

# Candidate strongly-lensed Type Ia supernovae in the ZTF archive

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MMS Annual Meeting 2024



# Motivation

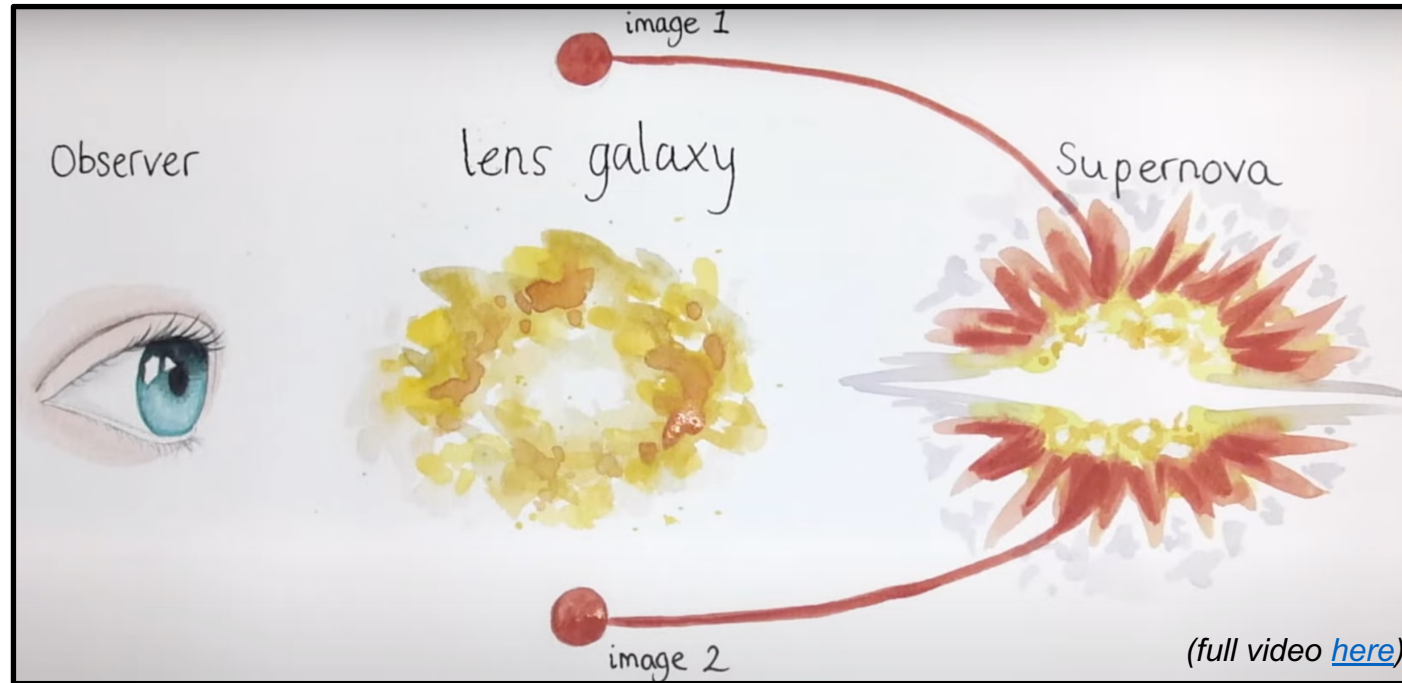


Image credit: Nikki Arendse

From gravitationally lensed SNe Ia (gISNe Ia), we can study...

Time delay cosmography to measure  $H_0$

High redshift supernovae physics

Matter distribution of lensing galaxy

# Motivation

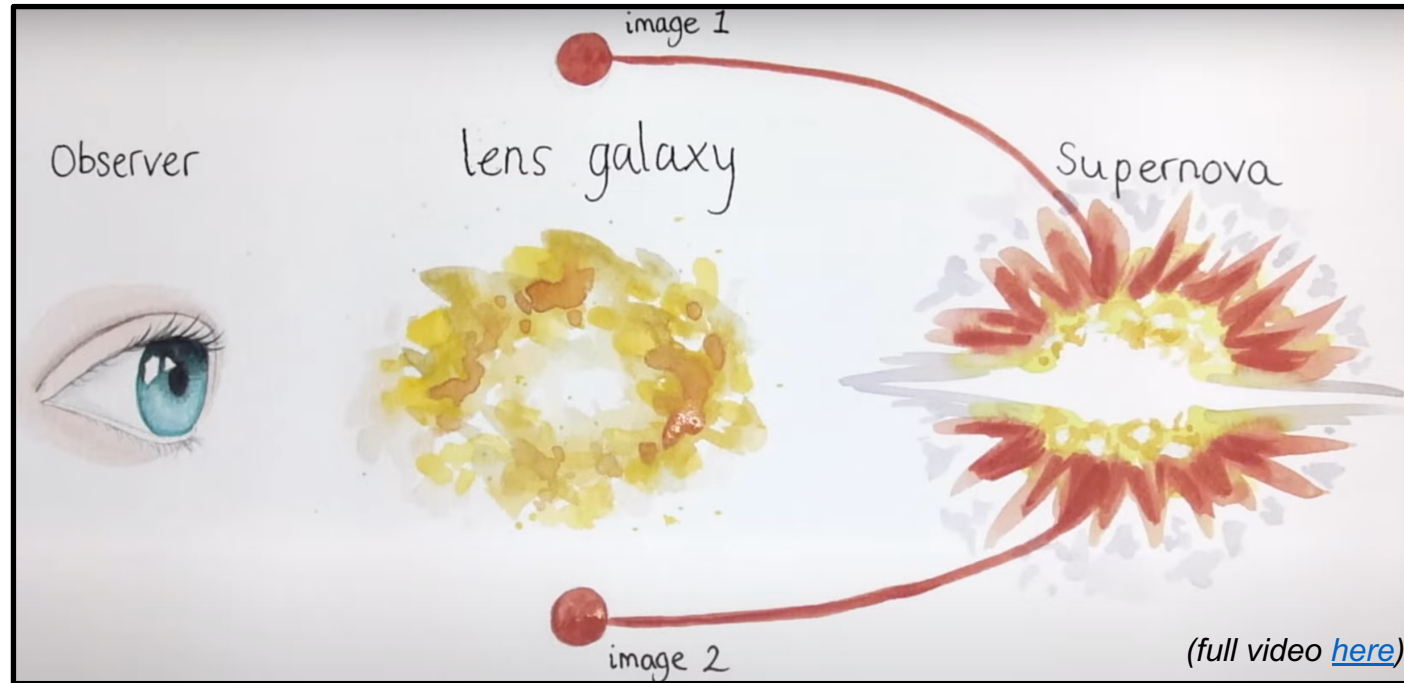
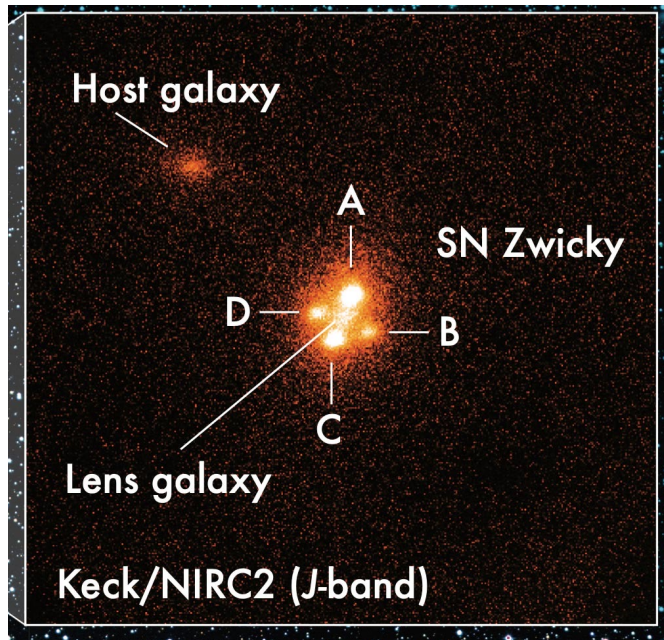


Image credit: Nikki Arendse

Only **three** found so far (from ground-based telescopes)...

