.21352750$
$t_0 = 2458493.3$
$x_0 = 2.6827823 \times 10^{-4}$
$x_1 = 8.3501711$

$c = 0.17711280$
mw $ebv = 0.068765168$
mw $r_v = 3.1000000$



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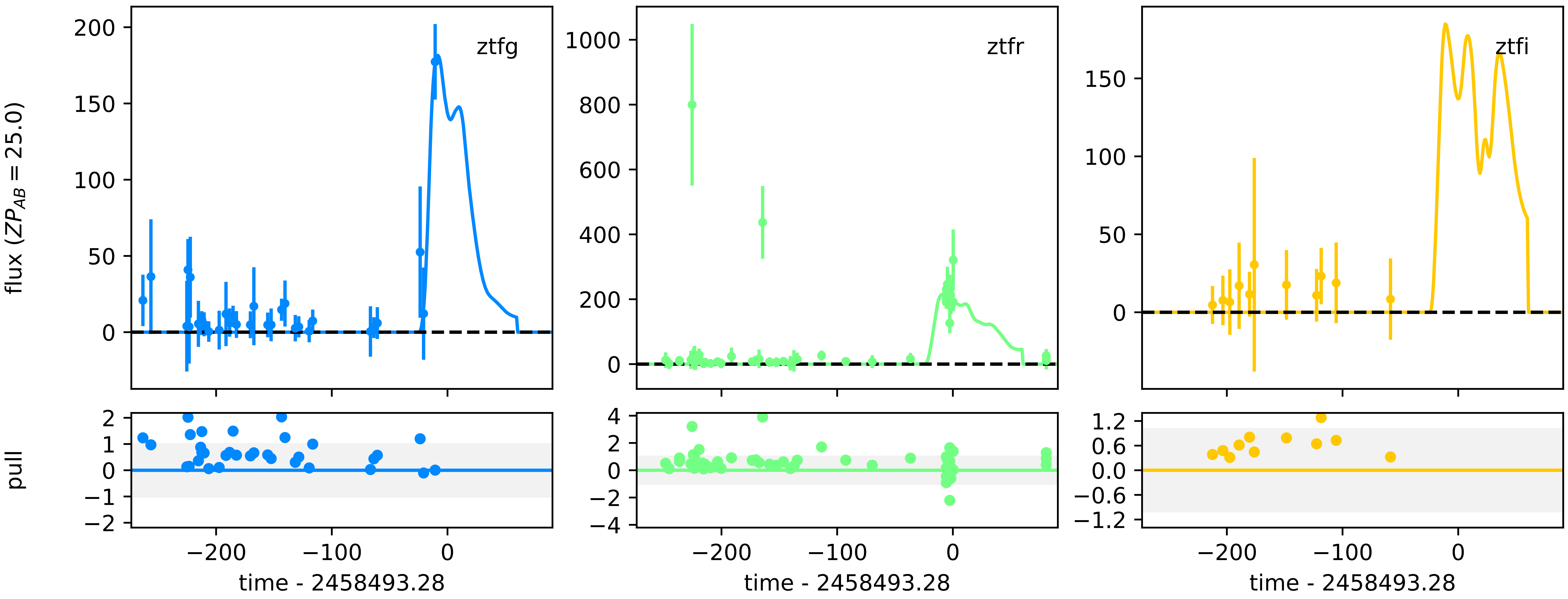
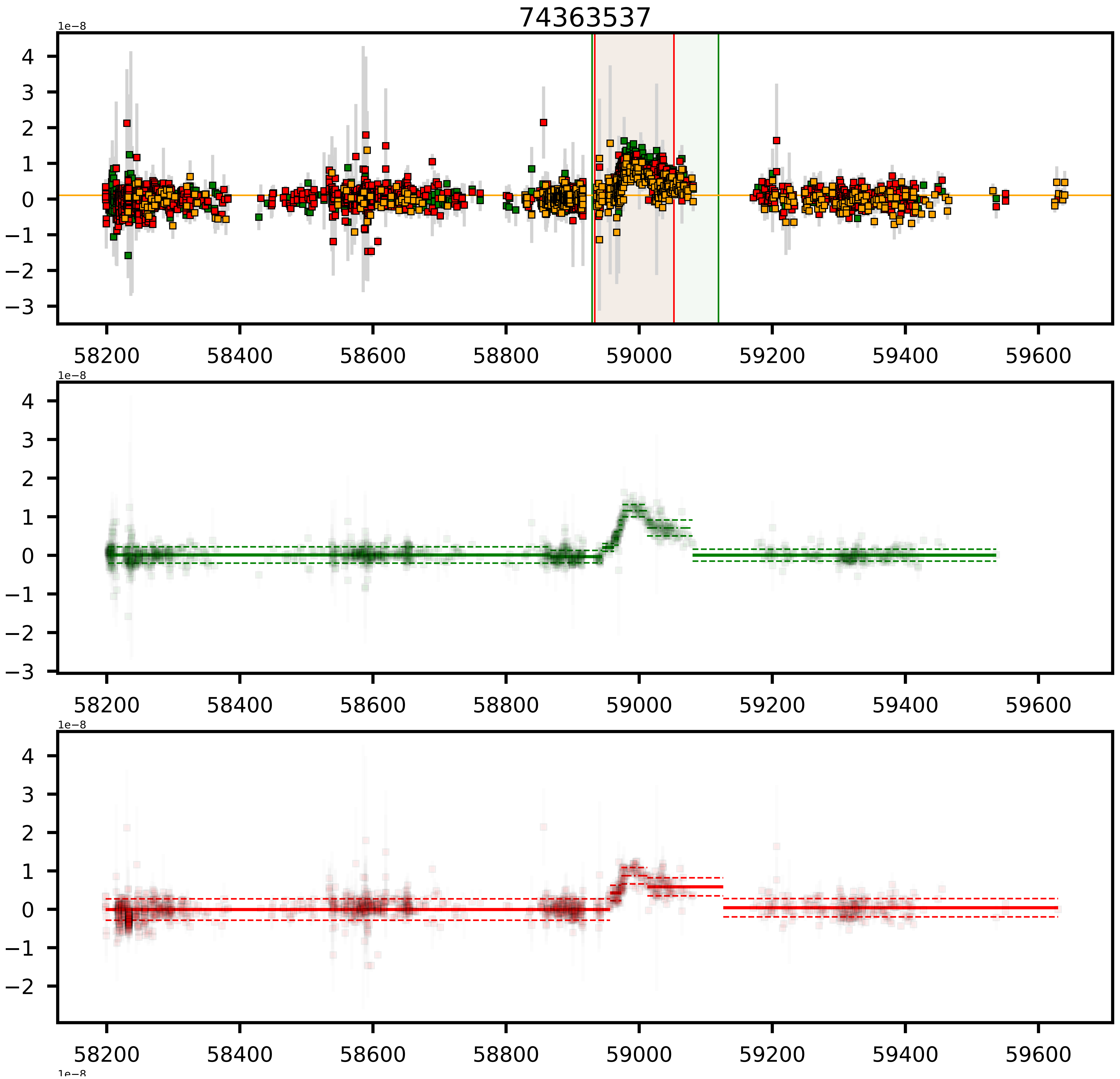


# Feature extraction

all bands

g-band

r-band

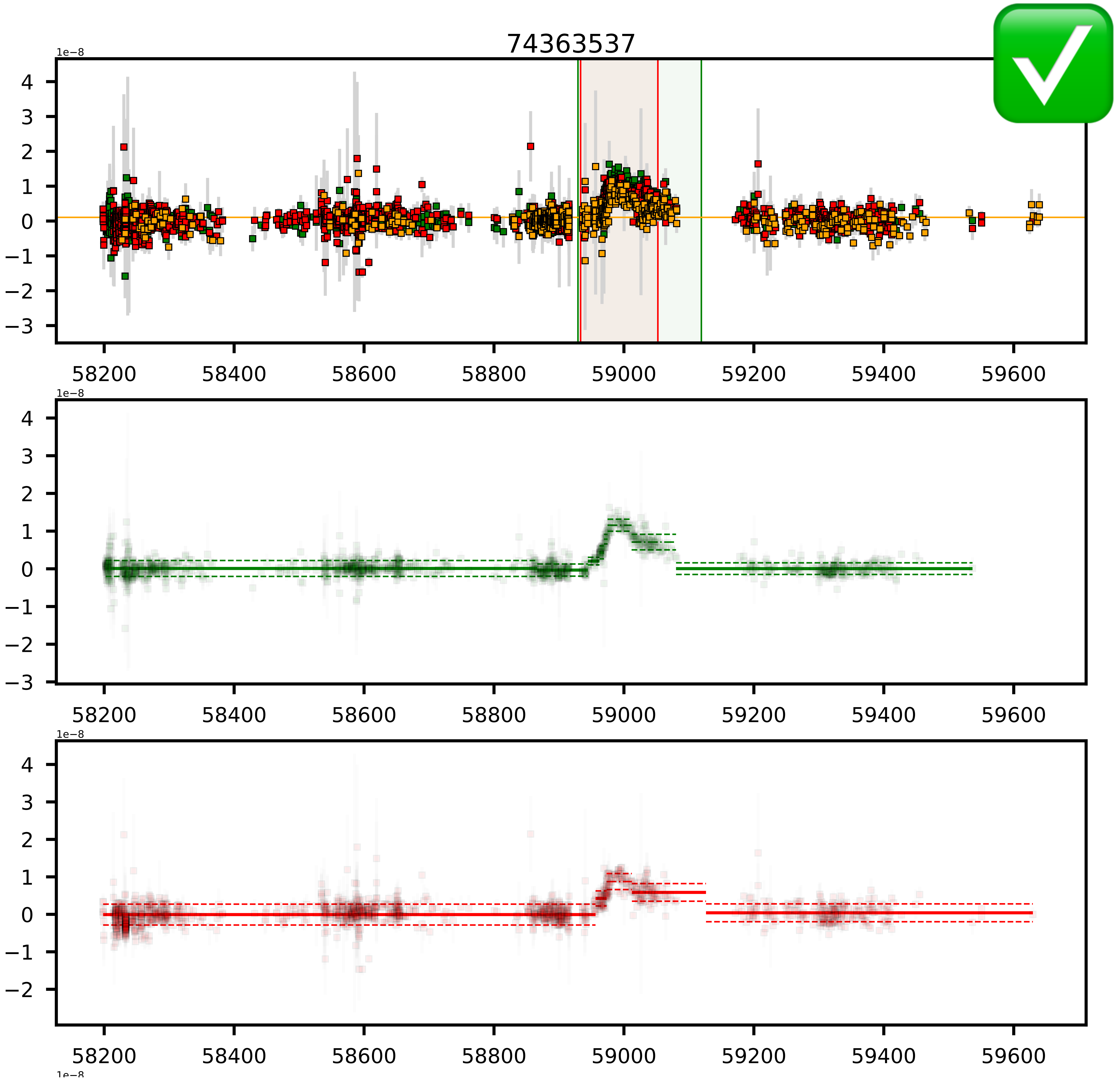


# Feature extraction

**all bands**

**g-band**

**r-band**



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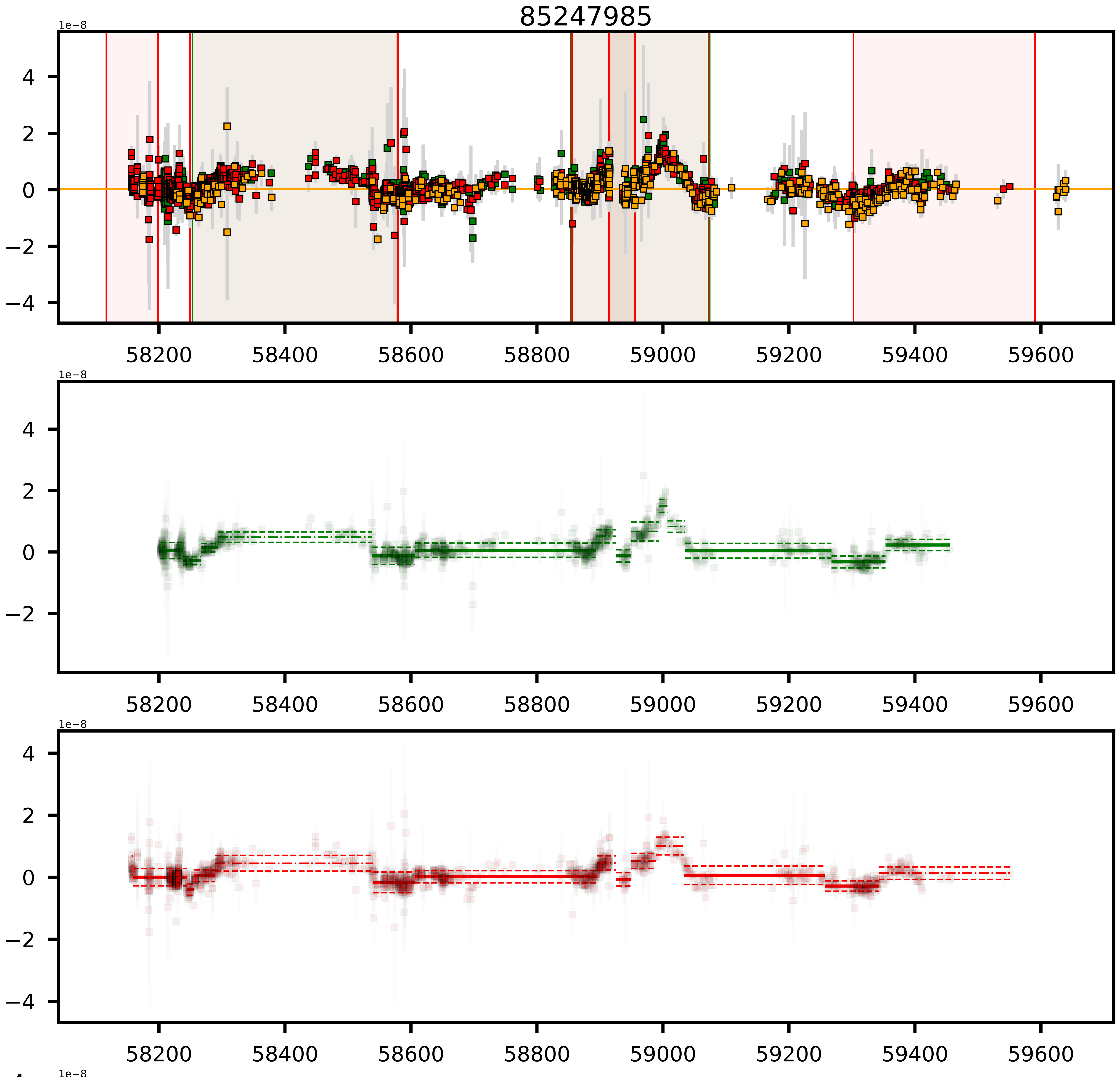
**all bands**

**g-band**

**r-band**

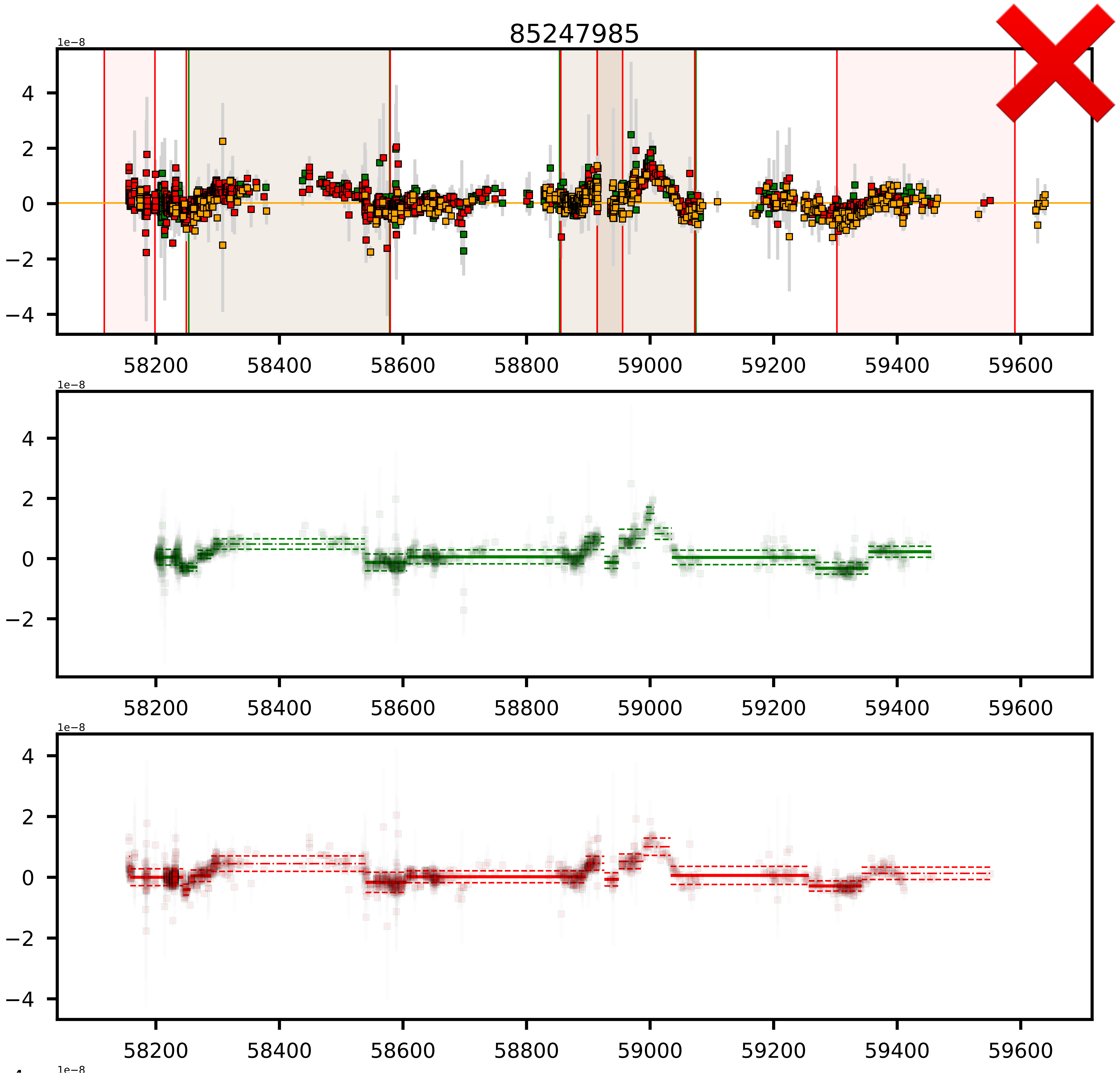


# Feature extraction

all bands

g-band

r-band



# Features used (20 in total)

peak apparent mag

sgscore

WISE colors (with scatter for noisified child lightcurves)