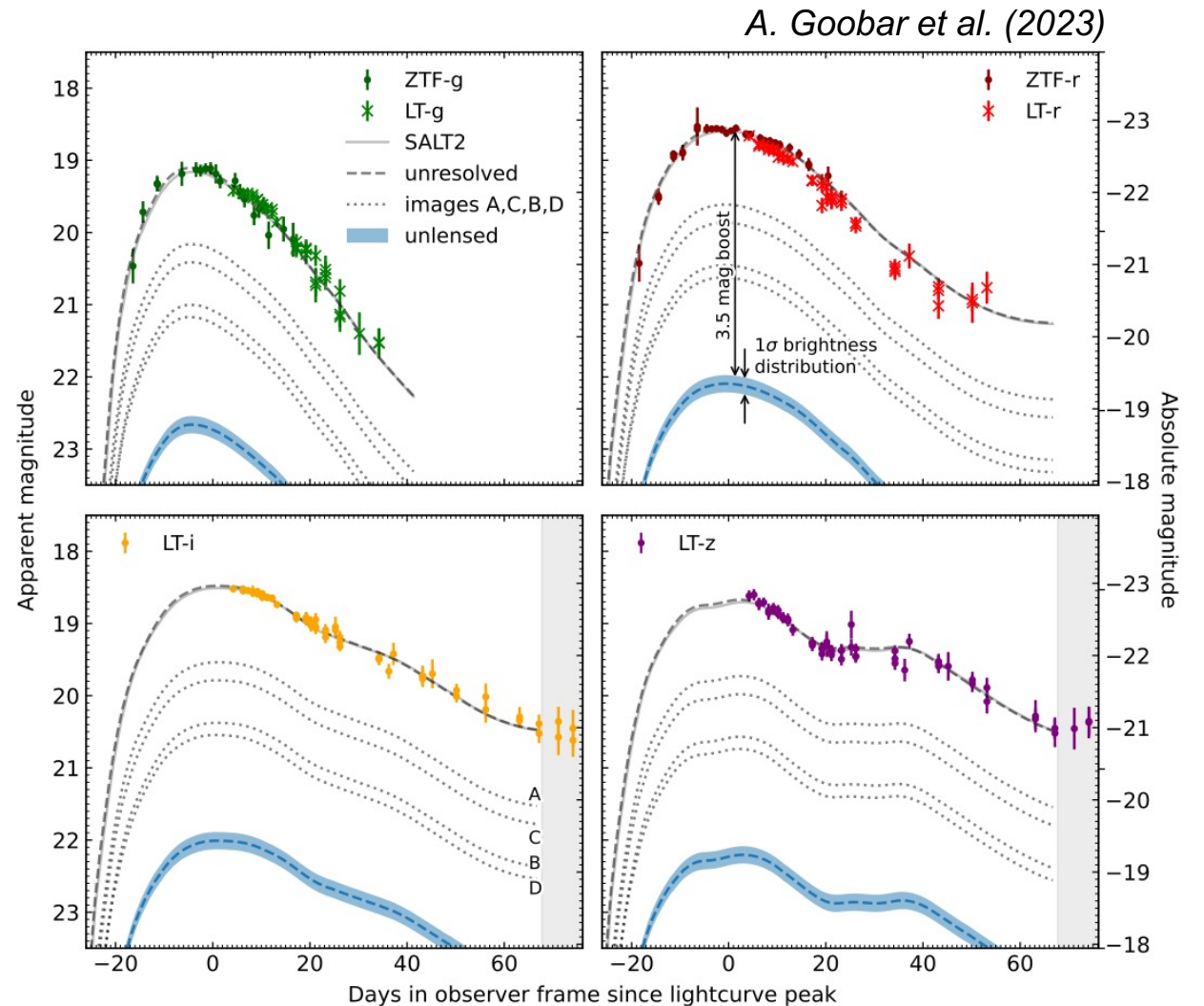
*Where are the rest?*

# Resolved vs. unresolved



Credit: Joel Johansson

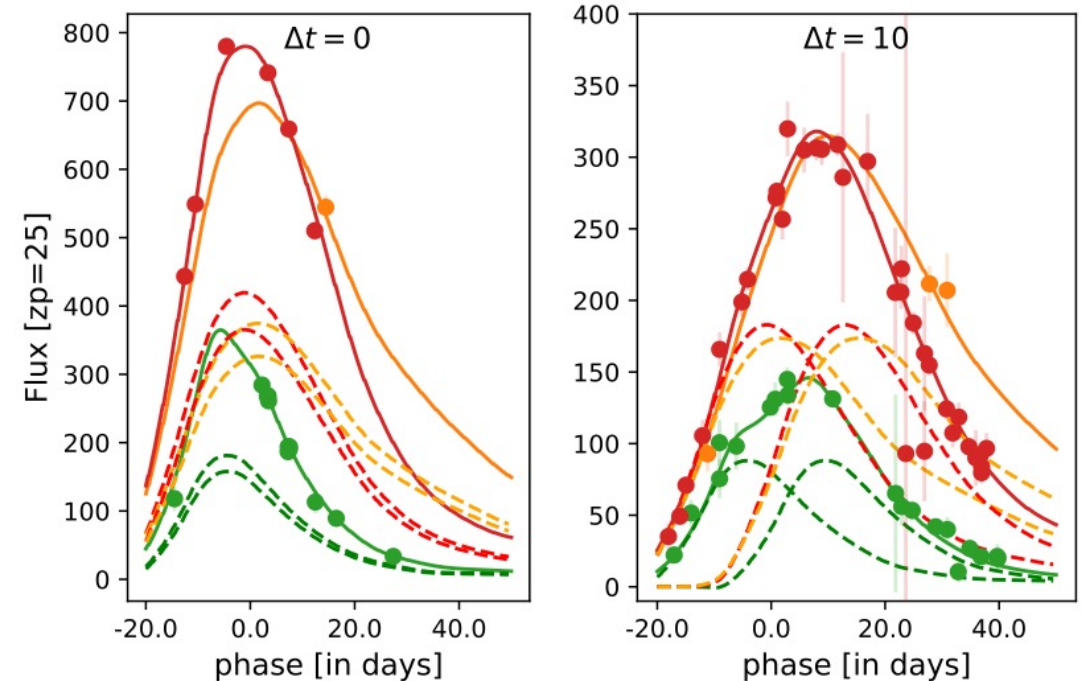
Observed by  
ZTF



# The ZTF archive study

From previous observations and simulations, gISNe Ia are...

- Over-luminous ( $M_B > -19.5$ )
- Higher redshift ( $z > 0.1$ )
- Near core of the lens galaxy ( $\theta < 3''$ )
- Redder light curves than normal SNe Ia
- Lensed by galaxies that are redder (than QSOs)



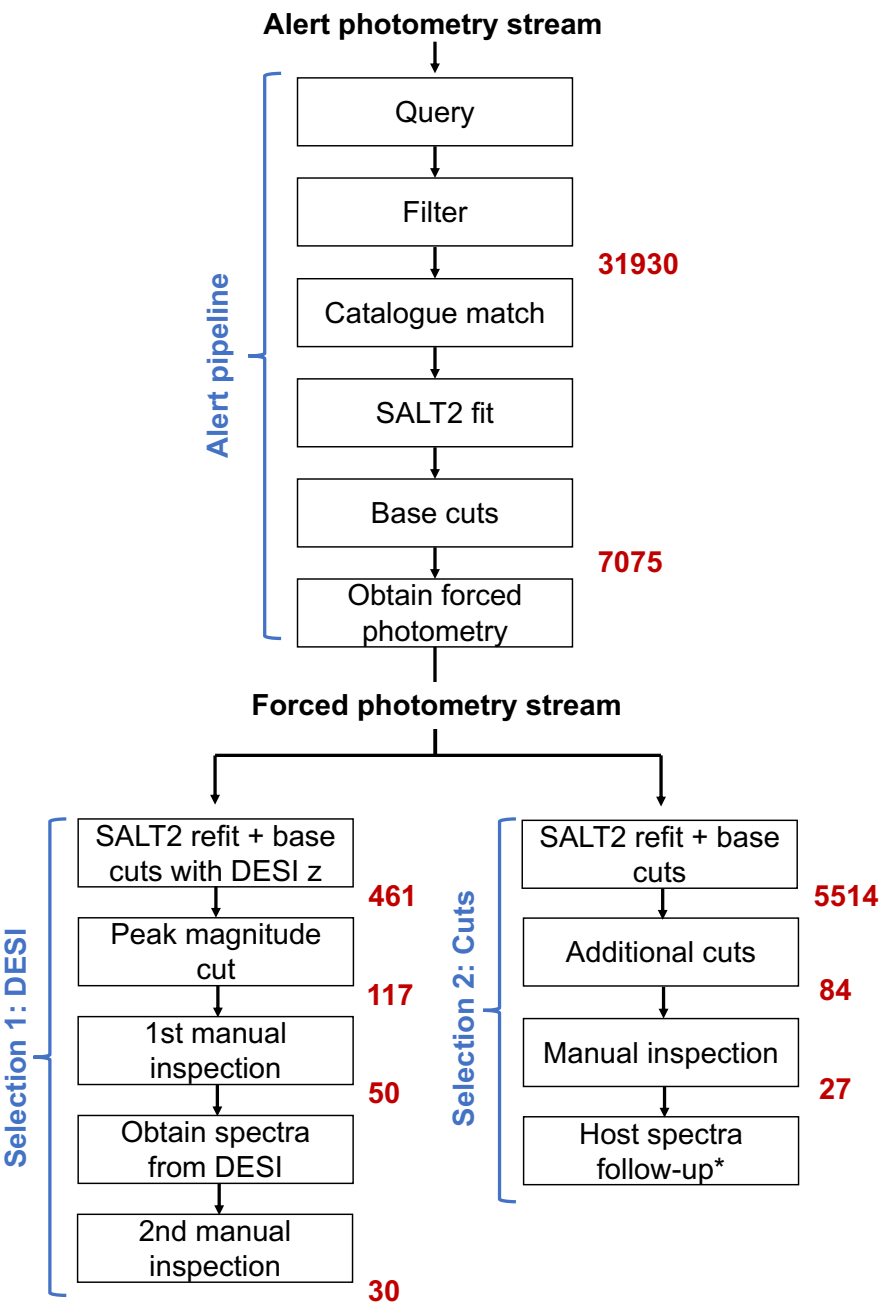
*A. Sagués Carracedo et al. (2024)*

**ZTF** is a wide-field, optical survey that has been scanning the transient sky for 5 years.

**How many objects like this did ZTF discover?**

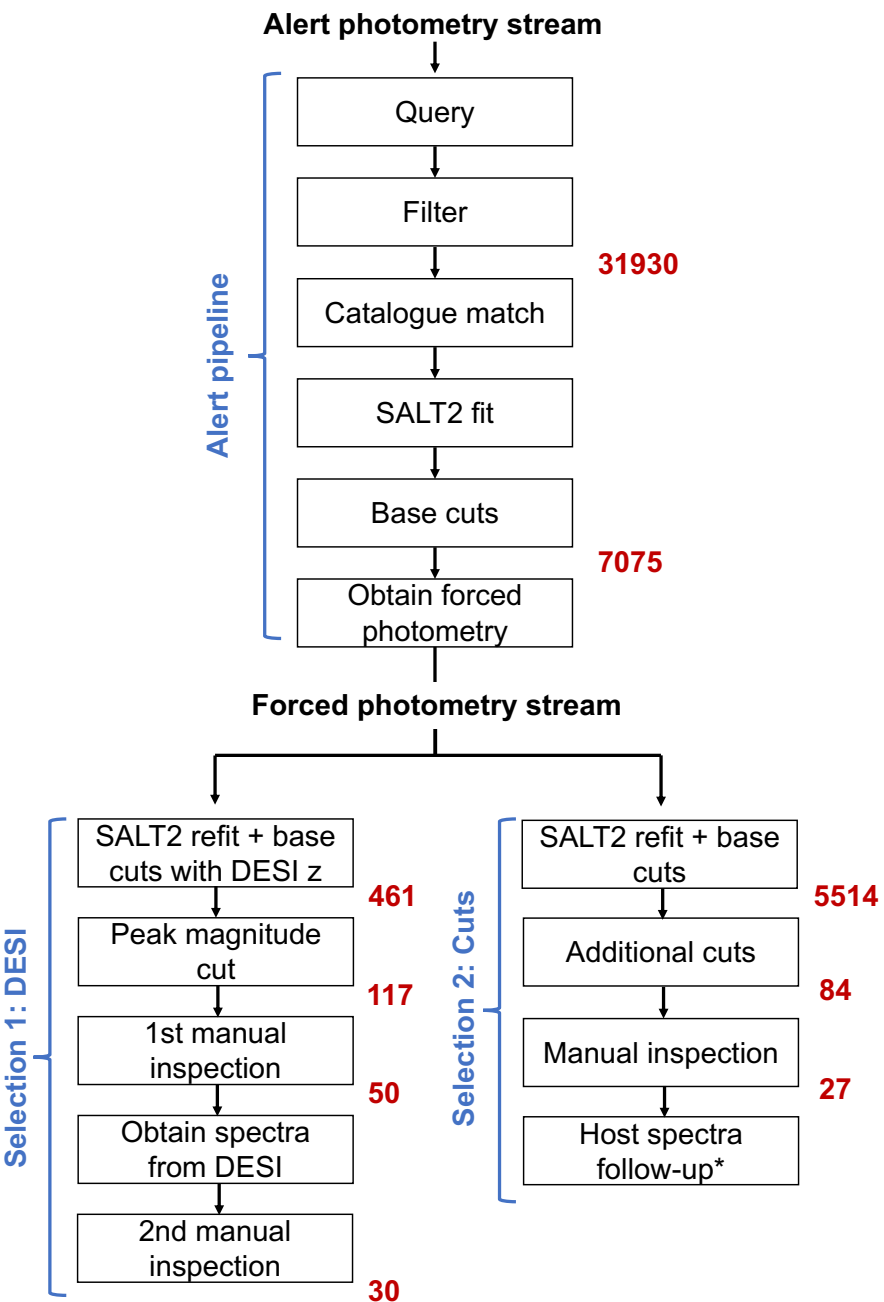
# Pipeline

- Queried ~ 3 years of ZTF alert stream.
- Need the right infrastructure to filter billions of alerts!
  - AMPEL is an alert processing platform that hosts the ZTF archive.