SALT fit results ($c$, $x_0$, $x_1$)

TDE fit results (rise, decay, temp, d_temp)

distnr (core distance, scaled for noisified child lightcurves)

Bayesian block analysis: overlapping regions

**no z** (only indirectly for some of the SALT fits)

# Noisification

K-correct (bandpasses see different flux depending on object redshift)

Redshift

Random dropout

Wiggle time a bit

Generate child lightcurves:

**SN Ia**: 12683 **TDE**: 10231 **SN $\neq$ Ia**: 10852 **AGN**: 8220 **star**: 505

**Children per object**

**SN Ia**: 4 **TDE**: 155 **SN $\neq$ Ia**: 10 **AGN**: 94 **star**: 0

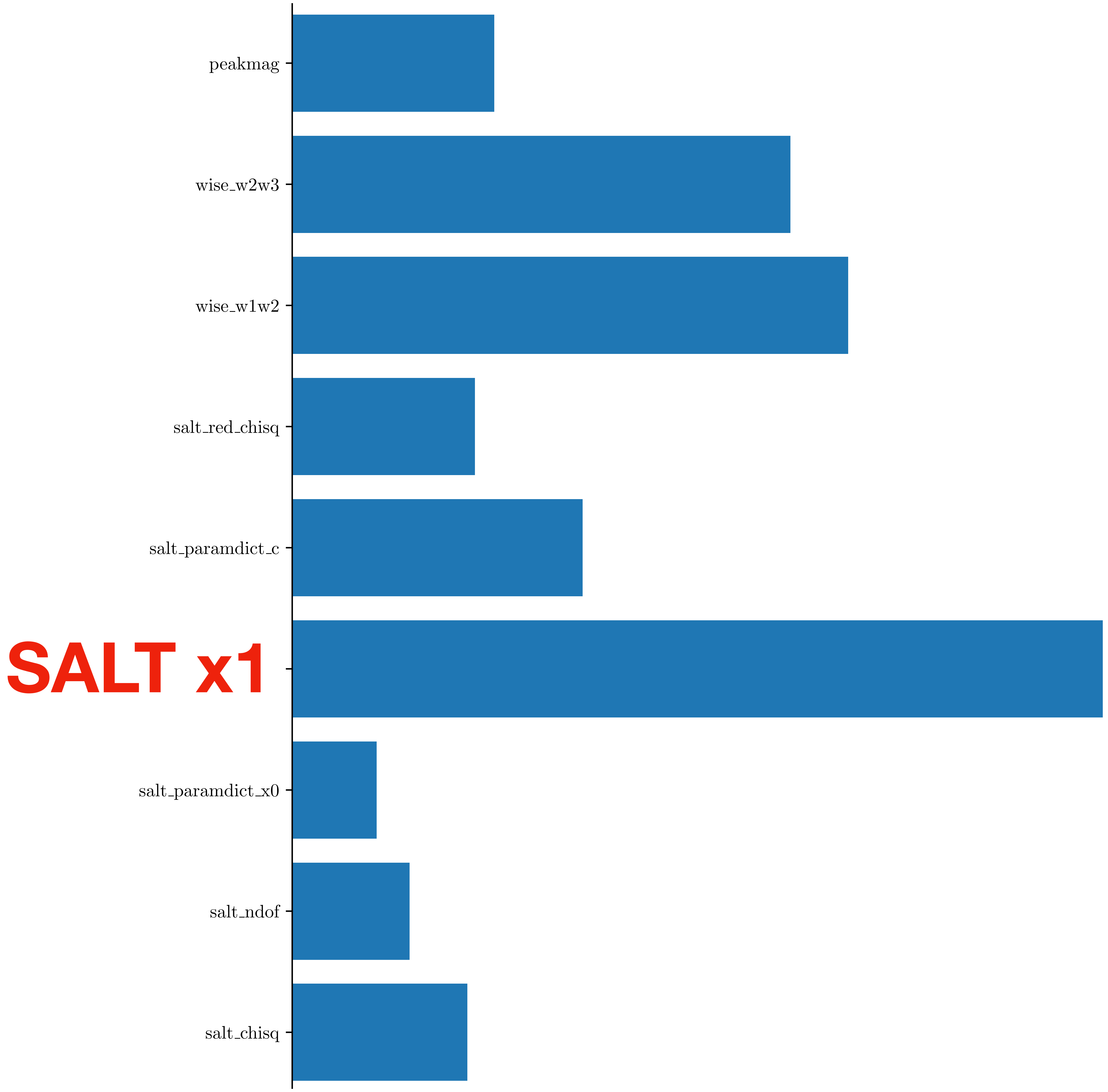
# Train XGBoost

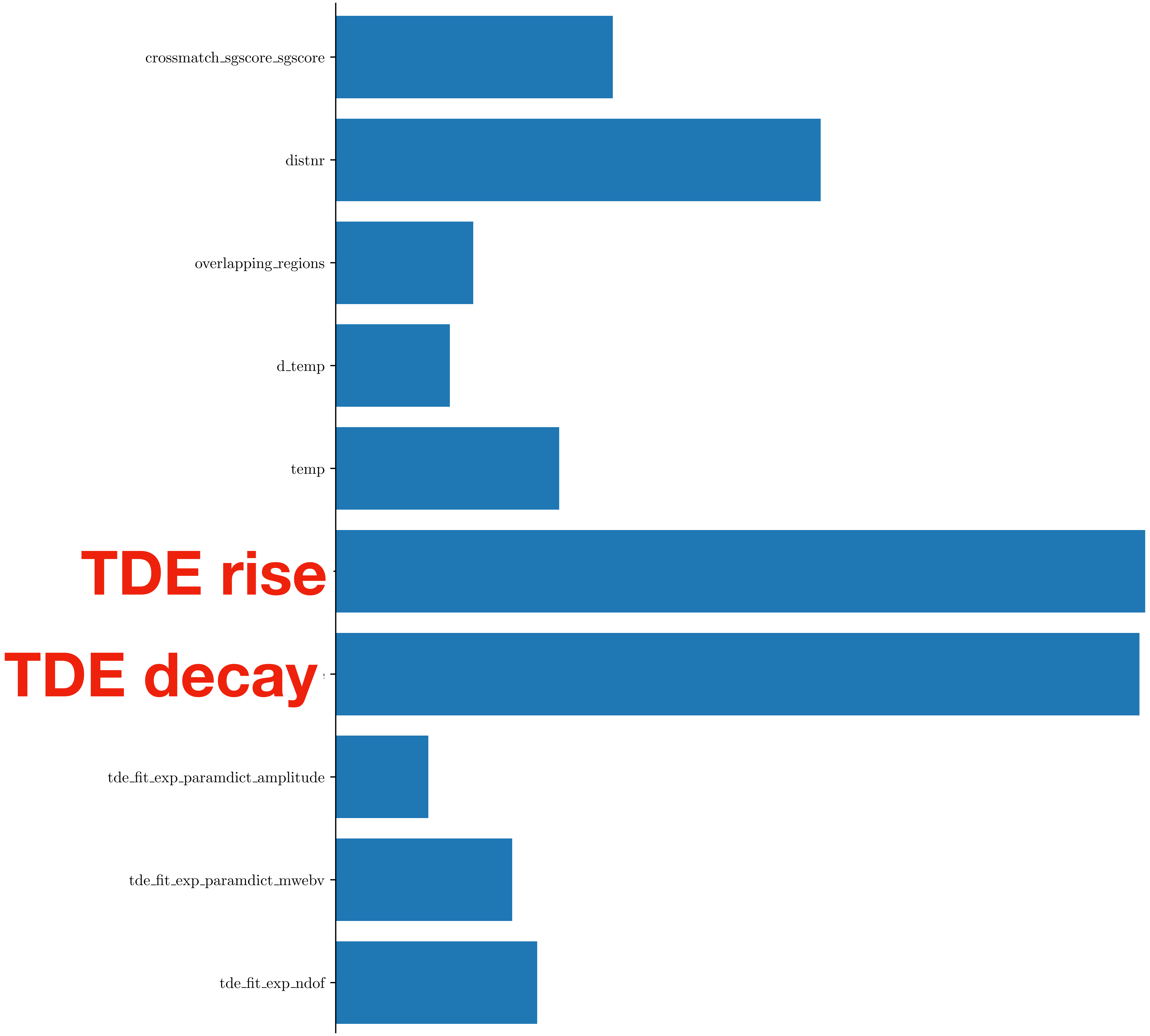
train-validation fraction = 0.7

test fraction = 0.3

hyper parameter search (9 parameters) with 50 iterations

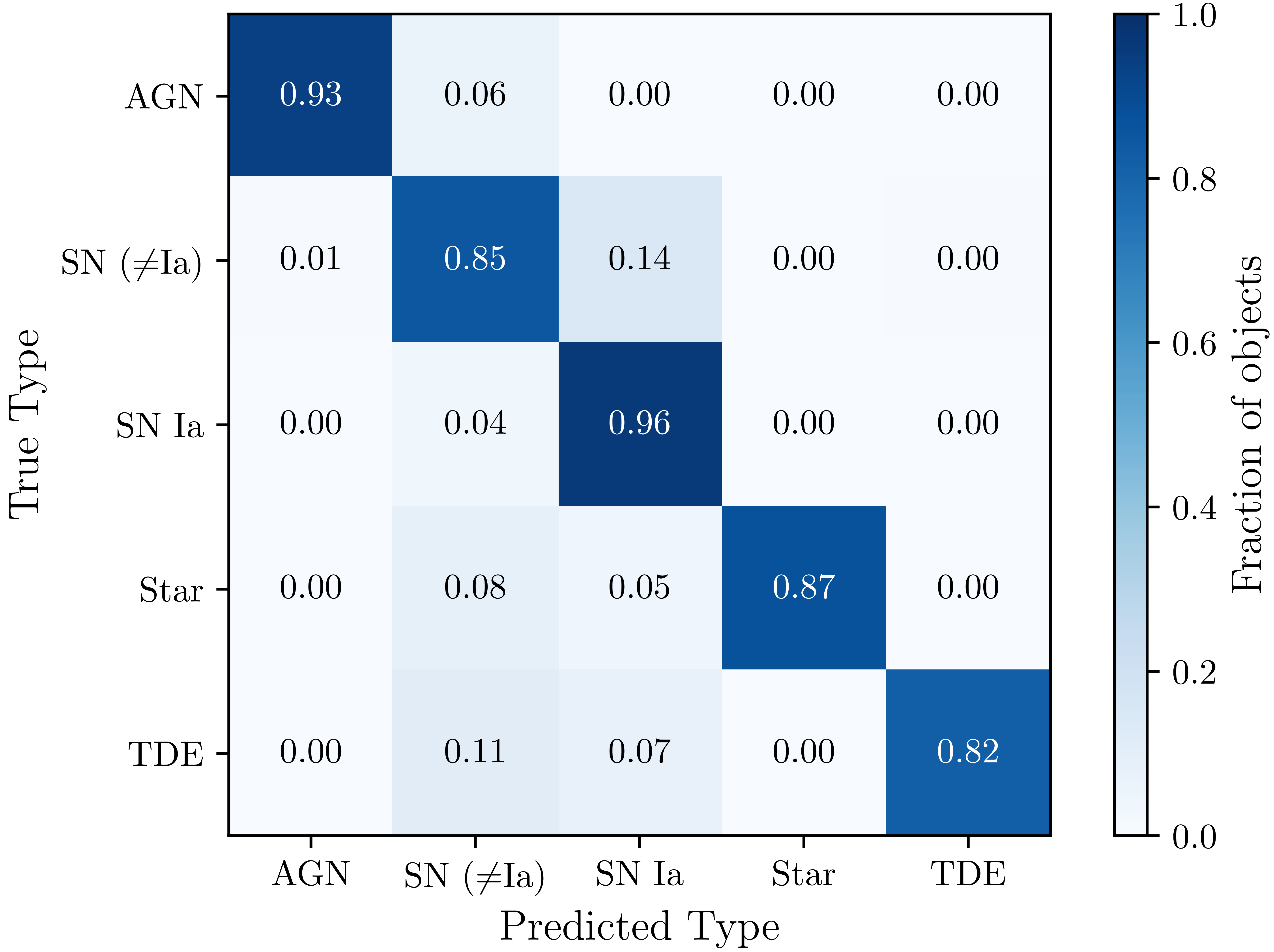
# XGBoost feature importance



# Evaluation with test sample

**Including** noisified lightcurves in the test sample



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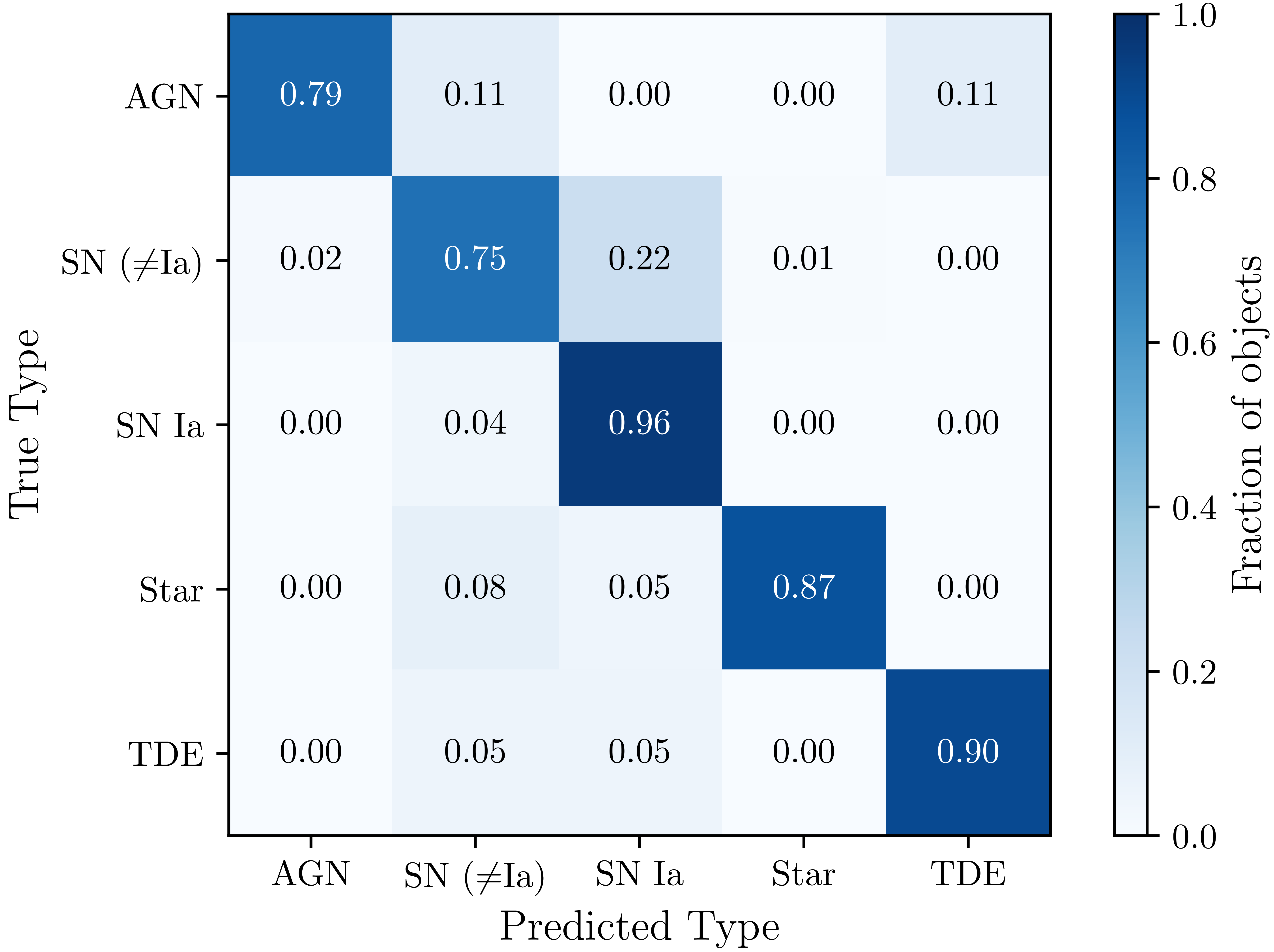
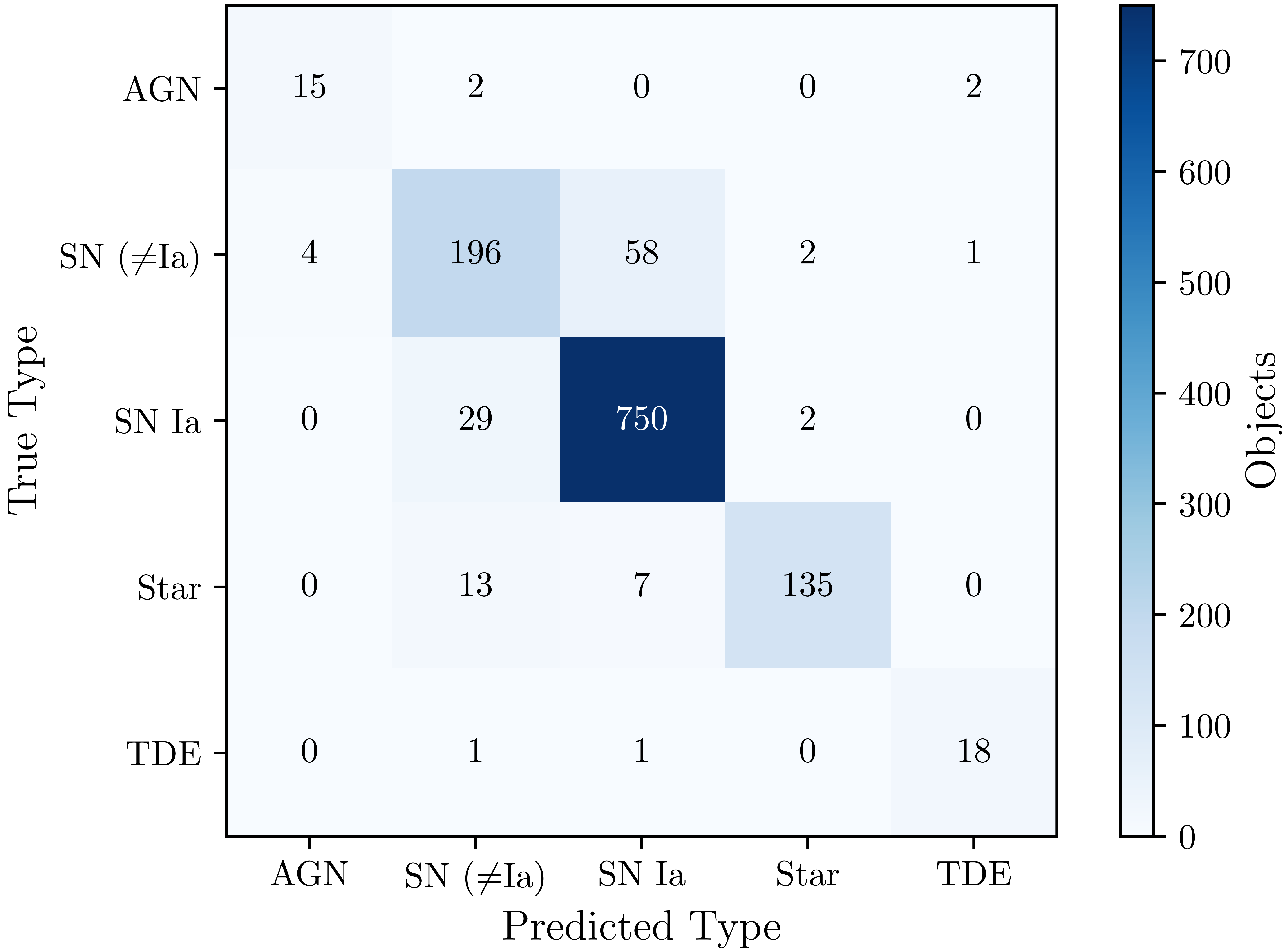


# Evaluation with test sample

**Not including** noisified lightcurves in the test sample

**absolute numbers**



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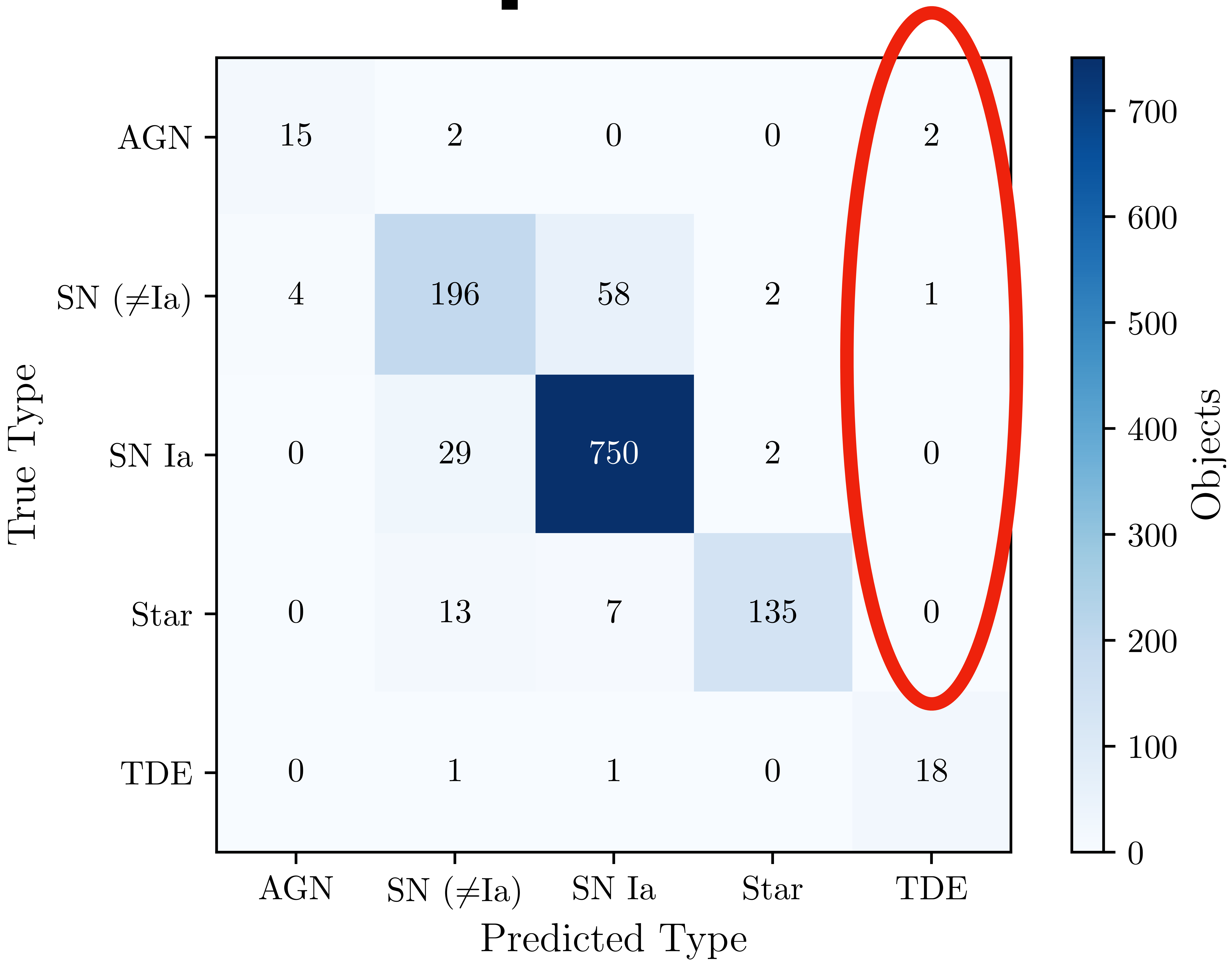
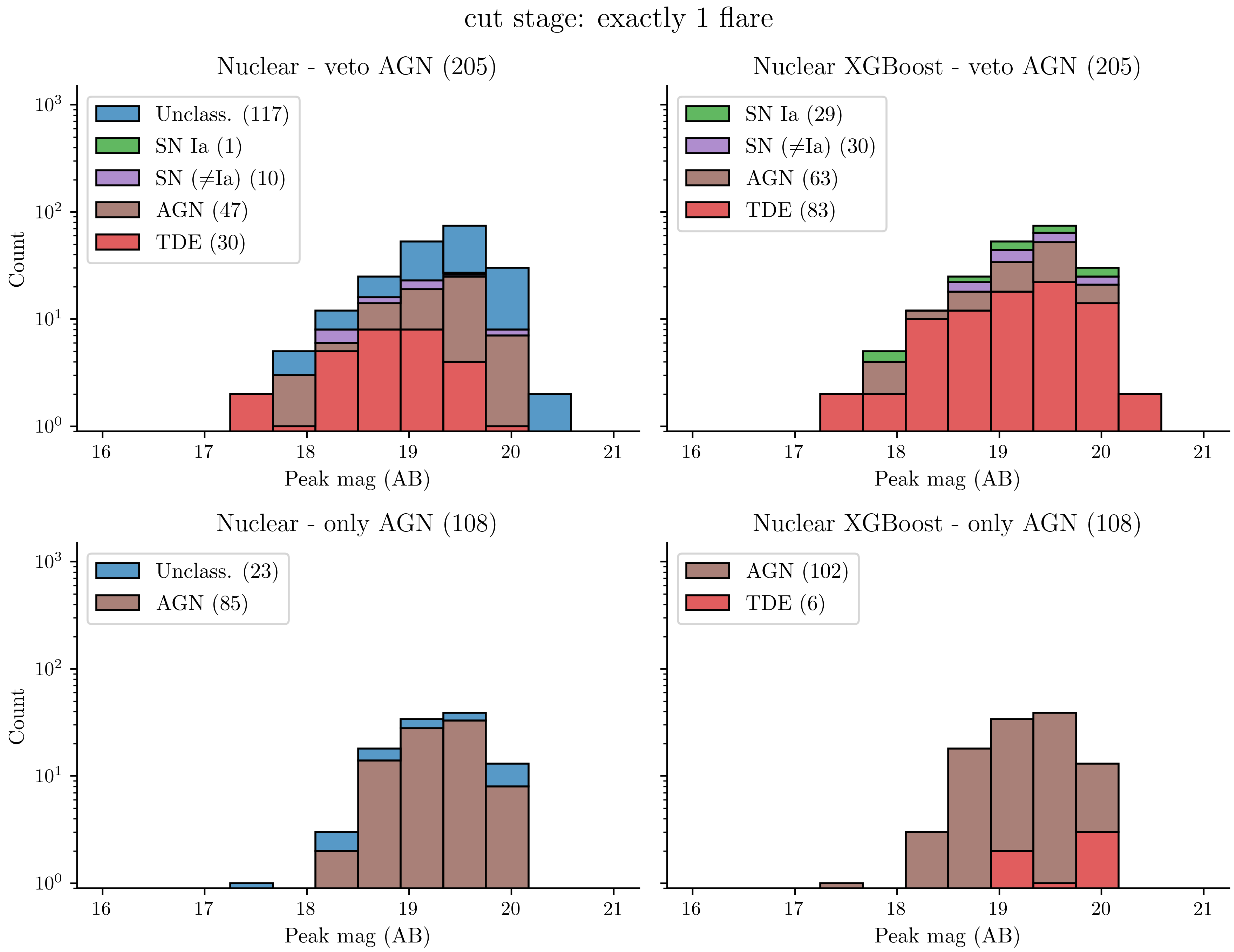


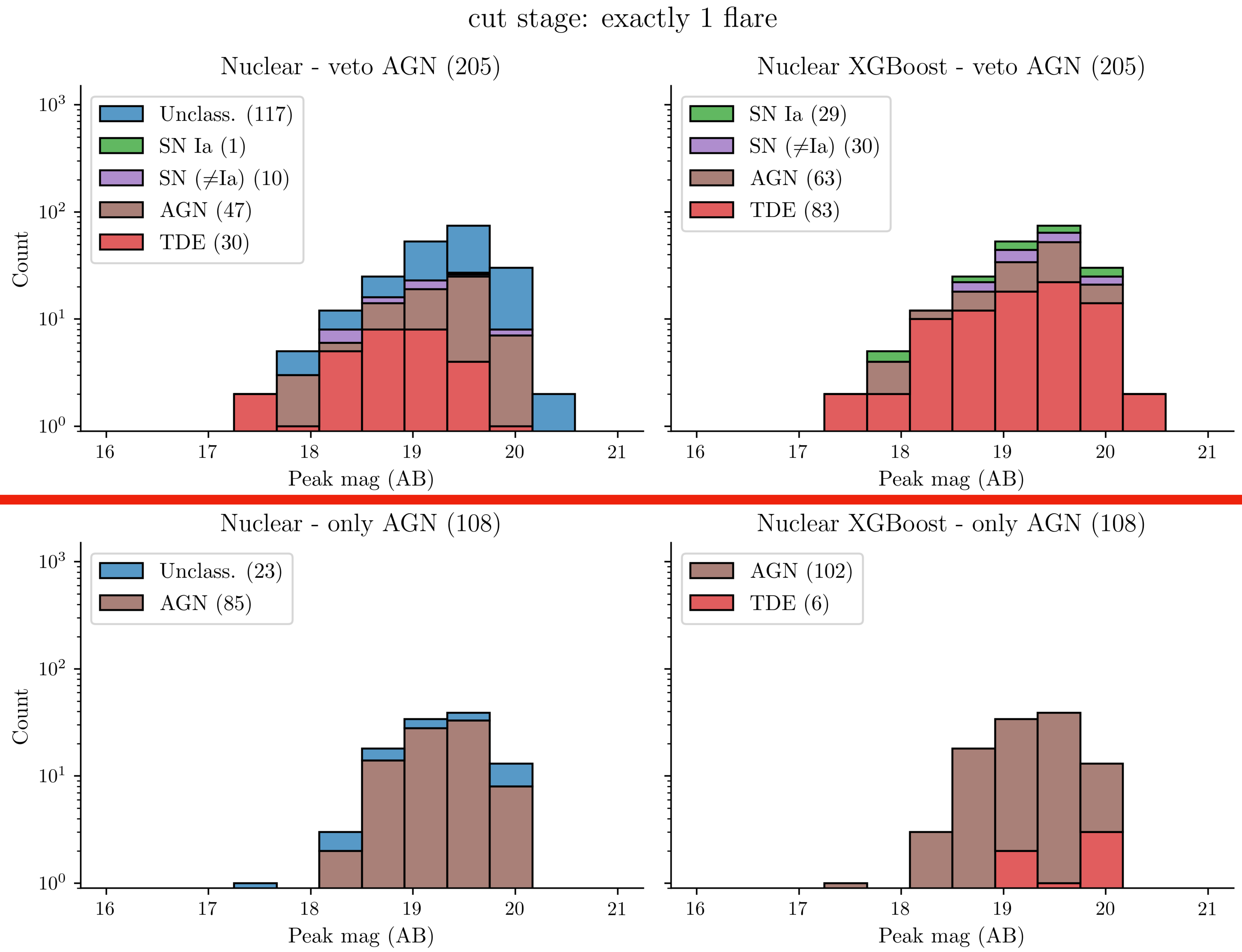
# No we apply the classifier to the nuclear sample