# Pipeline

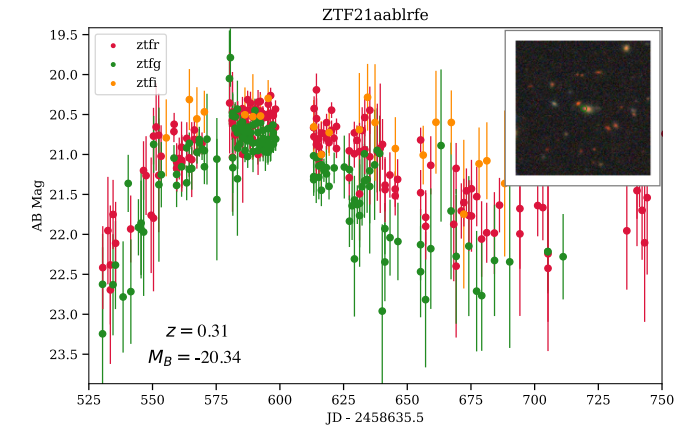
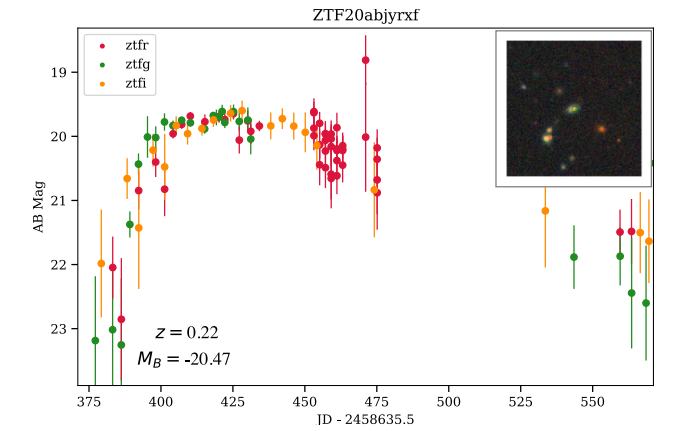
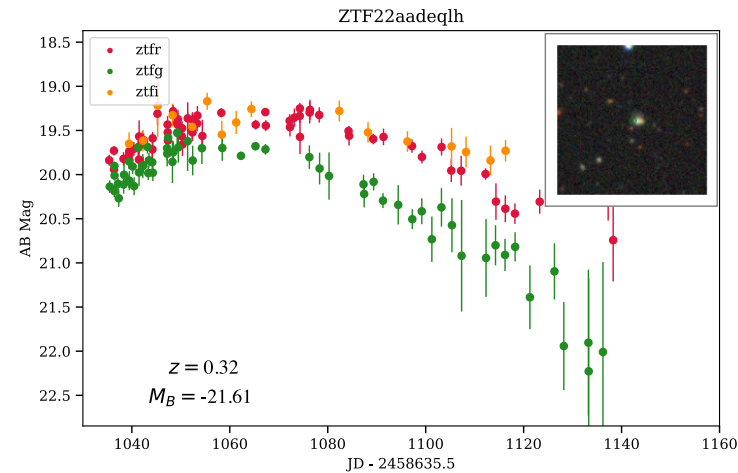
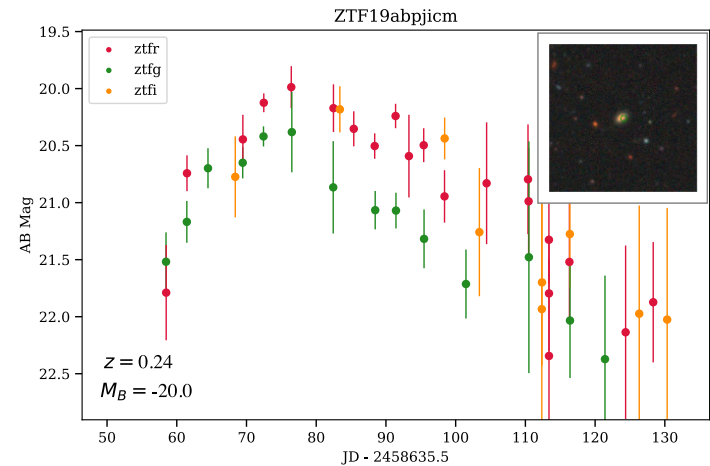
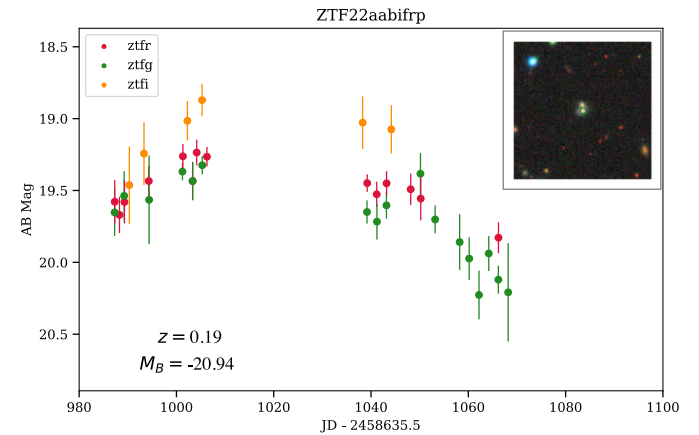
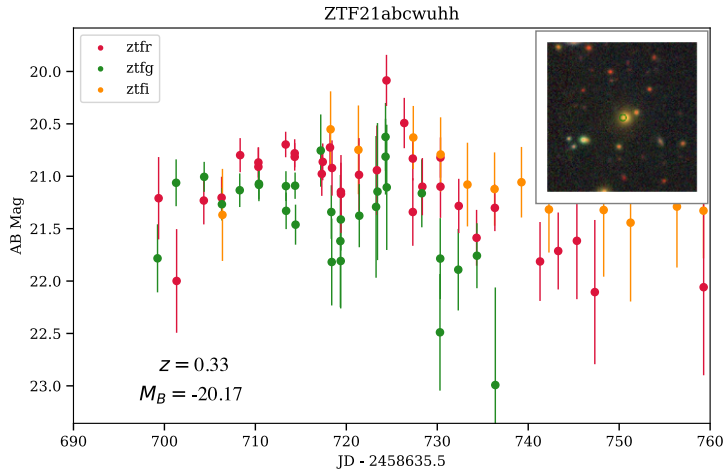
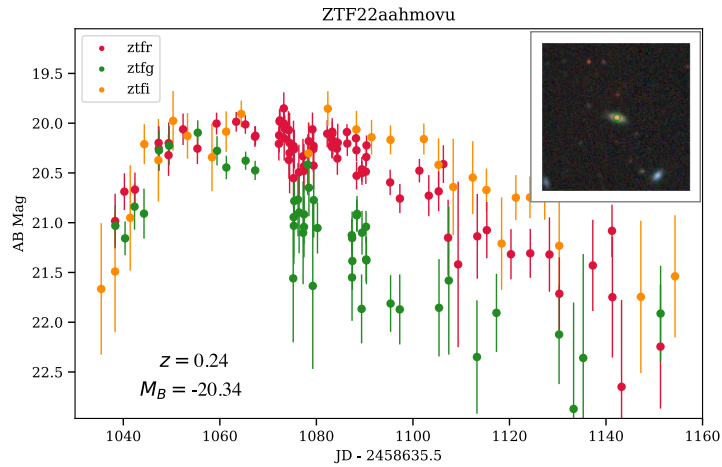
- Queried ~ 3 years of ZTF alert stream.
- Need the right infrastructure to filter billions of alerts!
  - AMPEL is an alert processing platform that hosts the ZTF archive.



We applied filters and cuts, resulting in two samples of candidates:

1. Less strict cuts + **spectroscopic redshift from DESI**
2. More strict cuts (e.g. light curve more closely resembling simulated gISNe Ia) + **photometric redshift**

# Gold sample candidates





# Gold sample candidates

However, we had to remove possible contaminants:

- AGN
- CSM interaction events
- TDEs
- **SLSNe**

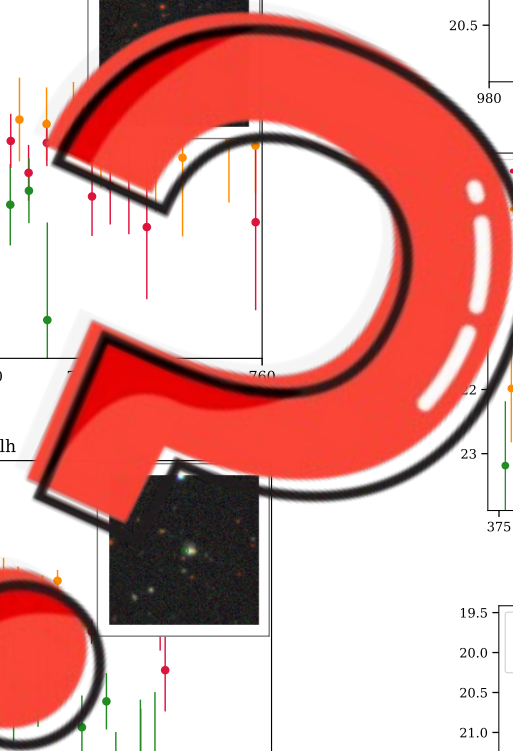
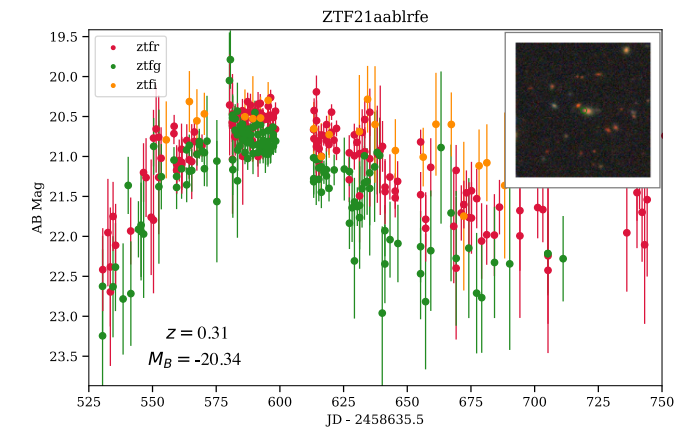
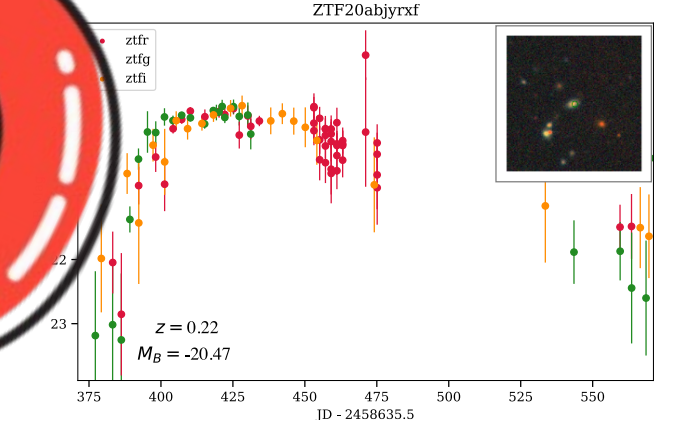
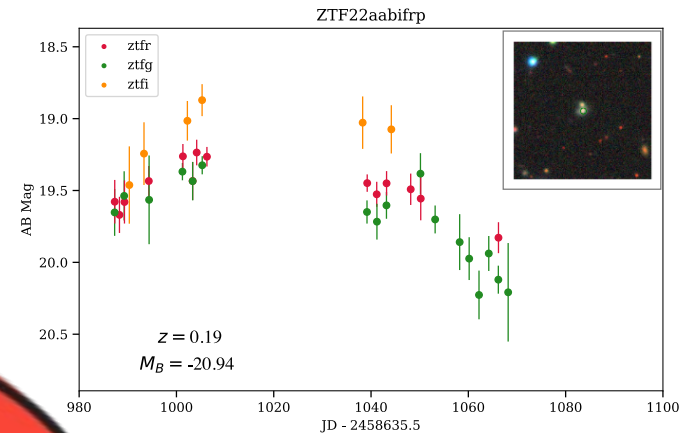
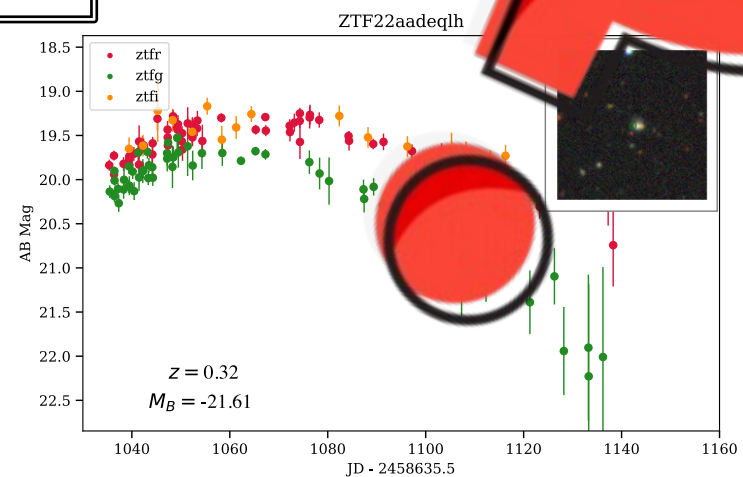
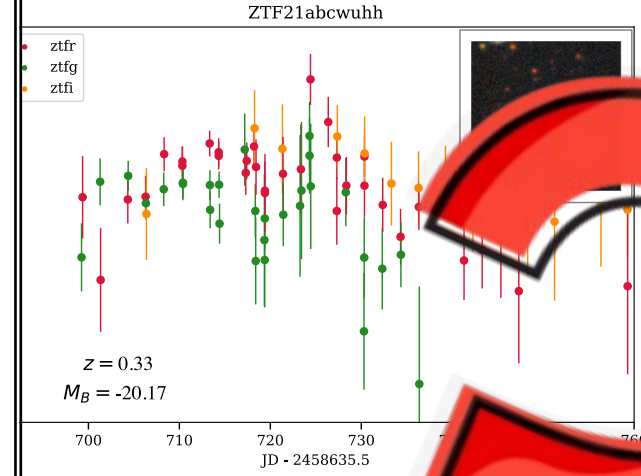
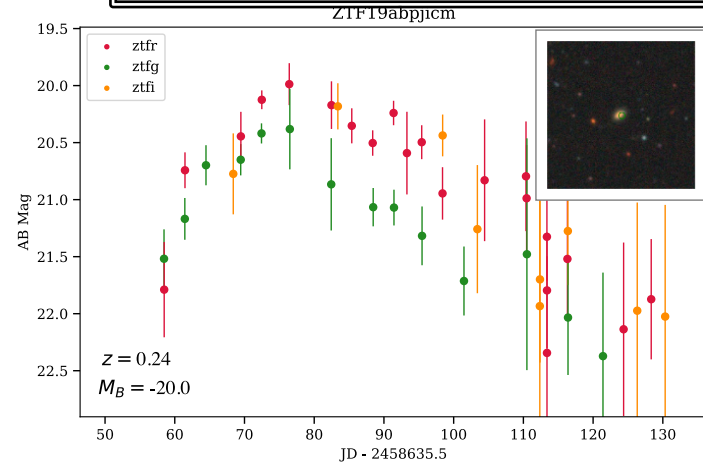
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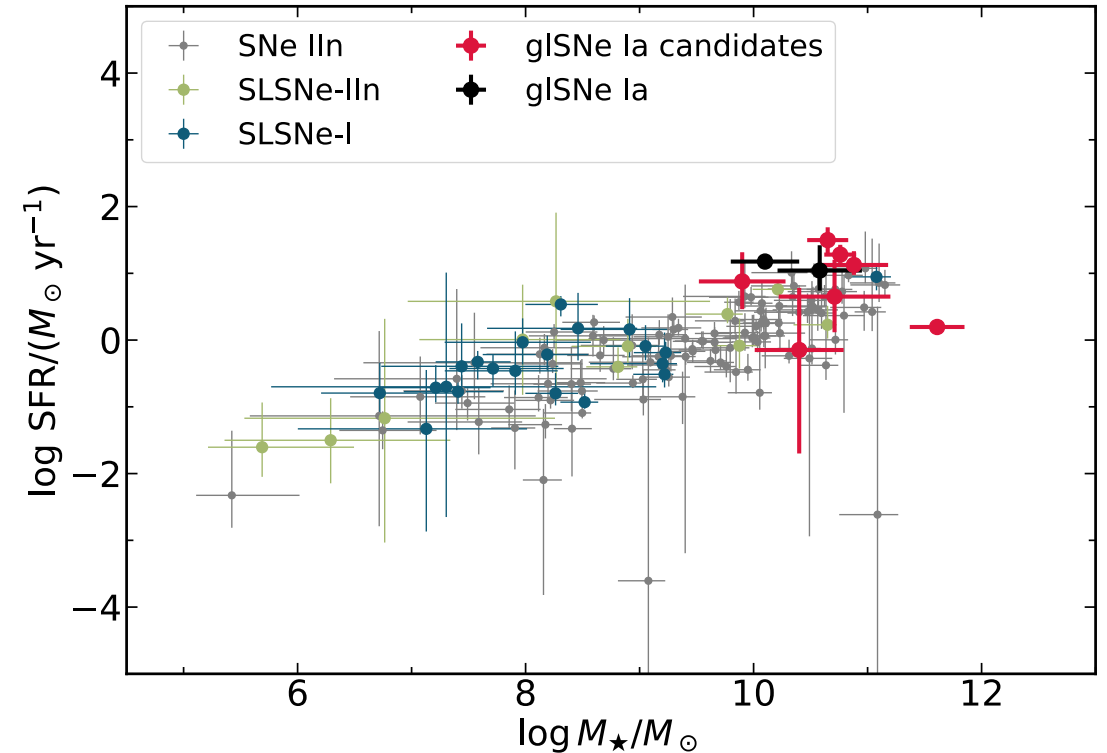
# Largest contaminant: SLSNe

SLSNe can be confused because they...

- are also **bright** (peak  $M_B \approx -21$ )
- can have **similar light curves** to gISNe Ia with larger time delays

However, could possibly distinguish them by...

- studying the host and/or possible lens **galaxy**
- comparing **rise/decline/duration** and light curve shape

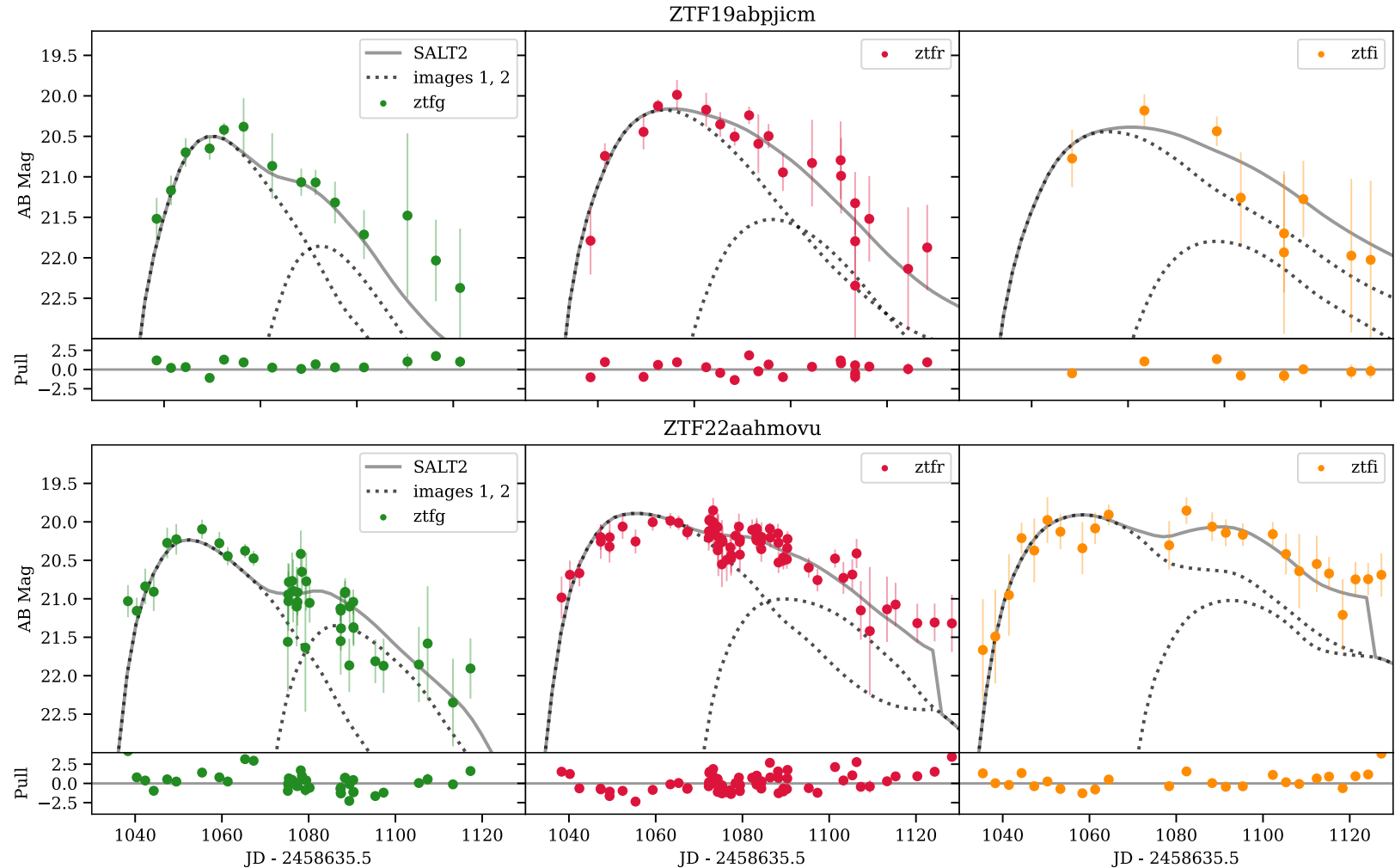


# Two likely gISNe Ia

We modelled a two-image lensed SN Ia by combining two SALT2 templates.