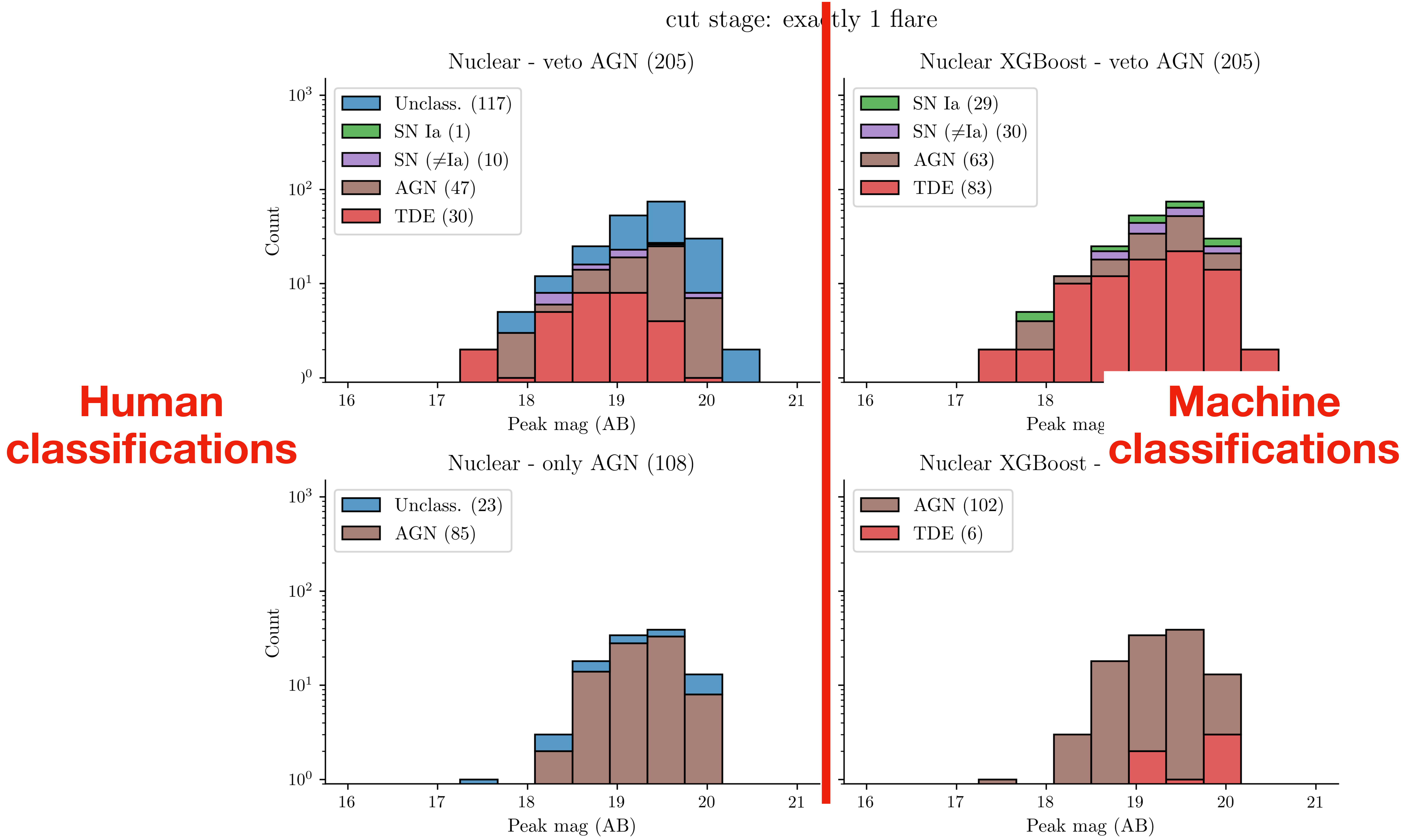
# after all cuts



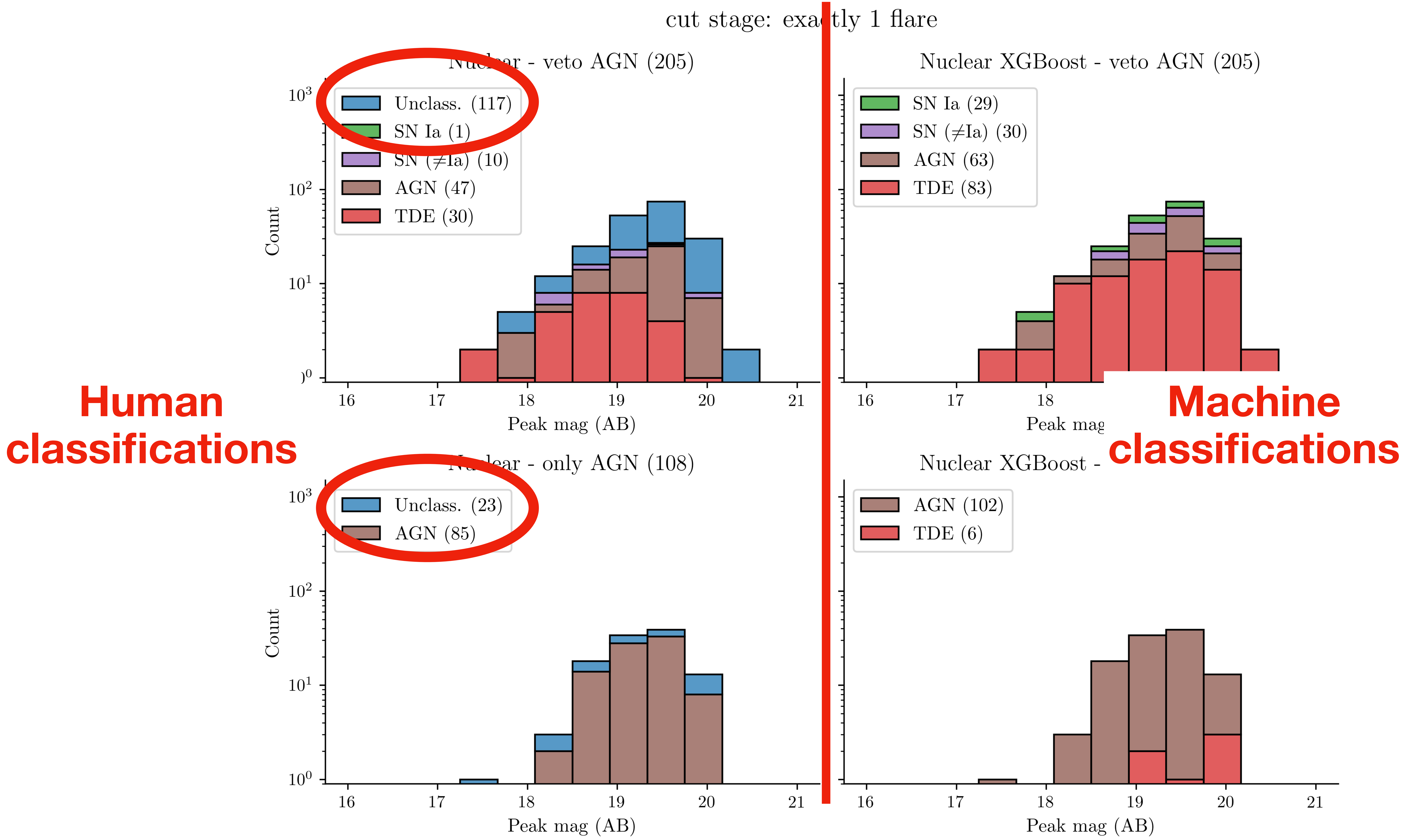
**no Milliquas match (not AGN)**

**has Milliquas match (AGN)**





cut stage: exactly 1 flare
Nuclear - veto AGN (205)
Unclass. (117)
SN Ia (1)
SN (≠Ia) (10)
AGN (47)
TDE (30)
Nuclear XGBoost - veto AGN (205)
SN Ia (29)
SN (≠Ia) (30)
AGN (63)
TDE (83)
Nuclear - only AGN (108)
Unclass. (23)
AGN (85)
Nuclear XGBoost -
AGN (102)
TDE (6)
Count
Peak mag (AB)
Human classifications
Machine classifications



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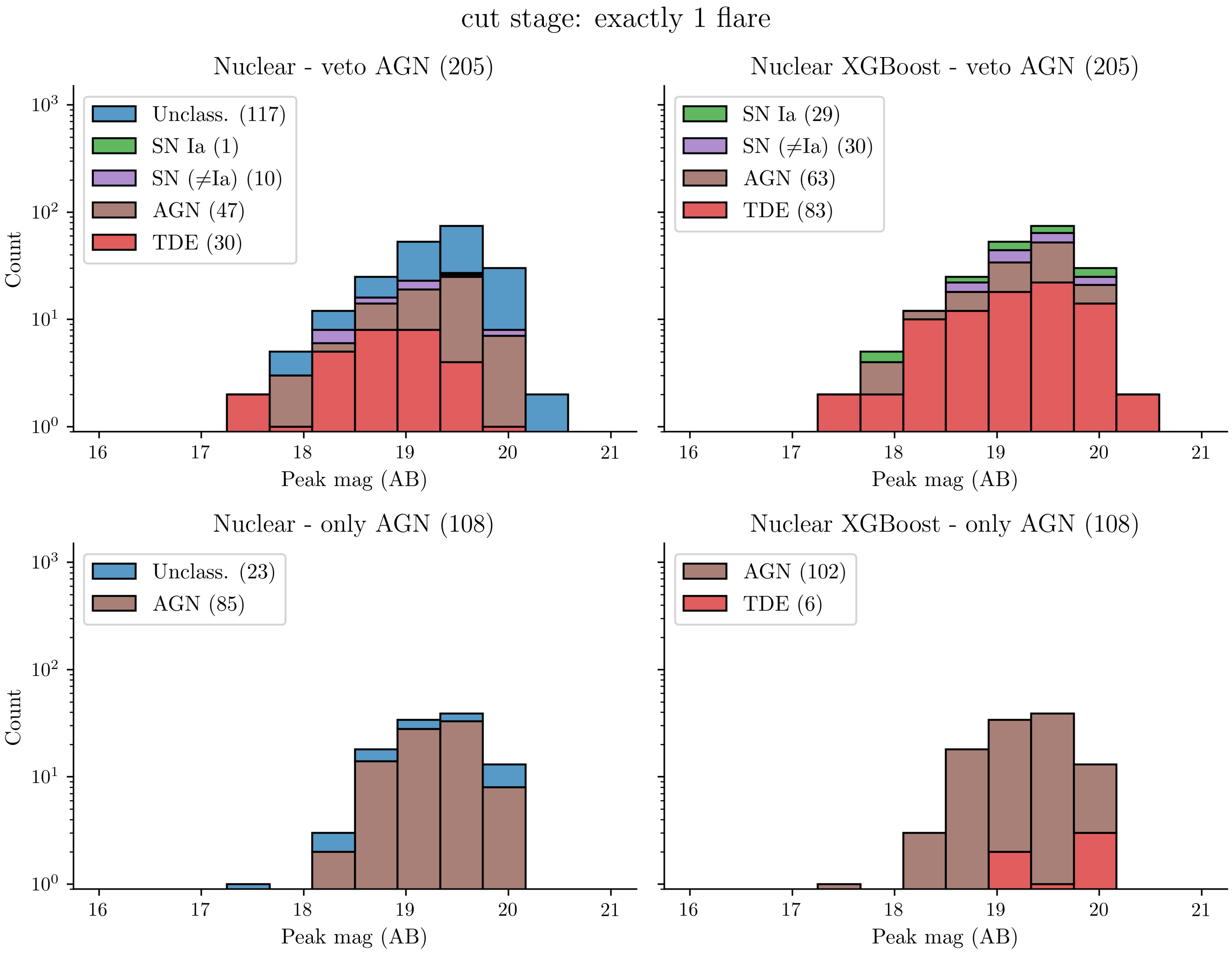

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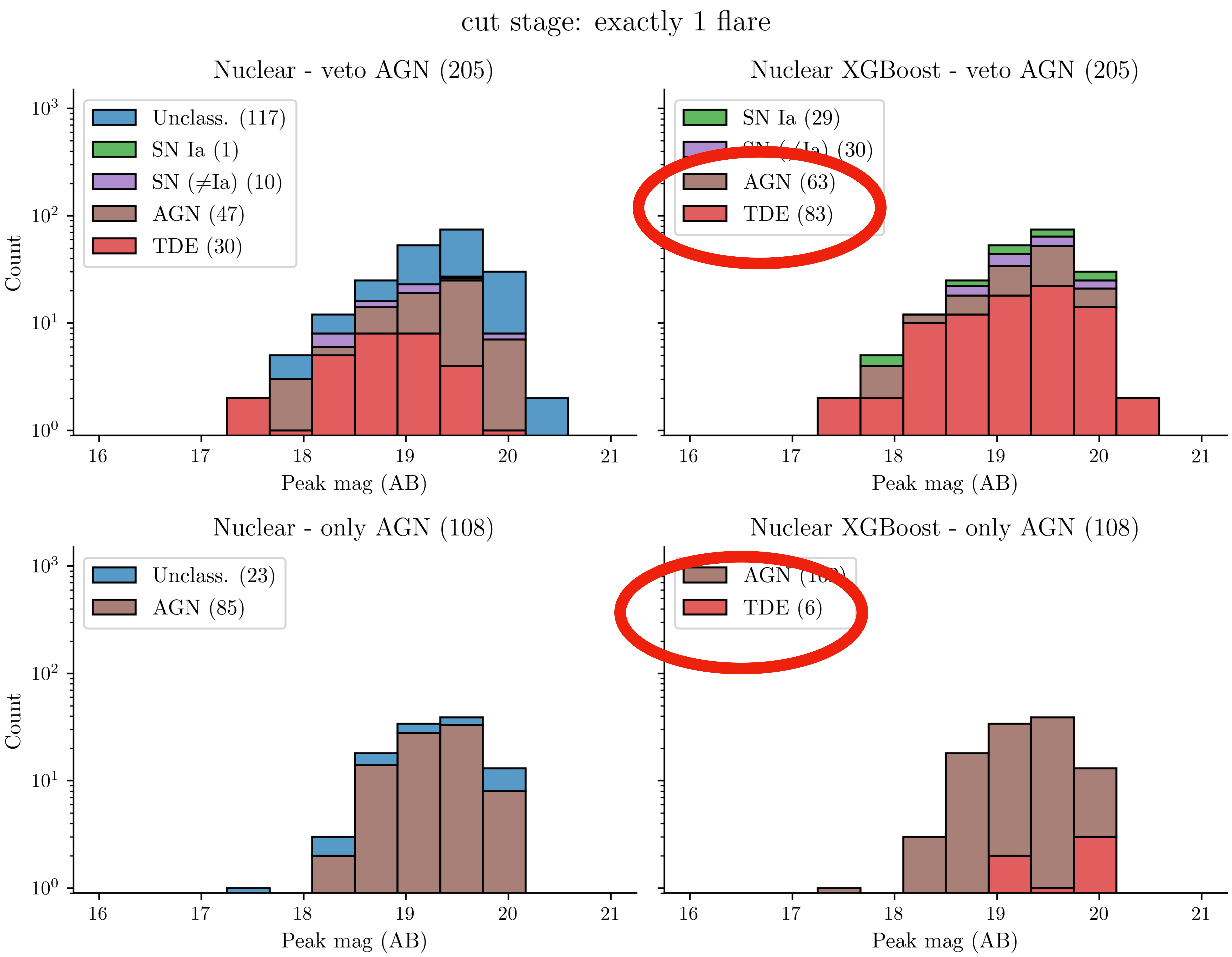
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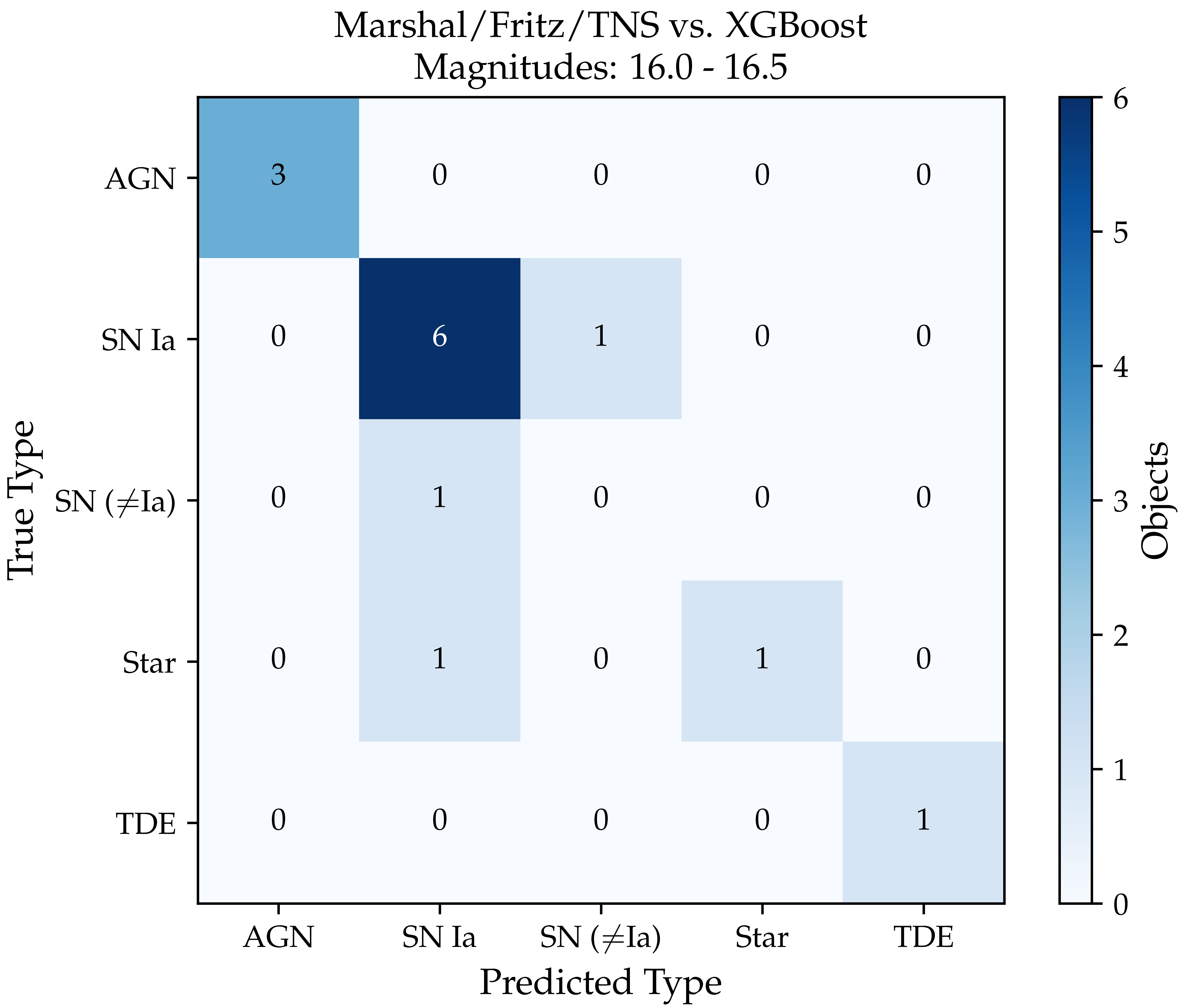
Nuclear - only AGN (108)
Unclass. (23)
AGN (85)
Nuclear XGBoost - only AGN (108)
AGN
TDE (6)
Count
Peak mag (AB)
10^0
10^1
10^2
10^3
16
17
18
19
20
21

# Compare to unsecure classifications pulled from the internet

# Evaluation with unsecure truth

## Mag:

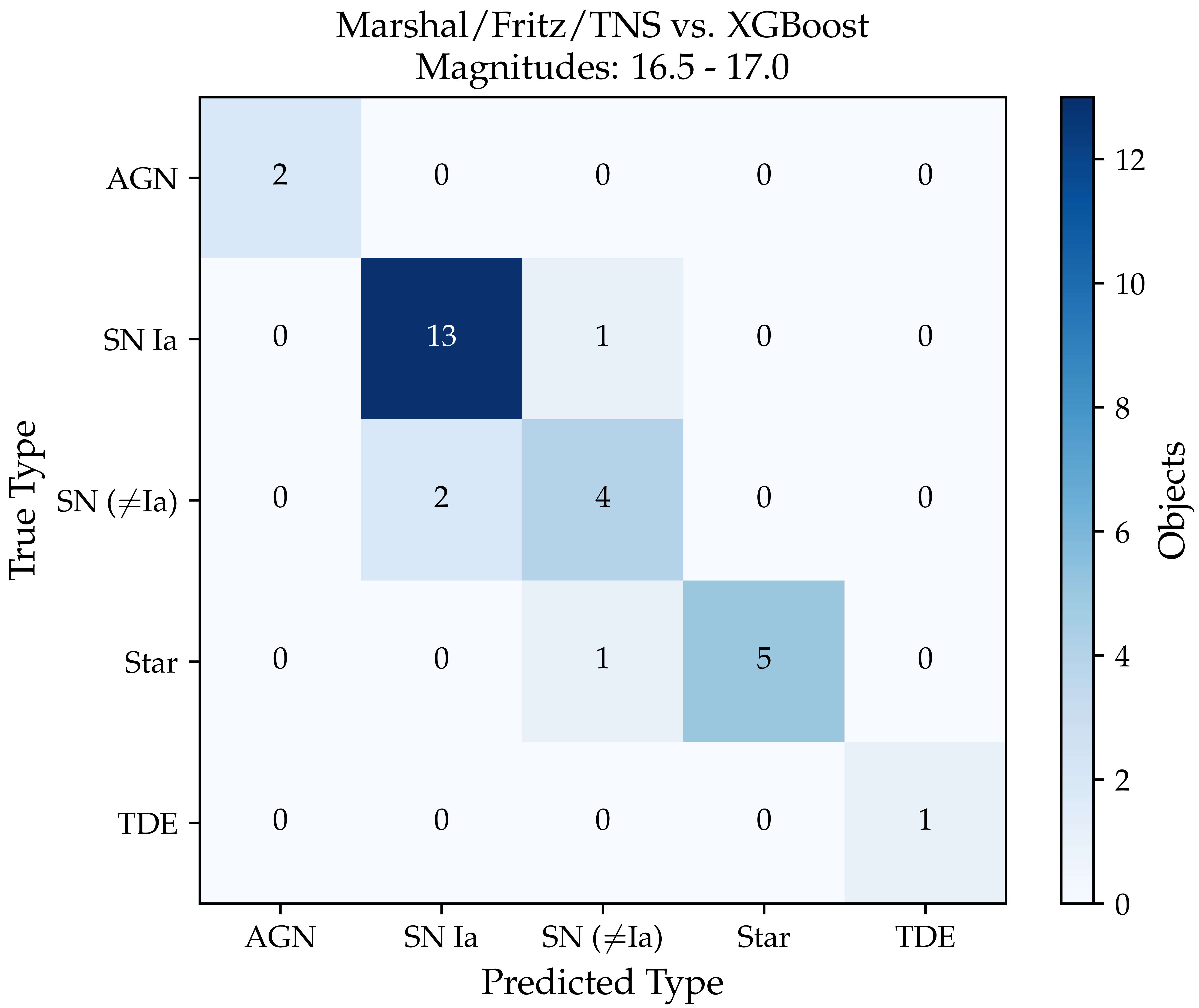
## 16.0-16.5



# Evaluation with unsecure truth

## Mag:

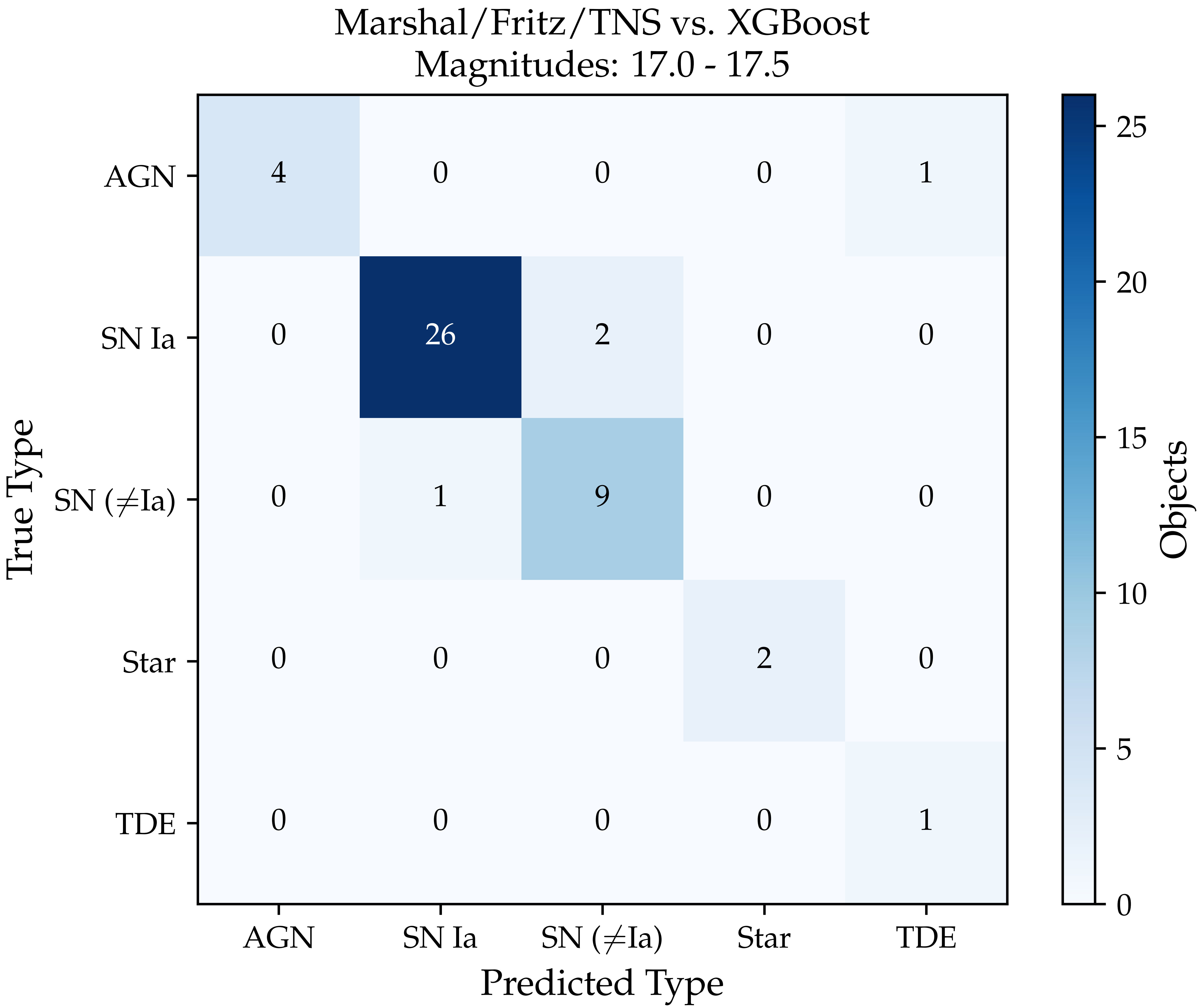
## 16.5-17.0



# Evaluation with unsecure truth

## Mag:

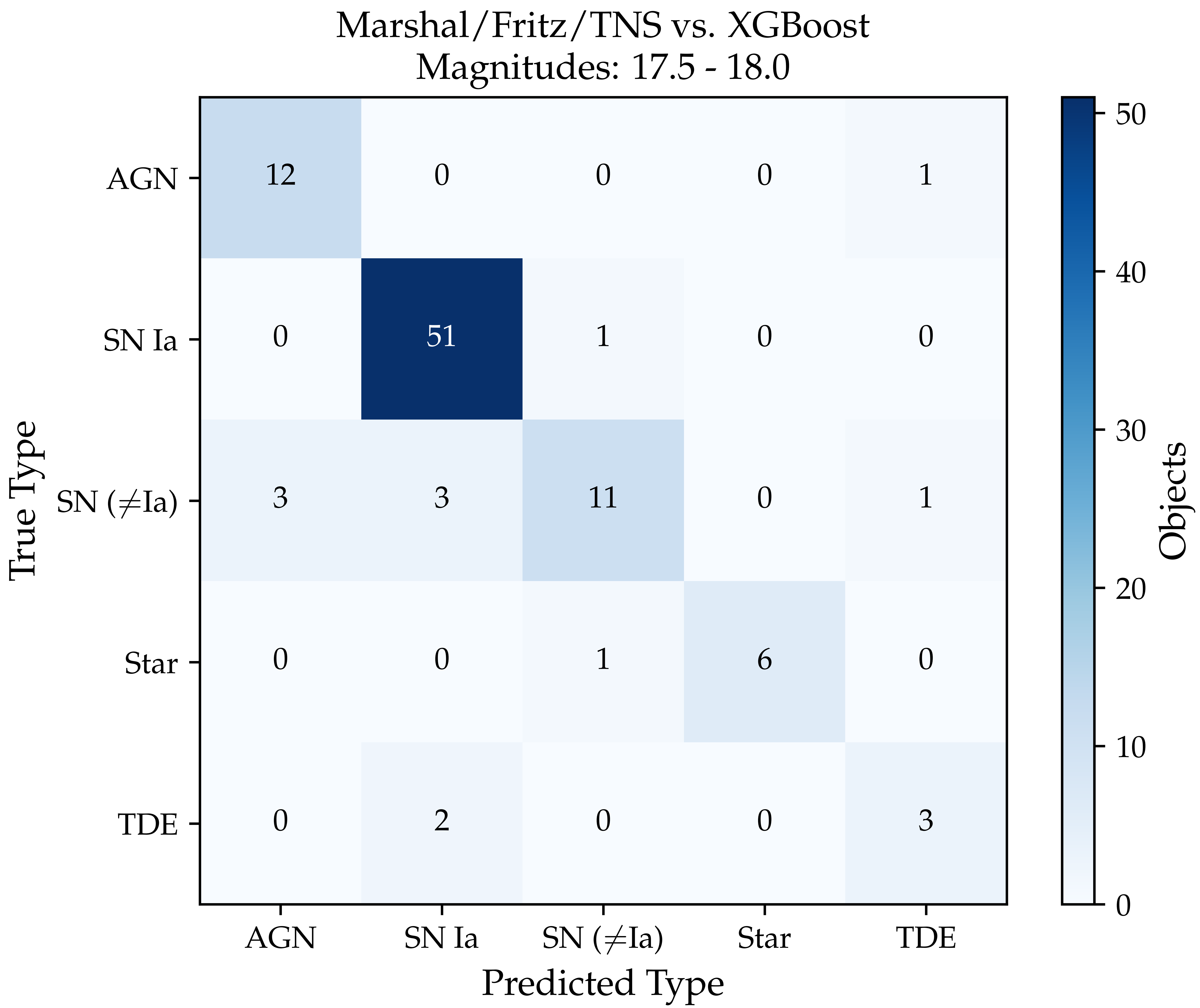
## 17.0-17.5



# Evaluation with unsecure truth

## Mag:

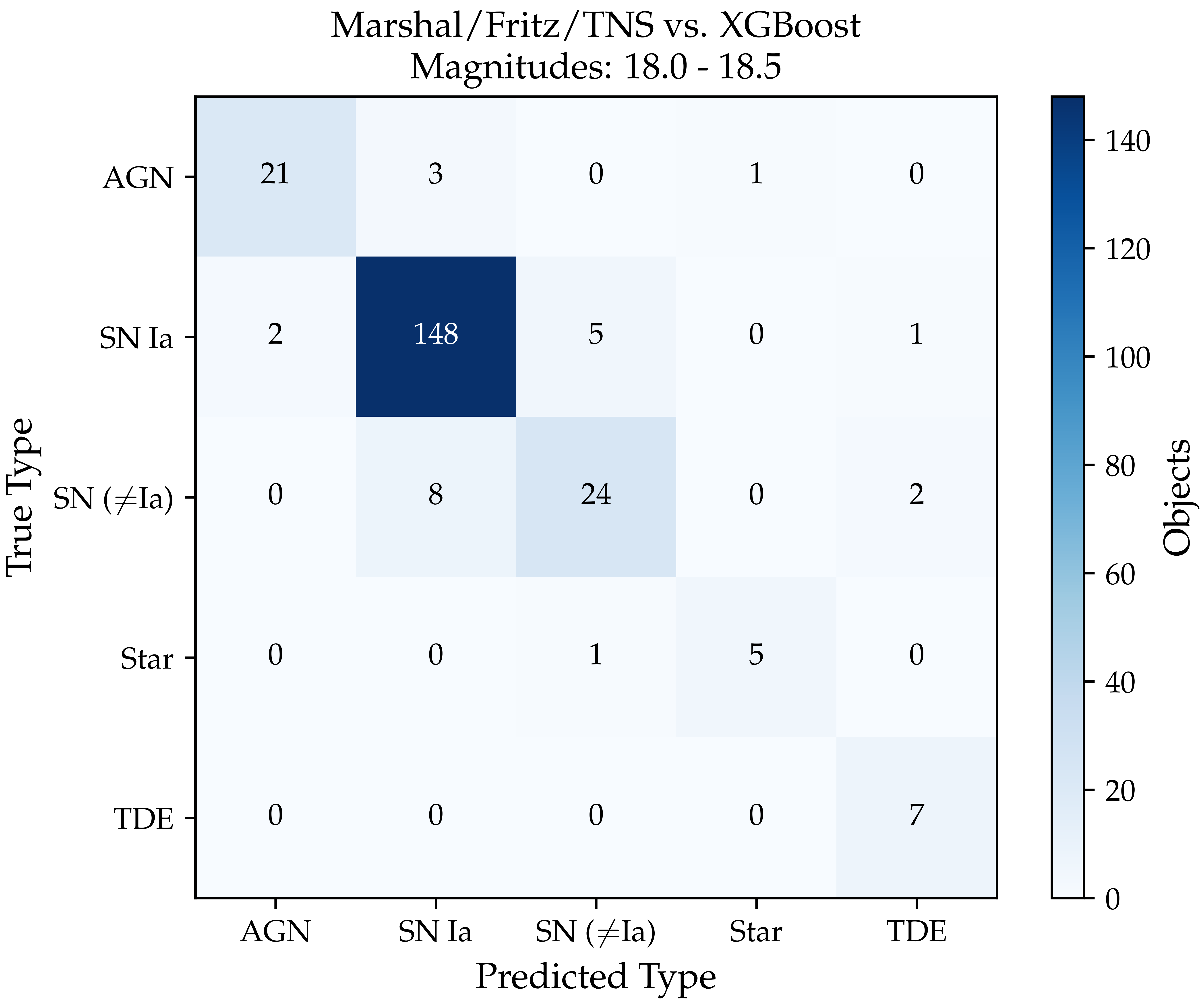
## 17.5-18.0



# Evaluation with unsecure truth

## Mag:

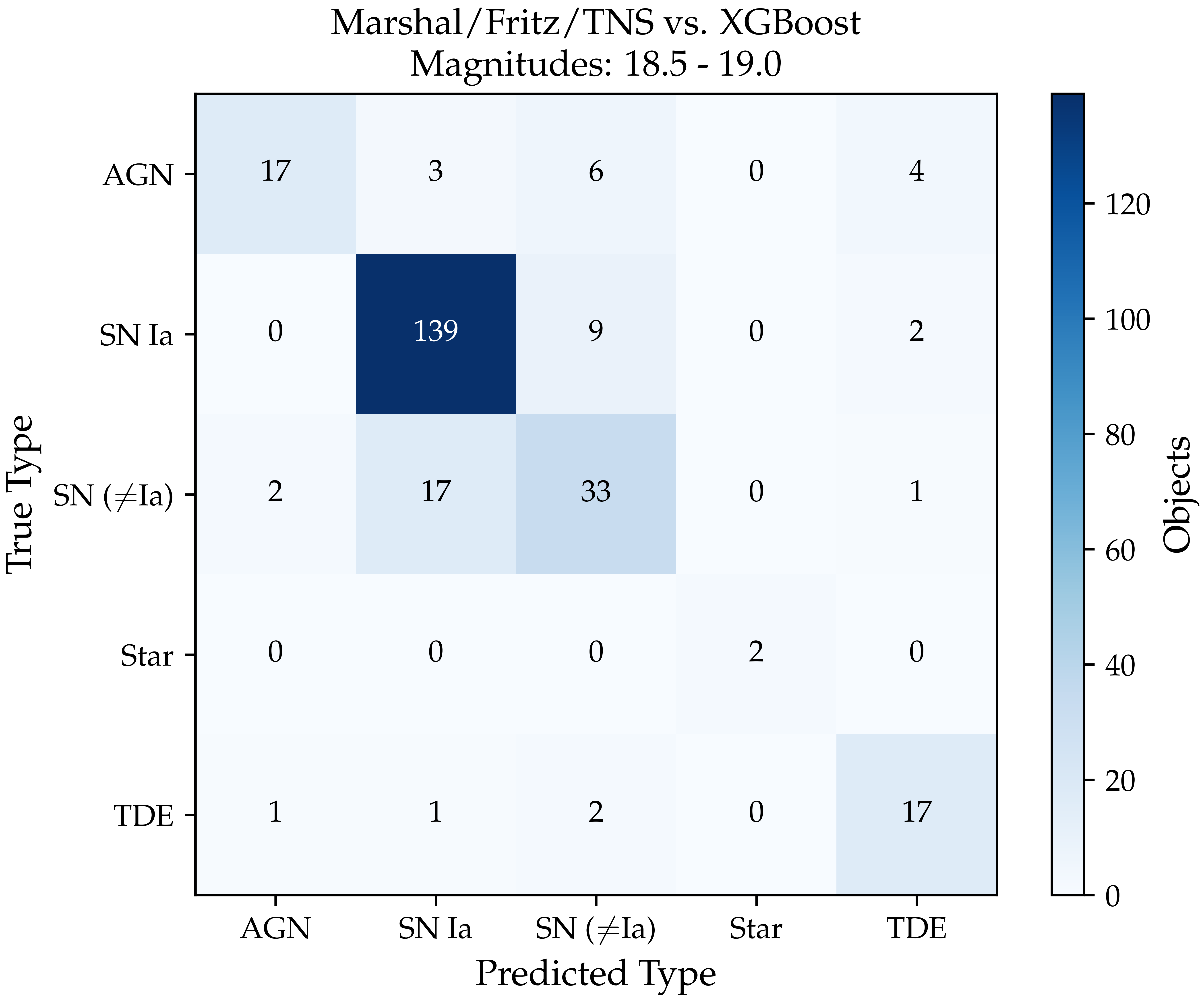
## 18.0-18.5



# Evaluation with unsecure truth

## Mag:

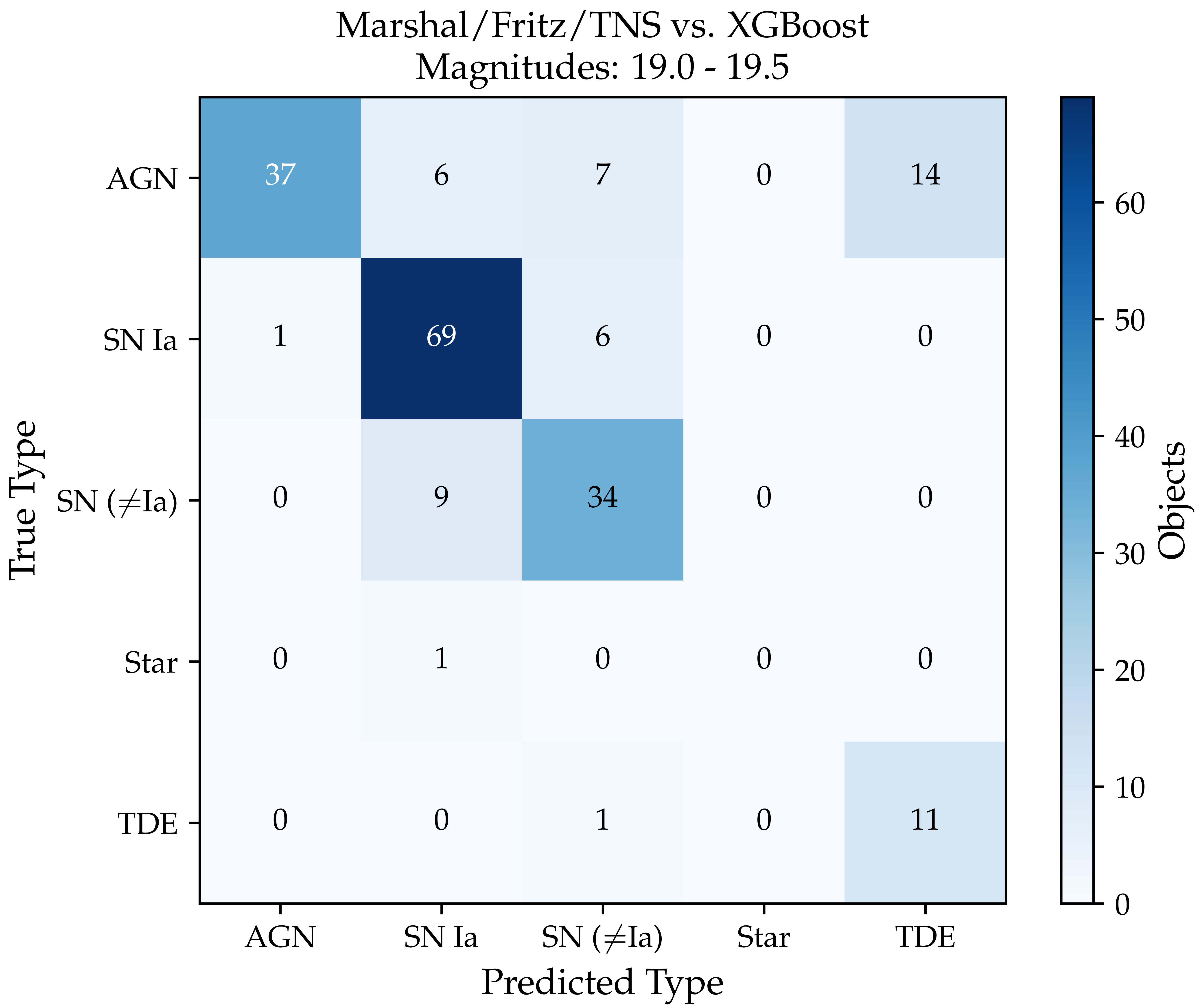