From this, we can estimate

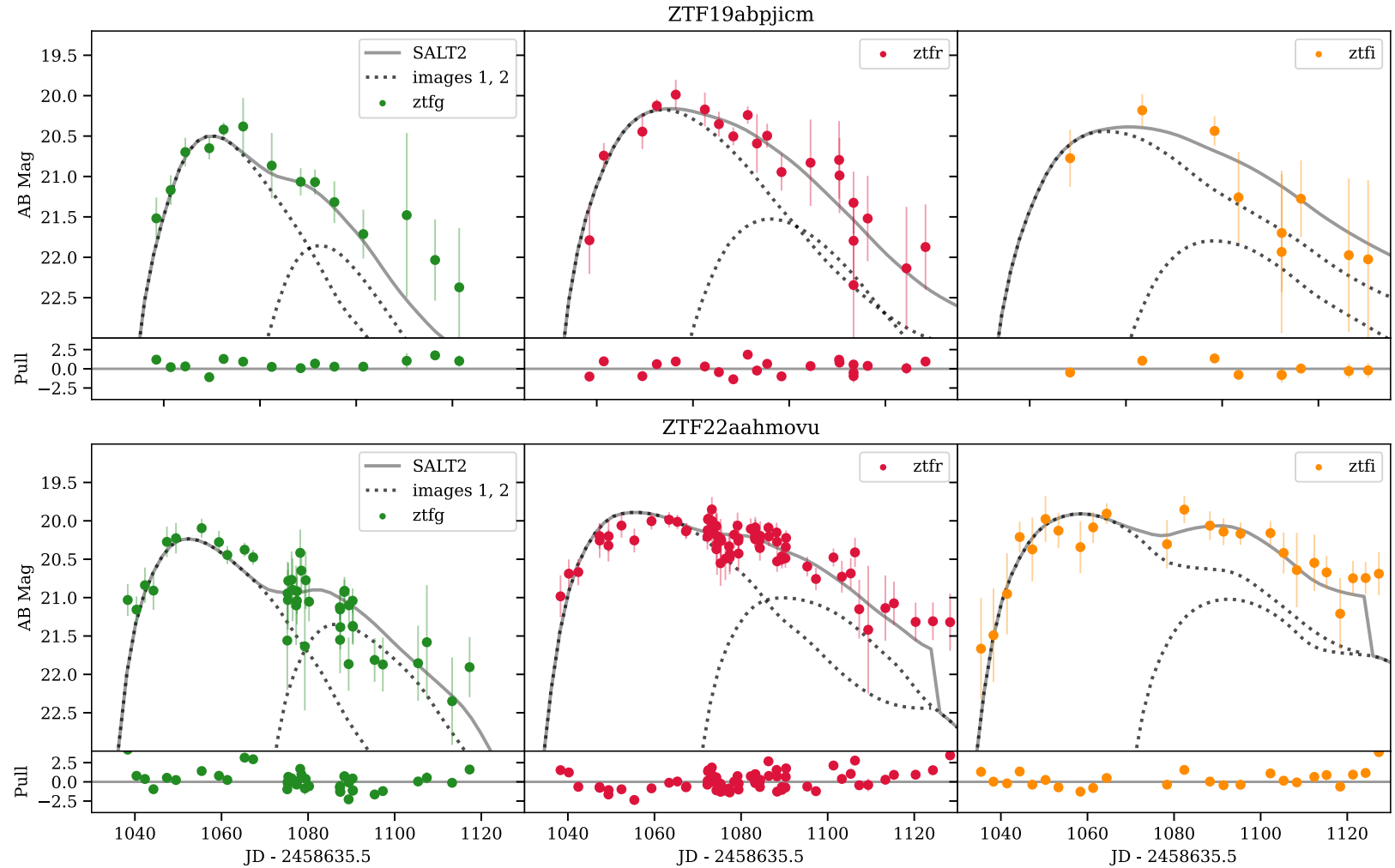
- Time delays
- Magnifications
- Image separation



# Two likely gISNe Ia

Time delay  $\Delta t = 22 \pm 3$  days  
 Magnification  $\mu_{\text{tot}} = 3.6 \pm 1.3$   
 Image separation  $\Delta\theta = 1.1''$

$\Delta t = 34 \pm 1$  days  
 $\mu_{\text{tot}} = 4.3 \pm 0.6$   
 $\Delta\theta = 1.7''$



# Summary

- Created a pipeline that filtered the **entire ZTF archive** for the specific criteria of a rare transient, gISNe Ia.
- Despite no spectra for the transients, we were able to identify and eliminate **contaminants**.
- **Two** gISNe Ia candidates with spectroscopic redshifts – and maybe more in the future.
- Opportunity with DESI to re-observe the gold sample galaxies at higher S/N (or follow-up with other telescopes).

→ **Paper is on the arXiv!**

# Summary

arXiv > astro-ph > arXiv:2405.18589

Astrophysics > High Energy Astrophysical Phenomena

[Submitted on 28 May 2024]

## Candidate strongly-lensed Type Ia supernovae in the Zwicky Transient Facility archive

A. Townsend, J. Nordin, A. Sagués Carracedo, M. Kowalski, N. Arendse, S. Dhawan, A. Goobar, J. Johansson, E. Mörtzell, S. Schulze, I. Andreoni, E. Fernández, A. G. Kim, P. E. Nugent, F. Prada, M. Rigault, N. Sarin, D. Sharma, E. C. Bellm, M. W. Coughlin, R. Dekany, S. L. Groom, L. Lacroix, R. R. Laher, R. Riddle, J. Aguilar, S. Ahlen, S. Bailey, D. Brooks, T. Claybaugh, A. de la Macorra, A. Dey, B. Dey, P. Doel, K. Fanning, J. E. Forero-Romero, E. Gaztañaga, S. Gontcho A Gontcho, K. Honscheid, C. Howlett, T. Kisner, A. Kremin, A. Lambert, M. Landriau, L. Le Guillou, M. E. Levi, M. Manera, A. Meisner, R. Miquel, J. Moustakas, E. Mueller, A. D. Myers, J. Nie, N. Palanque-Delabrouille, C. Poppett, M. Rezaie, G. Rossi, E. Sanchez, D. Schlegel, M. Schubnell, H. Seo, D. Sprayberry, G. Tarlé, H. Zou

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Gravitationally lensed Type Ia supernovae (gISNe Ia) are unique astronomical tools for studying cosmological parameters, distributions of dark matter, the astrophysics of the supernovae and the intervening lensing galaxies themselves. Only a few highly magnified gISNe Ia have been discovered by ground-based telescopes, such as the Zwicky Transient Facility (ZTF), but simulations predict the existence of a fainter, undetected population. We present a systematic search in the ZTF archive of alerts from 1 June 2019 to 1 September 2022. Using the AMPEL platform, we developed a pipeline that distinguishes candidate gISNe Ia from other variable sources. Initial cuts were applied to the ZTF alert photometry before forced photometry was obtained for the remaining candidates. Additional cuts were applied to refine the candidates based on their light curve colours, lens galaxy colours, and the resulting parameters from fits to the SALT2 SN Ia template. Candidates were also cross-matched with the DESI spectroscopic catalogue. Seven transients passed all the cuts and had an associated galaxy DESI redshift, which we present as gISN Ia candidates. While superluminous supernovae (SLSNe) cannot be fully rejected, two events, ZTF19abpjcm and ZTF22aahmovu, are significantly different from typical SLSNe and their light curves can be modelled as two-image gISN Ia systems. From this two-image modelling, we estimate time delays of  $22 \pm 3$  and  $34 \pm 1$  days for the two events, respectively, which suggests that we have uncovered a population with longer time delays. The pipeline is efficient and sensitive enough to parse full alert streams. It is currently being applied to the live ZTF alert stream to identify and follow-up future candidates while active. This pipeline could be the foundation for gISNe Ia searches in future surveys, like the Vera C. Rubin Observatory's Legacy Survey of Space and Time.