## 18.5-19.0



# Evaluation with unsecure truth

## Mag:

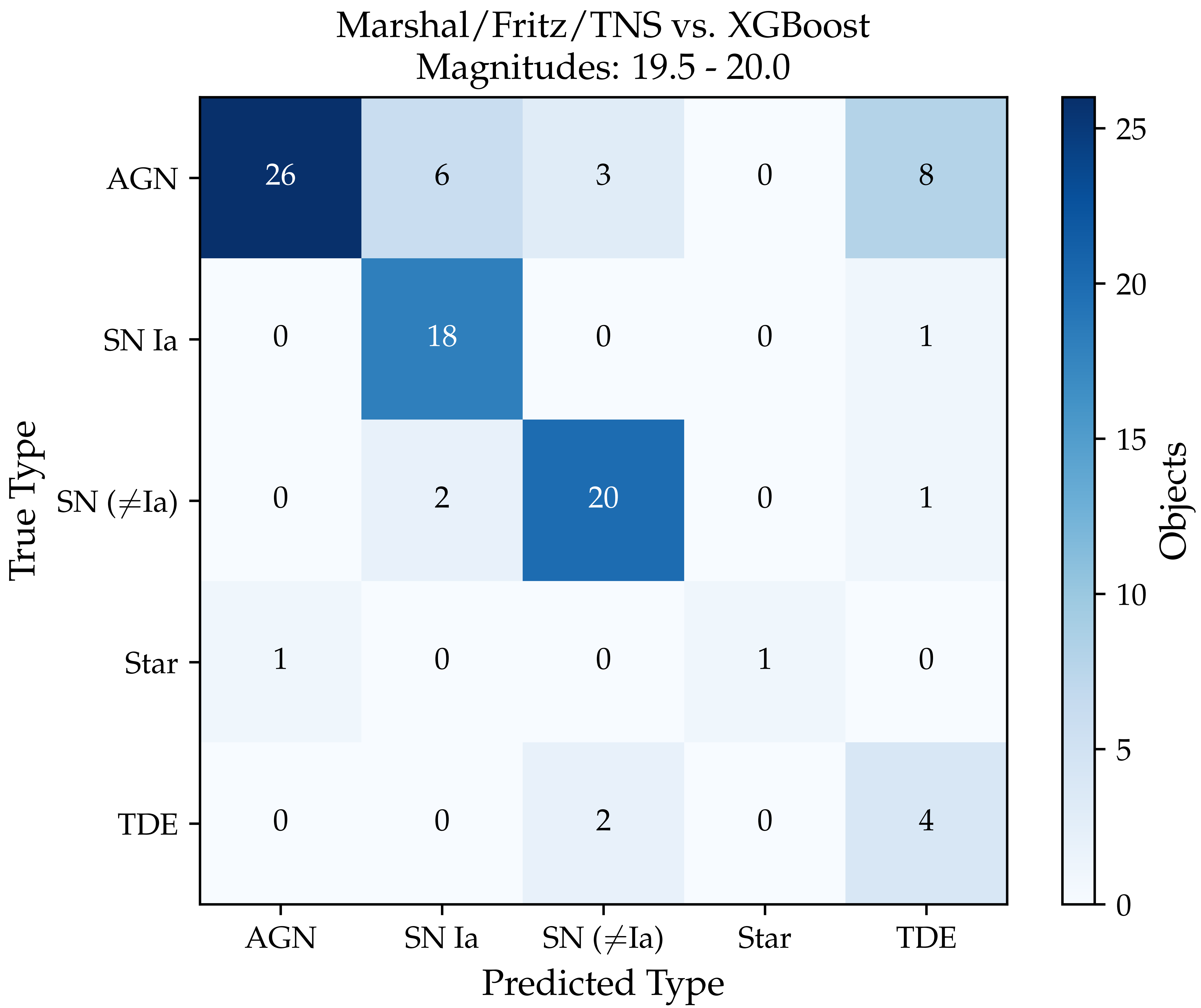
## 19.0-19.5



# Evaluation with unsecure truth

## Mag:

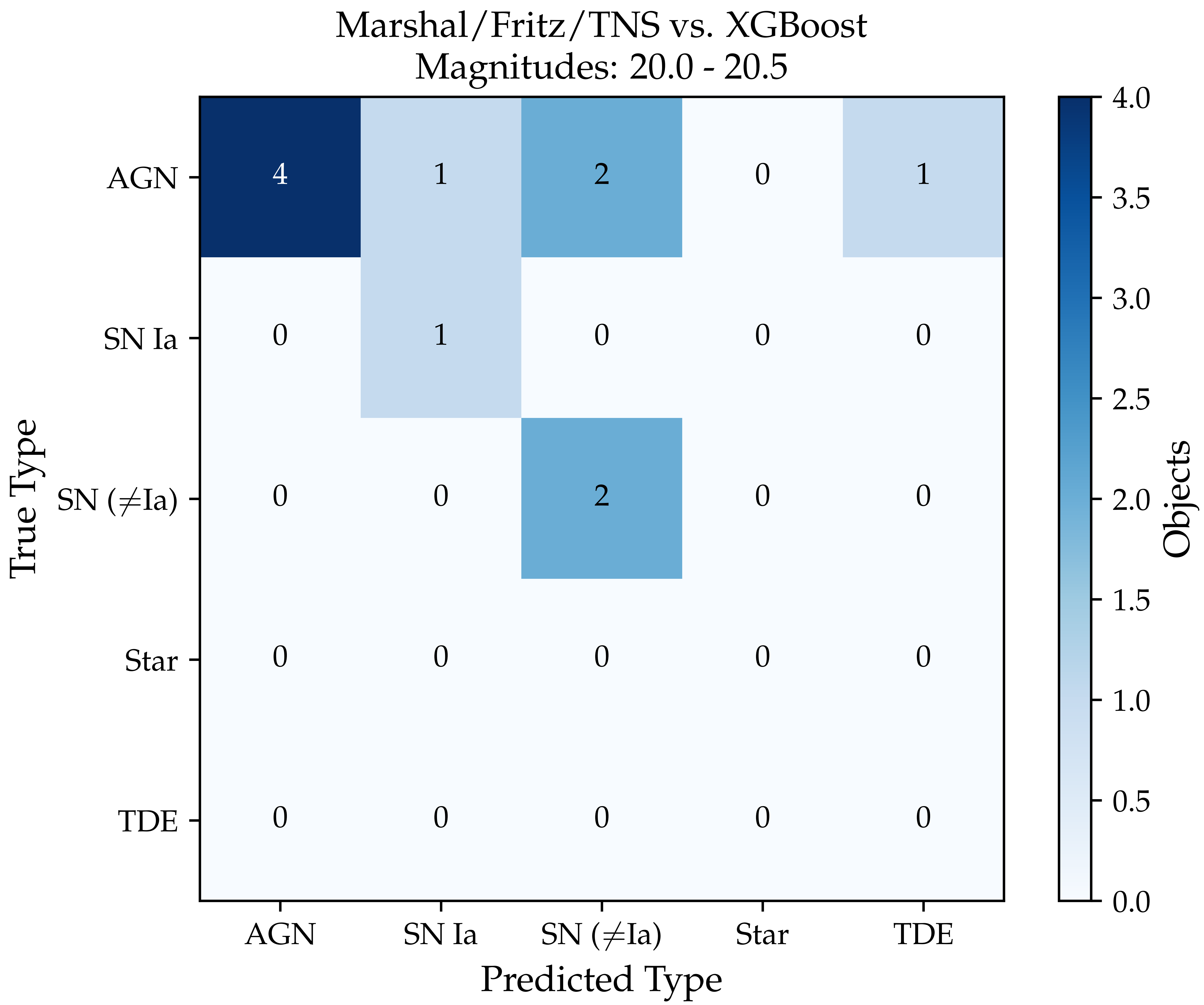
## 19.5-20.0



# Evaluation with unsecure truth

## Mag:

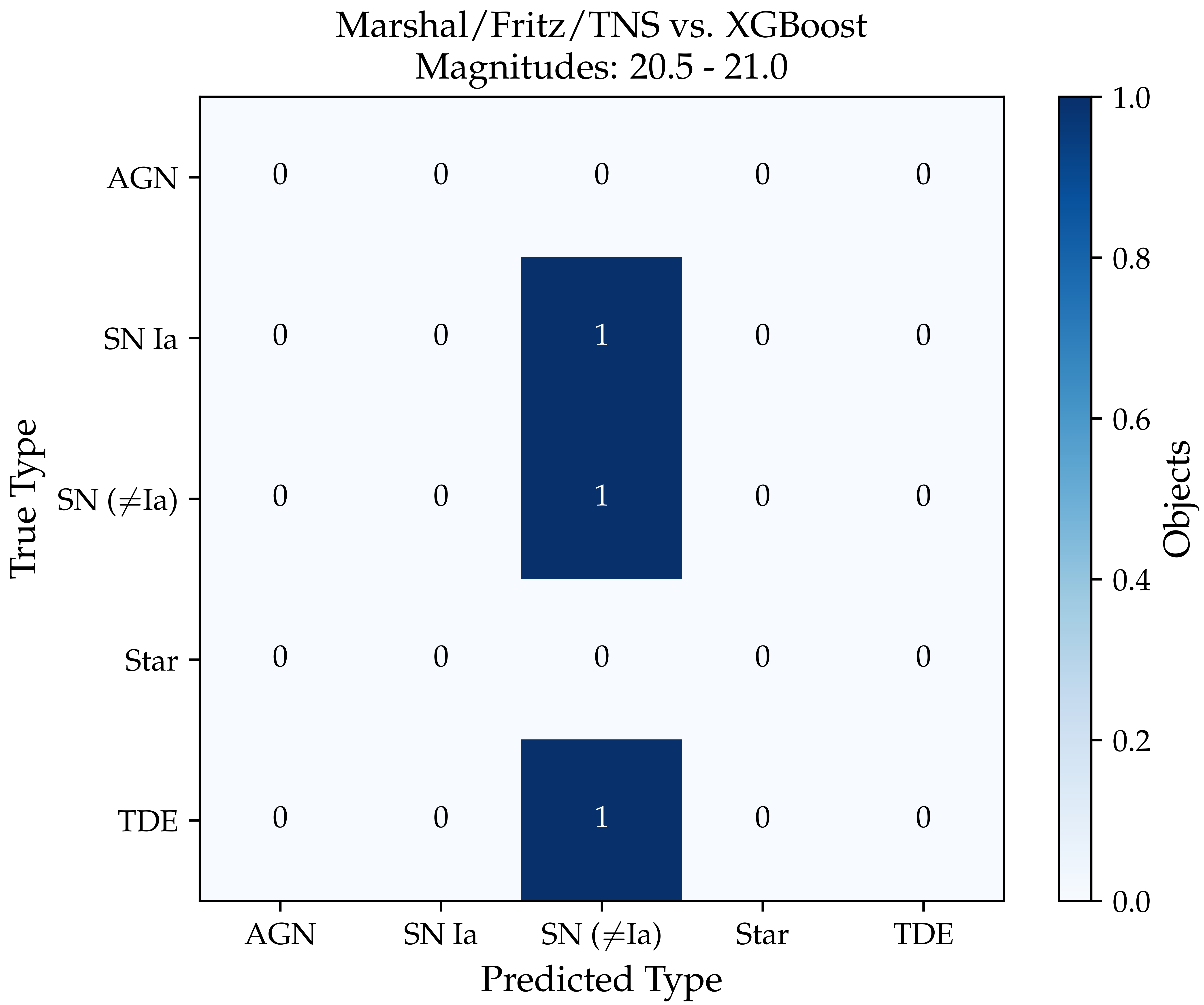
## 20.0-20.5



# Evaluation with unsecure truth

## Mag:

## 20.5-21.0



# Questions

How to address uncertain classifications?

Way to discard "bad" predictions?

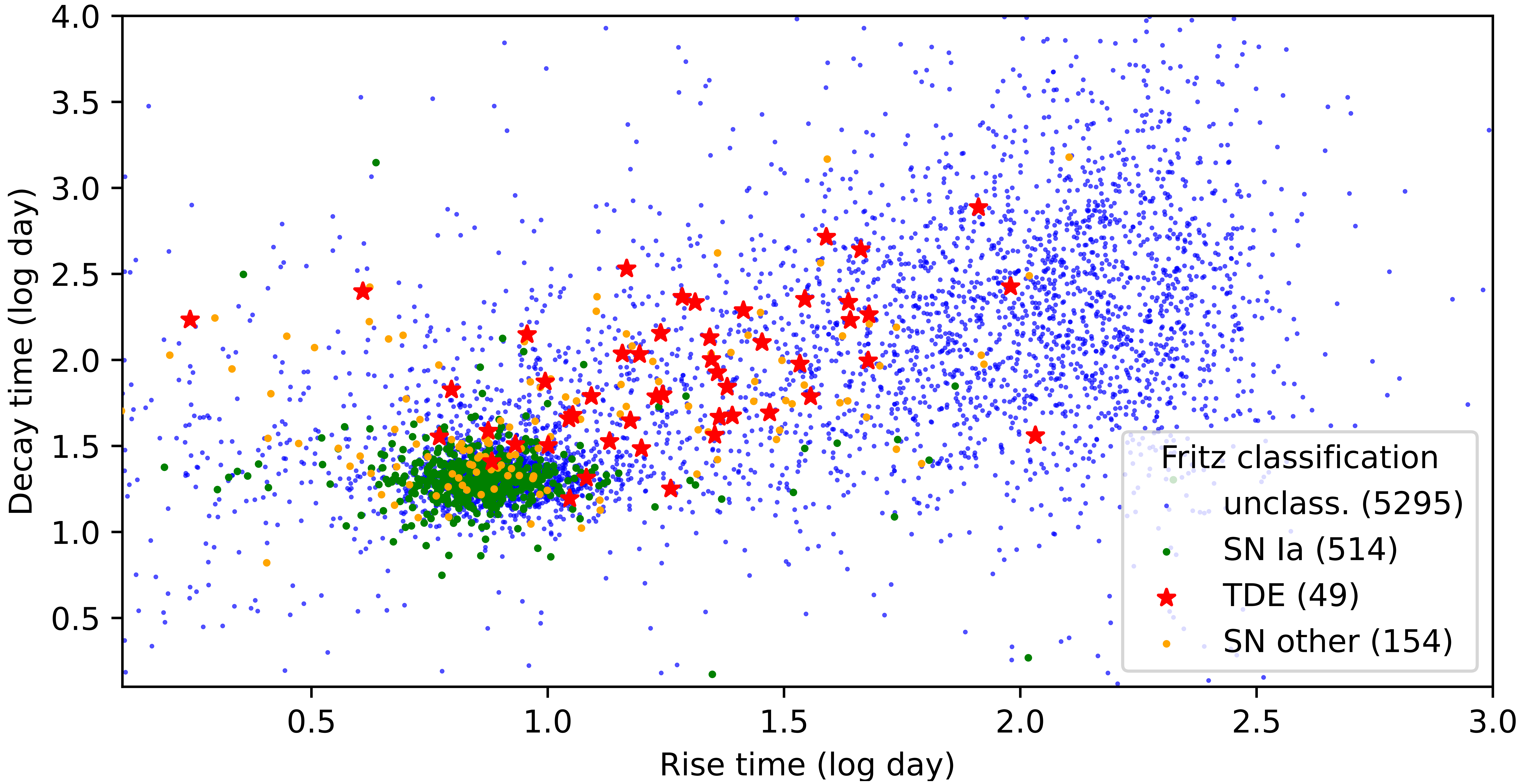
Waterfall plots?

Suggestions to improve on the training? E.g: normalization of features (numerical values)?

Anomaly detection?

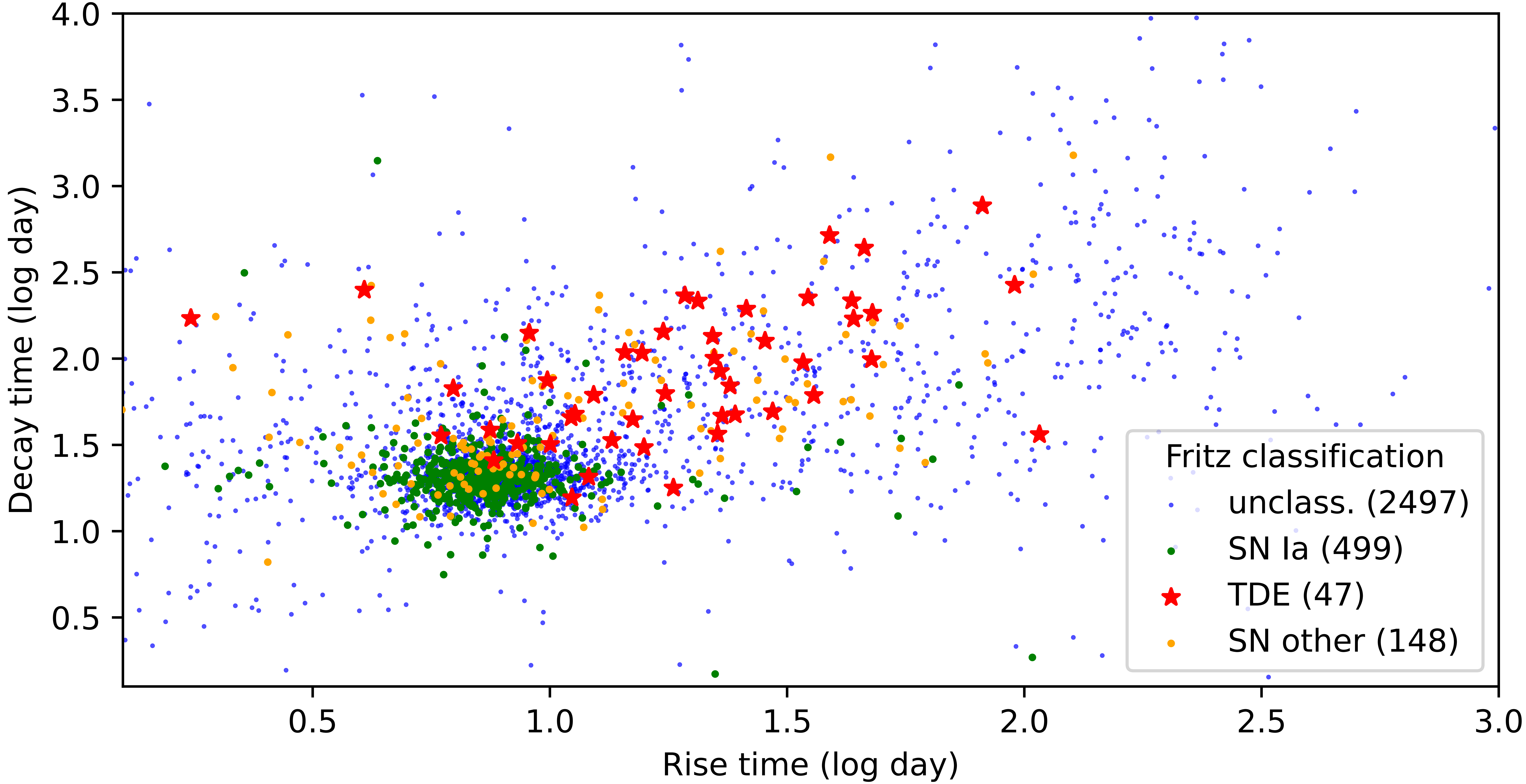
# No cut (6012 transients)

Purity: 0.8% / Efficiency: 100.0 %



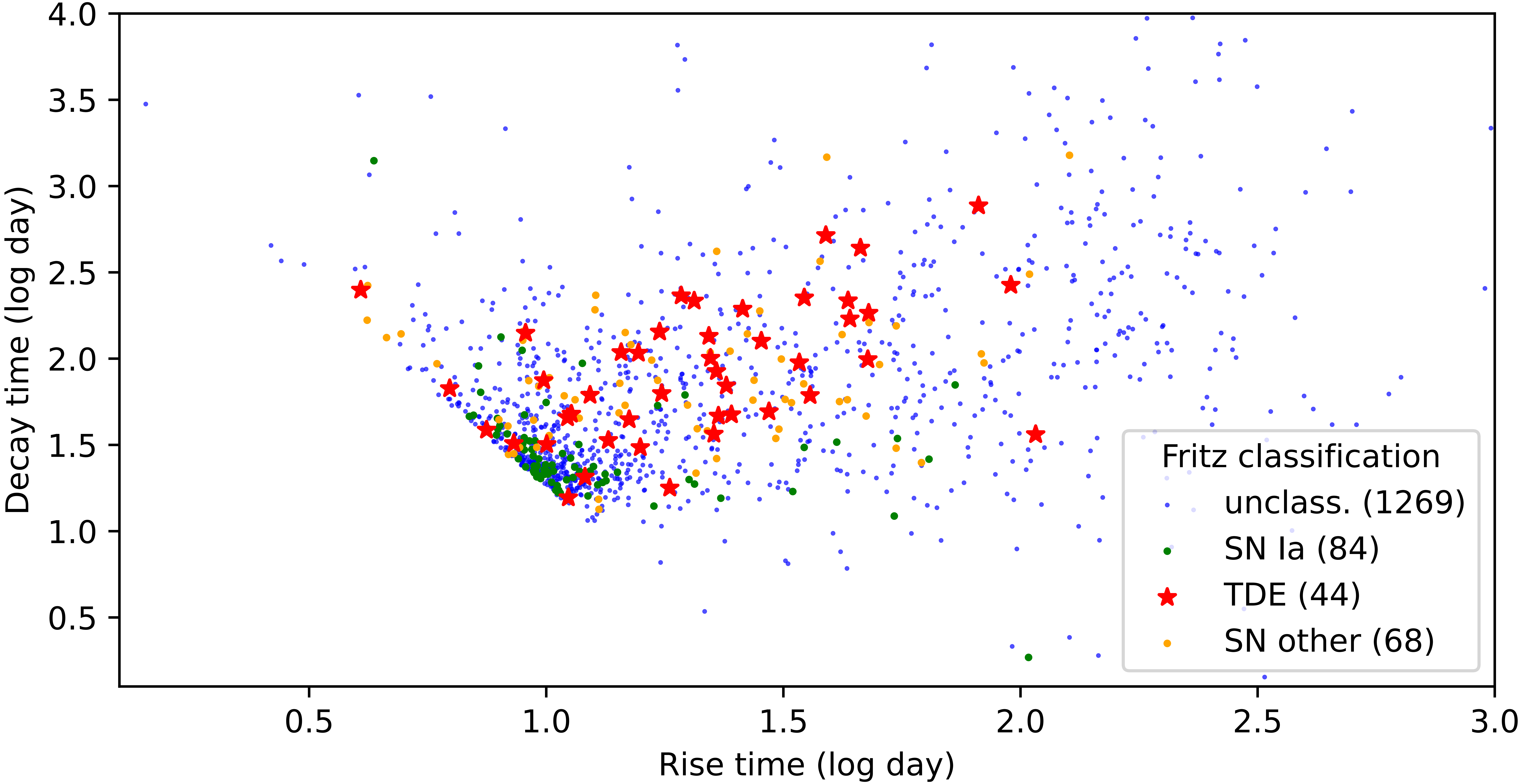
# WISE colors (3191 transients)

Purity: 1.5% / Efficiency: 95.9 %



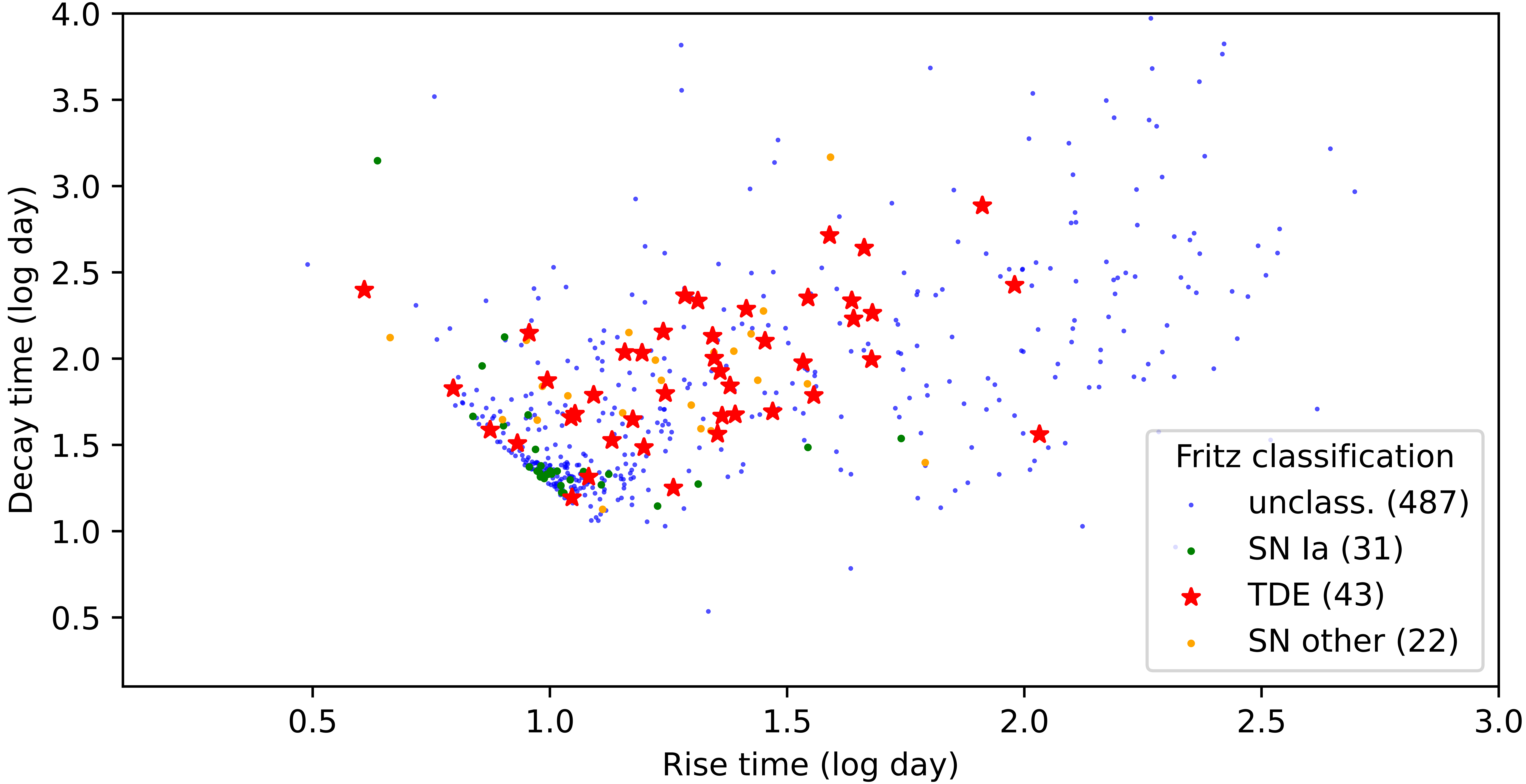
# Diagonal cut (1465 transients)

Purity: 3.0% / Efficiency: 89.8 %



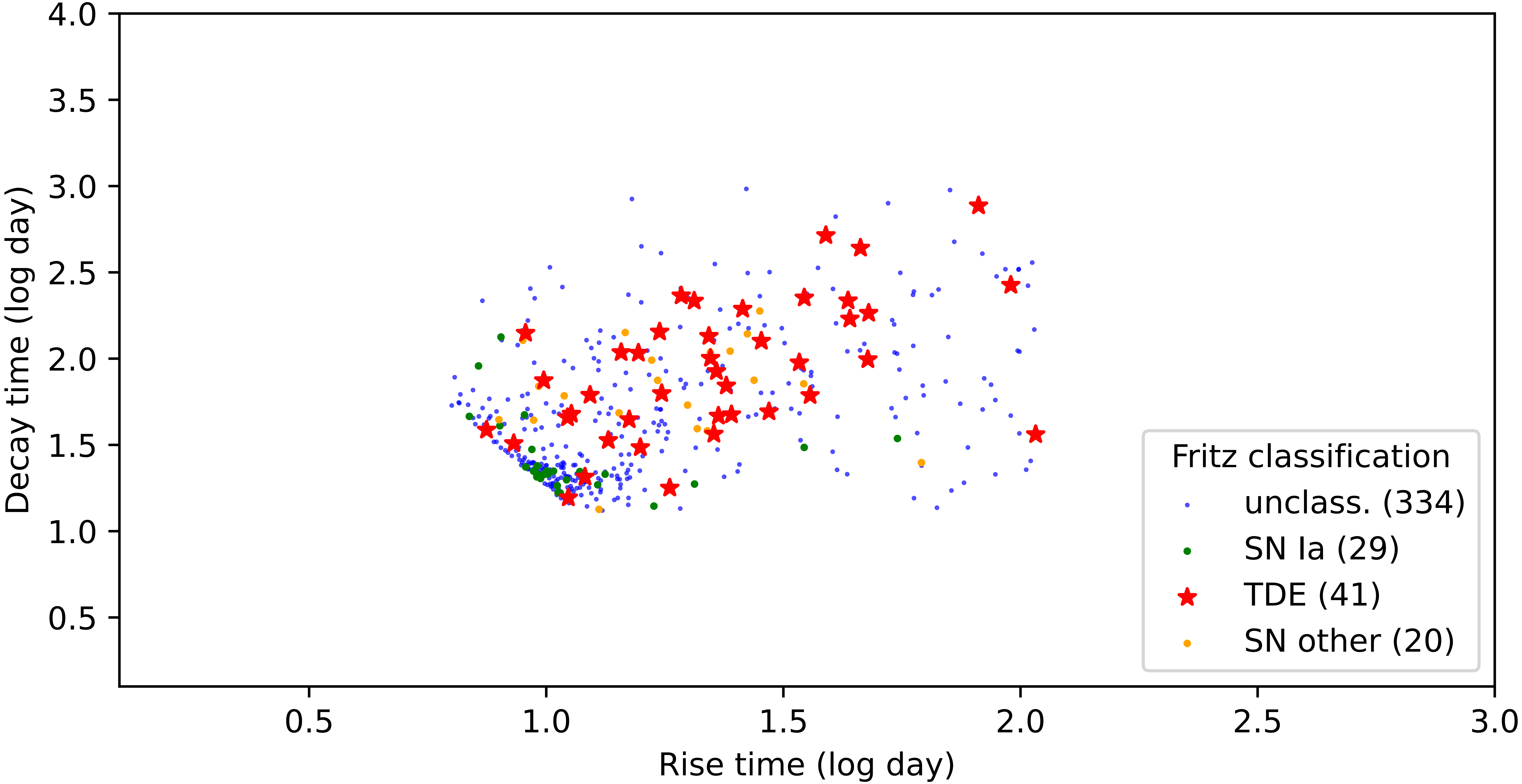
# Temperature cut (583 transients)

## Purity: 7.4% / Efficiency: 87.8 %



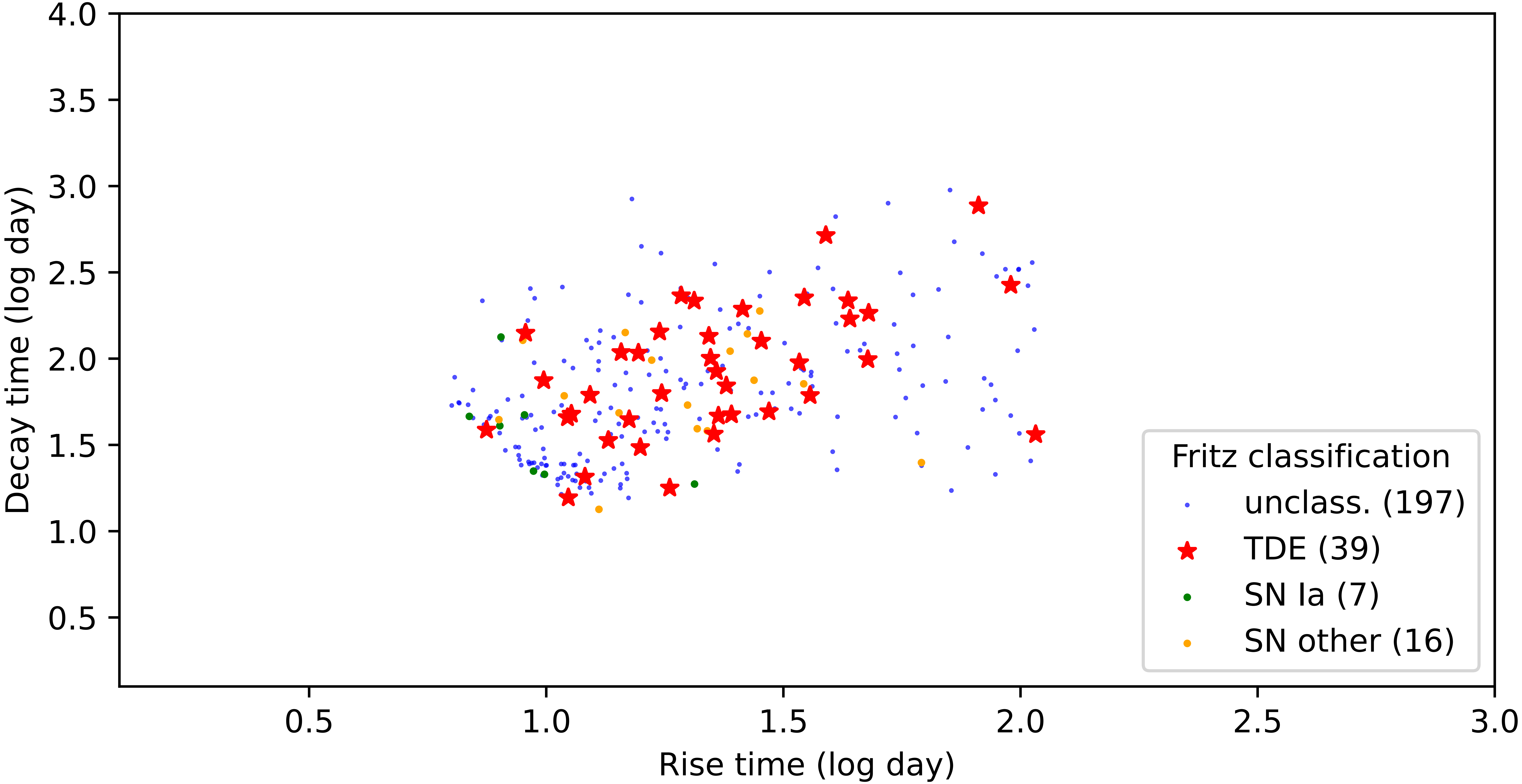
# Rise-decay cut (424 transients)