Criteria of a rare

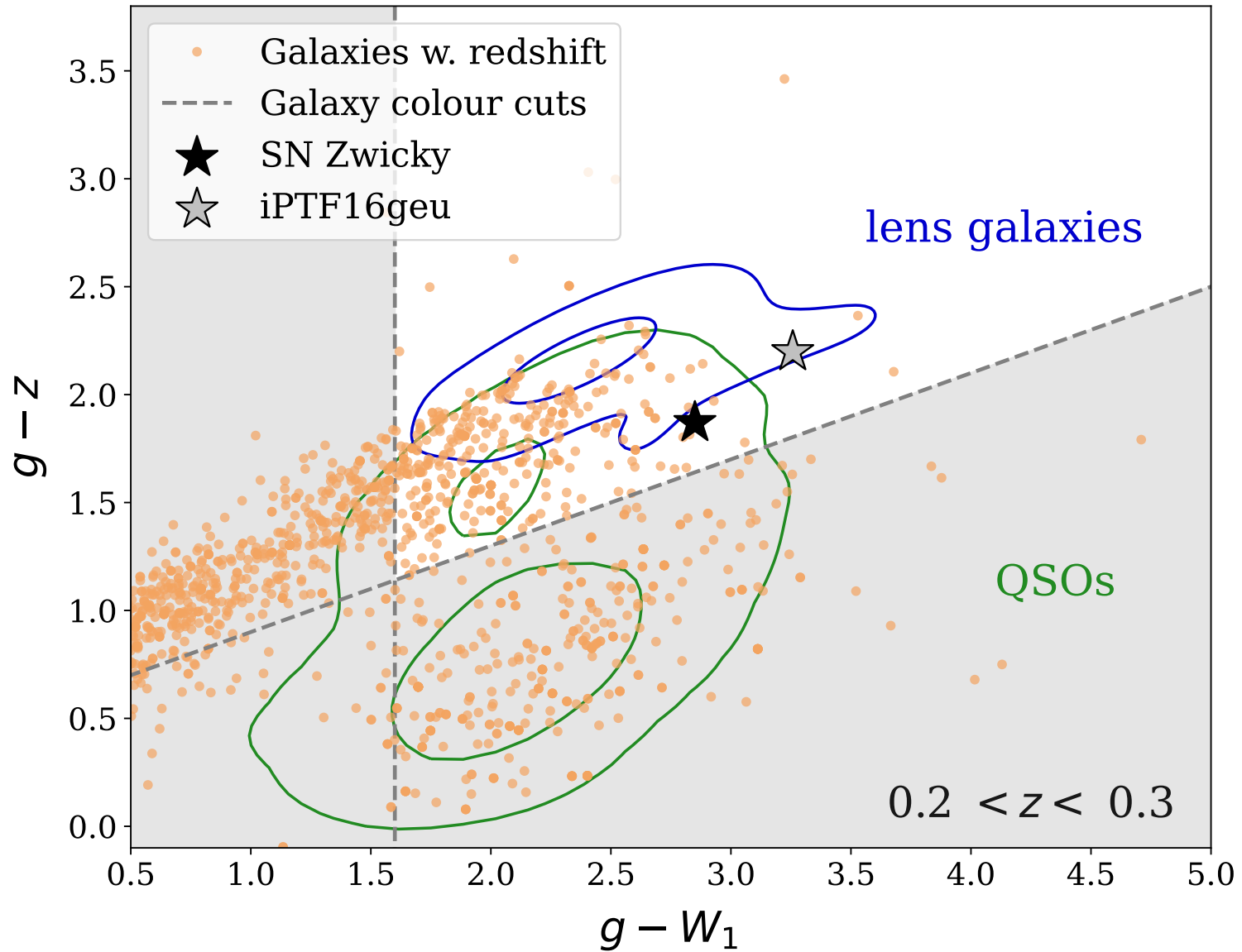
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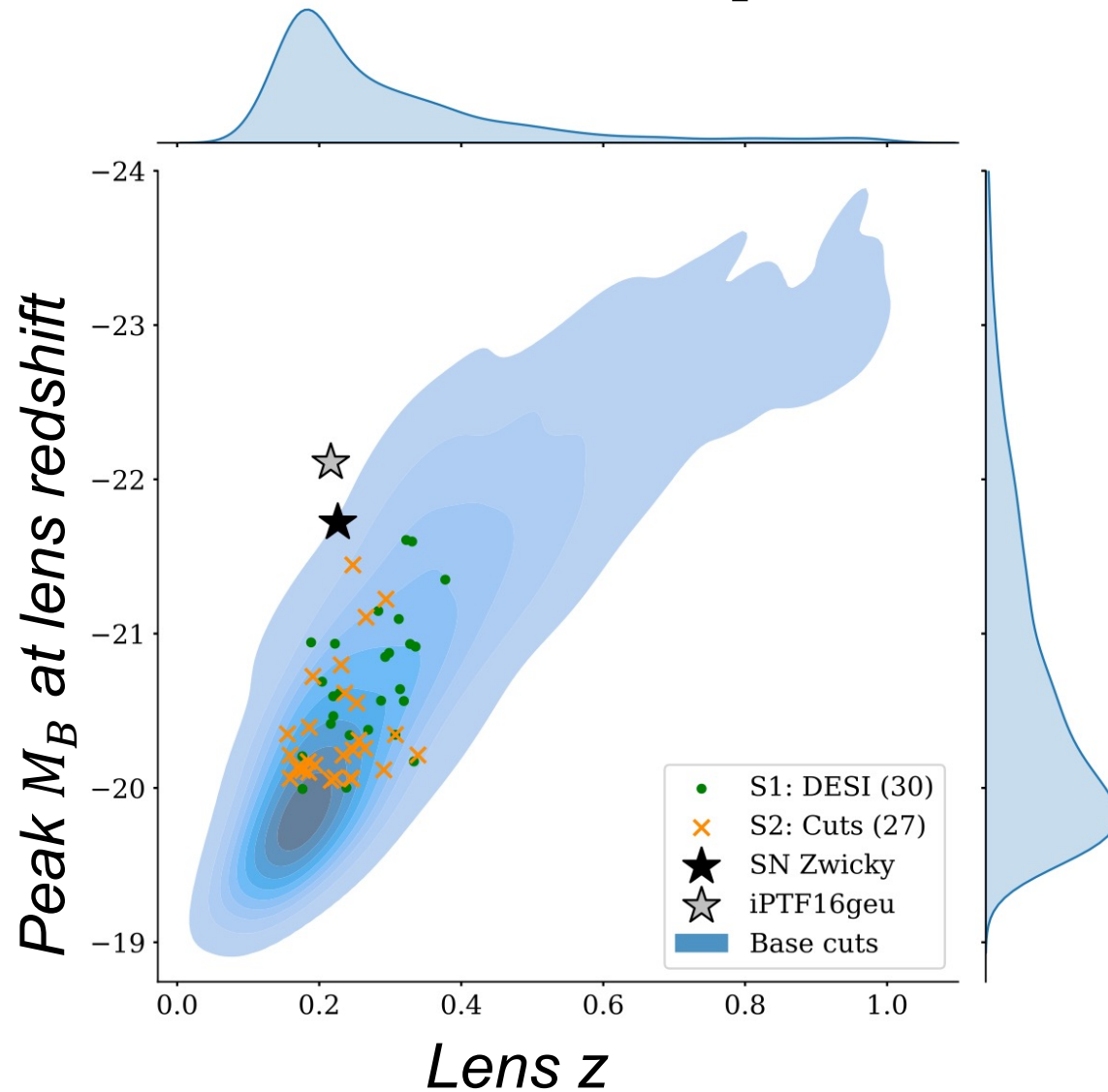