Purity: 9.7% / Efficiency: 83.7 %



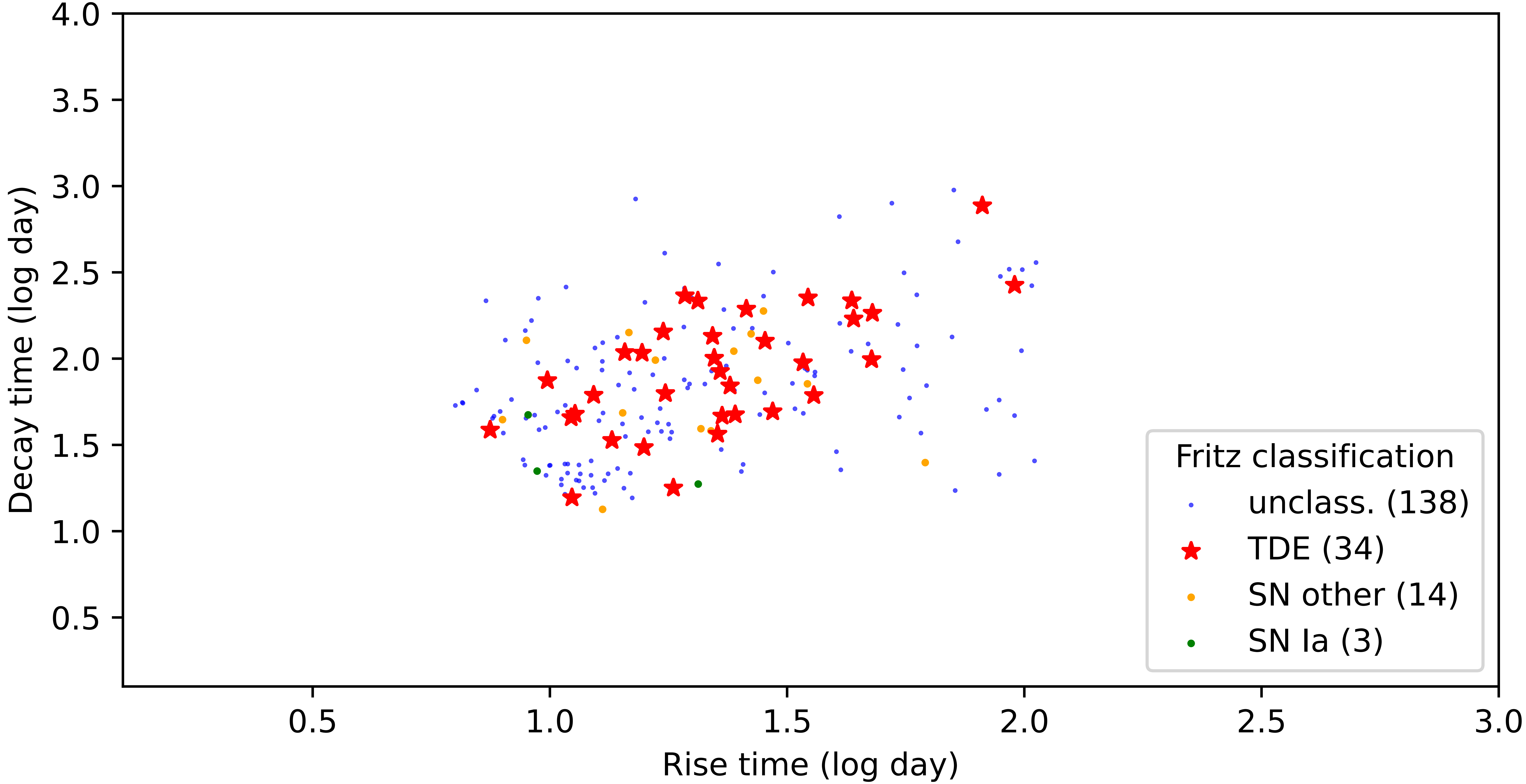
# Chisquare cut (259 transients)

Purity: 15.1% / Efficiency: 79.6 %

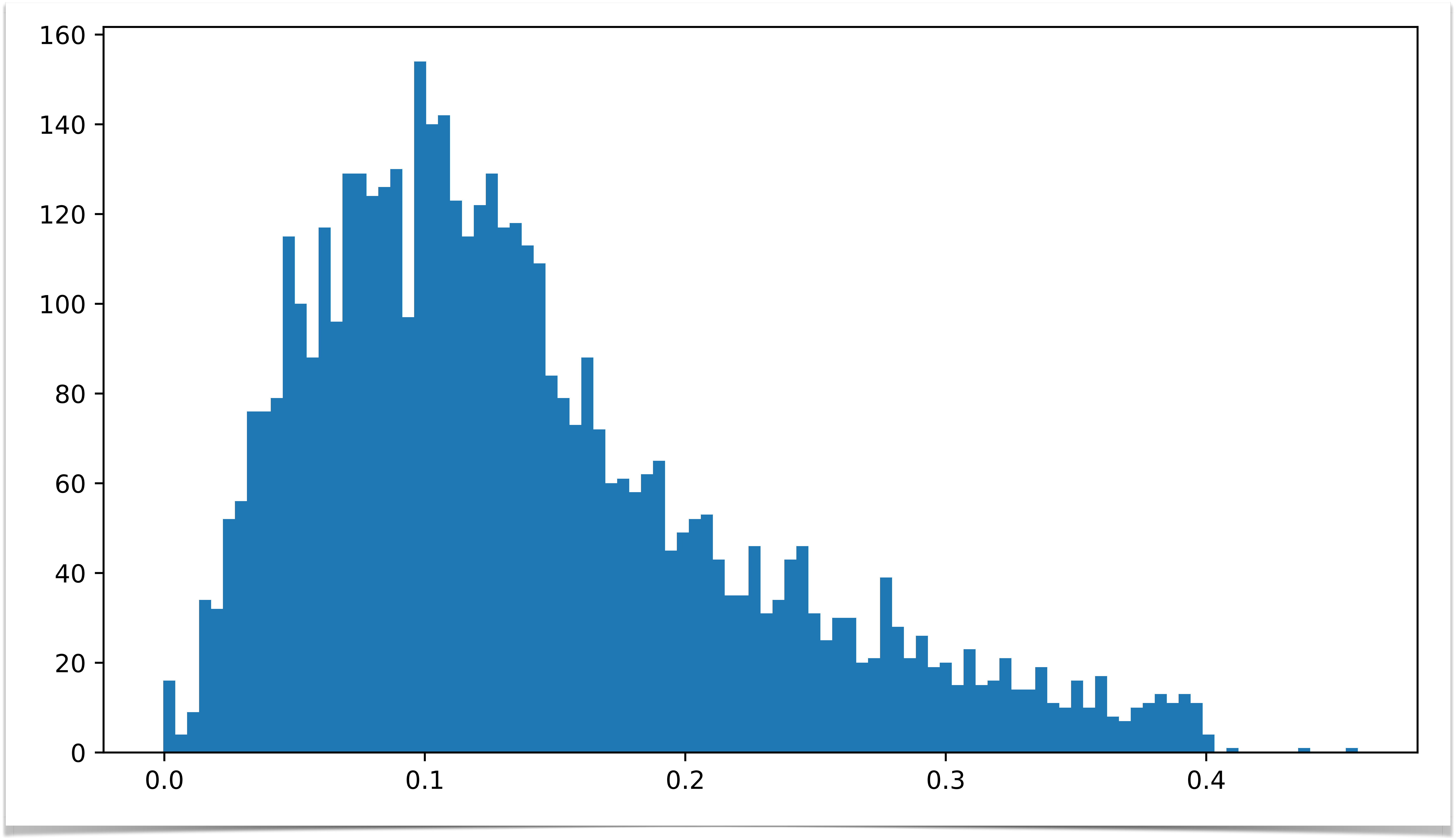


# Bayesian block cut (189 transients)

Purity: 18.0% / Efficiency: 69.4 %

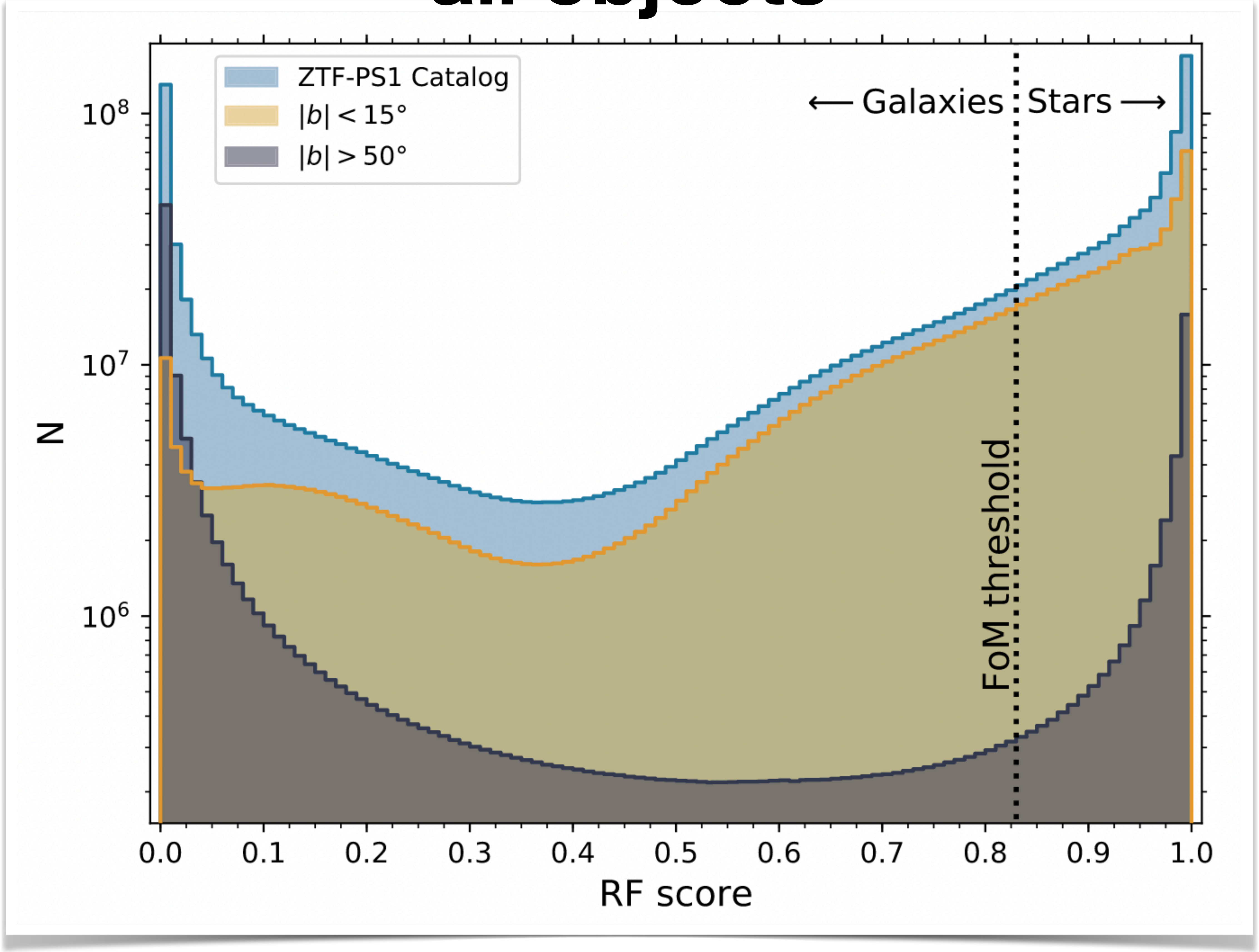


# Redshift distribution (including photoz, n=4883)

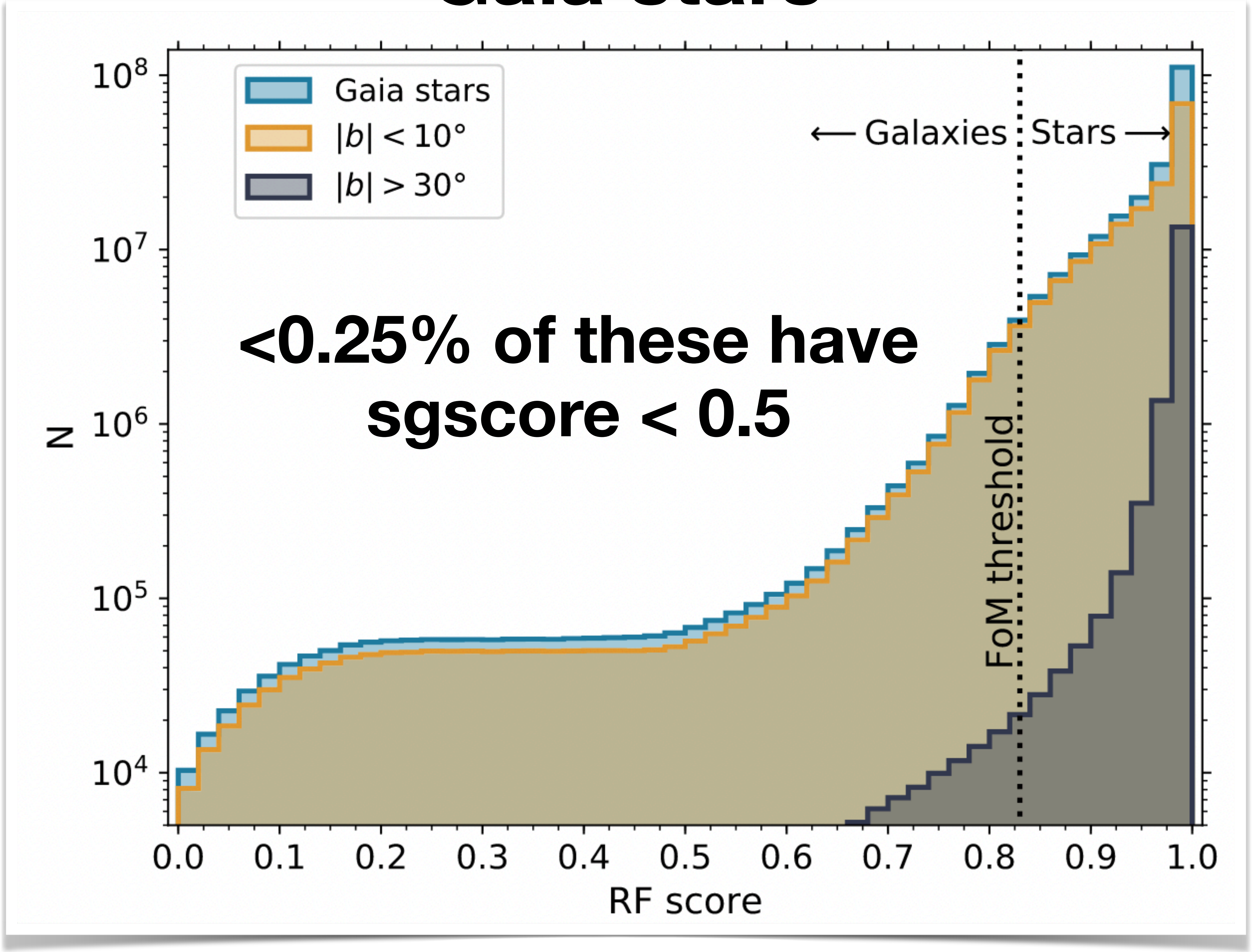


# `sgscore` distribution

## all objects



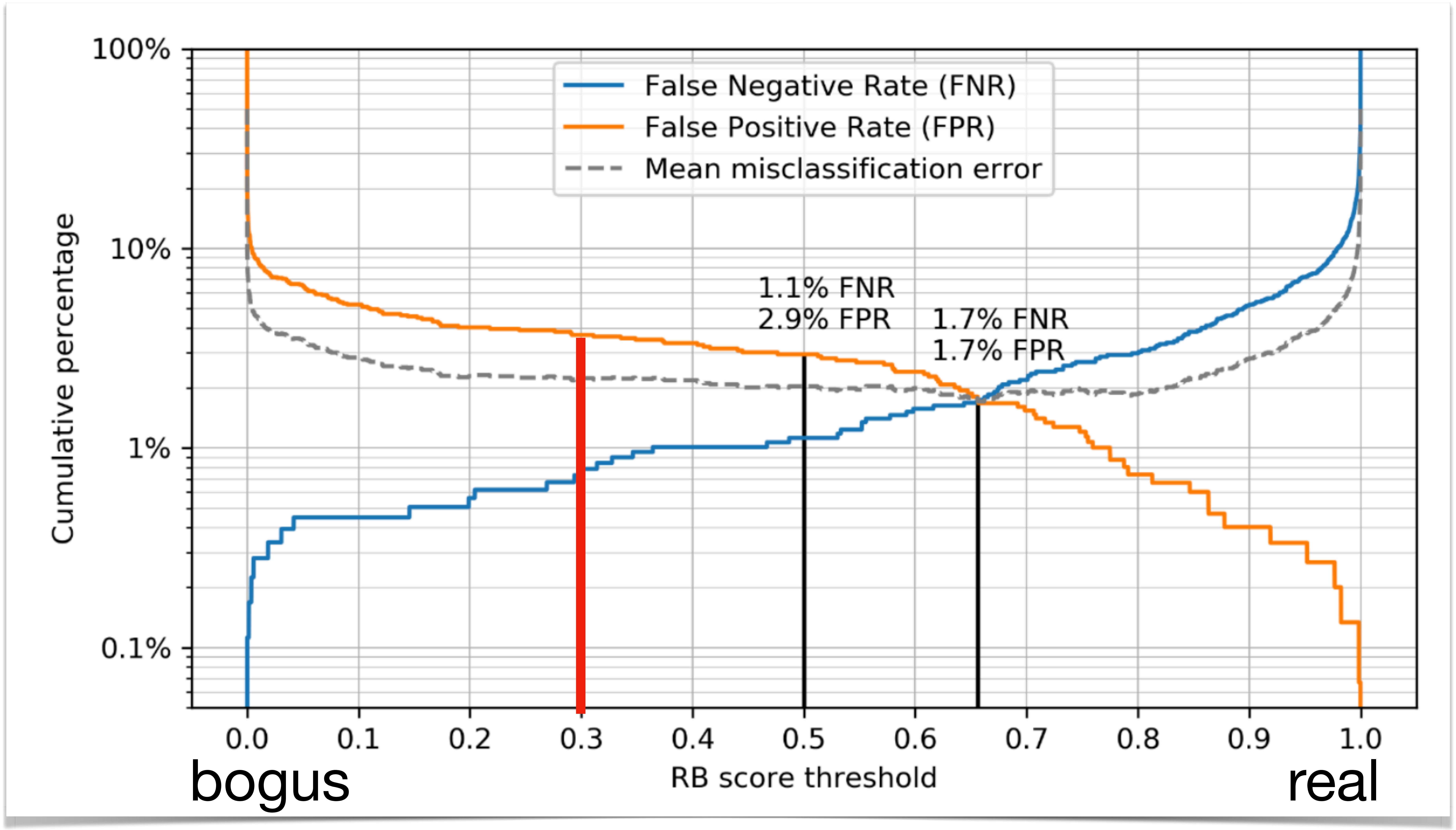

## Gaia stars




**<0.25% of these have sgscore < 0.5**

Tachibana & Miller, 2018 (PASP)

# rb distribution




0.7% FNR
4 % FPR

Duev et al., 2019
(MNRAS)