# Extra slides





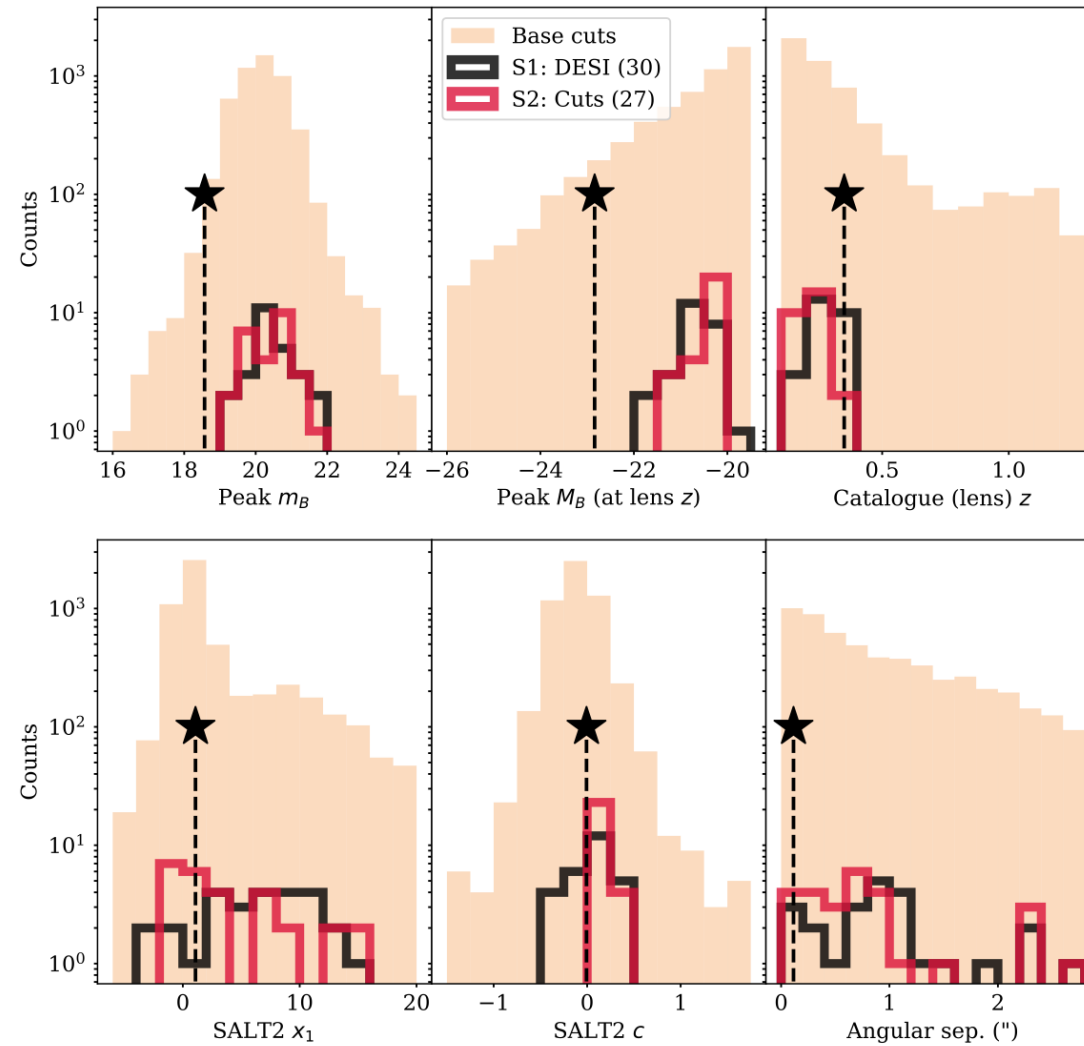
# Sample statistics



Detected gISNe Ia (**SN Zwicky** and **iPTF16geu**) match the brightest magnification tail.

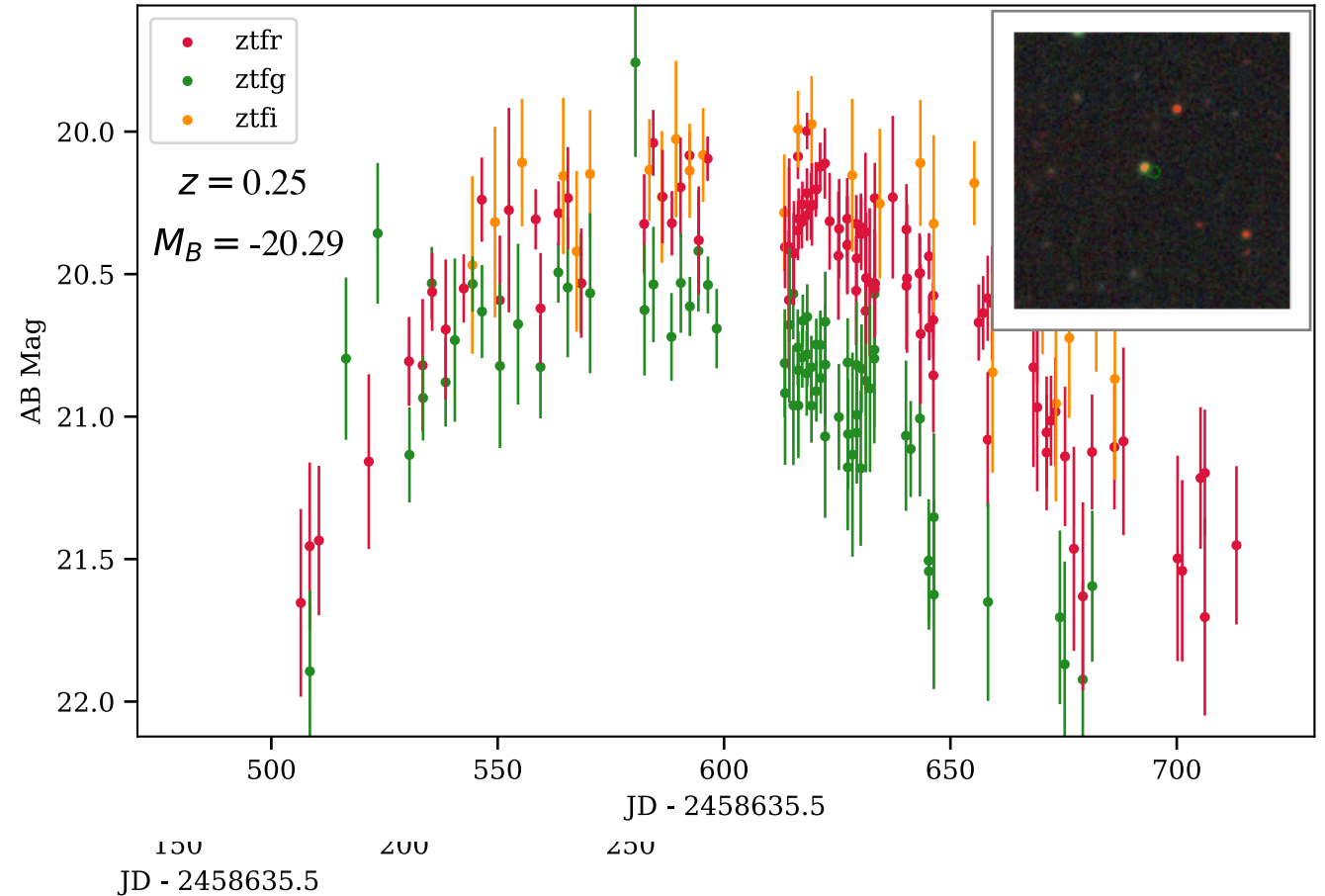
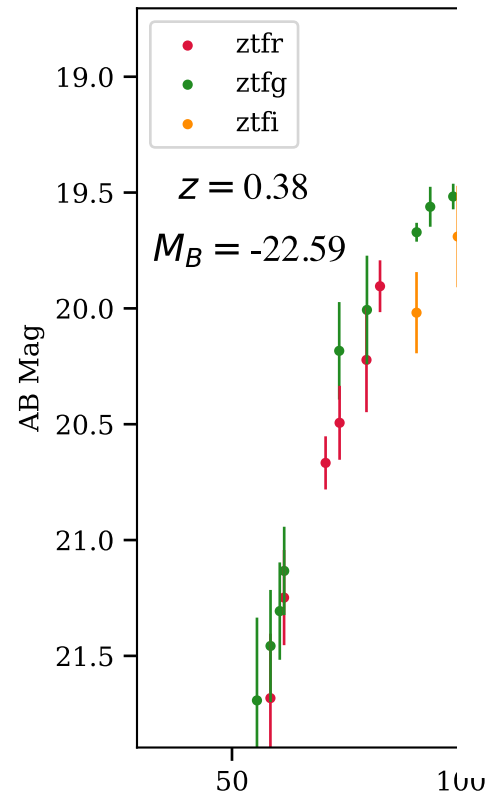
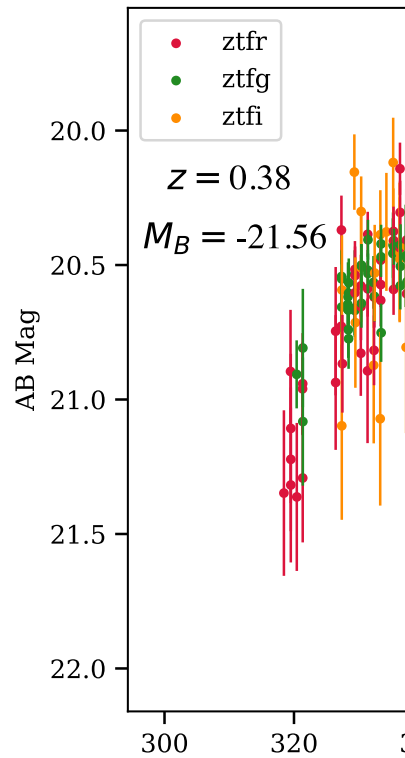
We have identified a large population of less magnified *candidate* gISNe Ia.

# Sample statistics



# Contaminants – SLSNe

and many, many more...

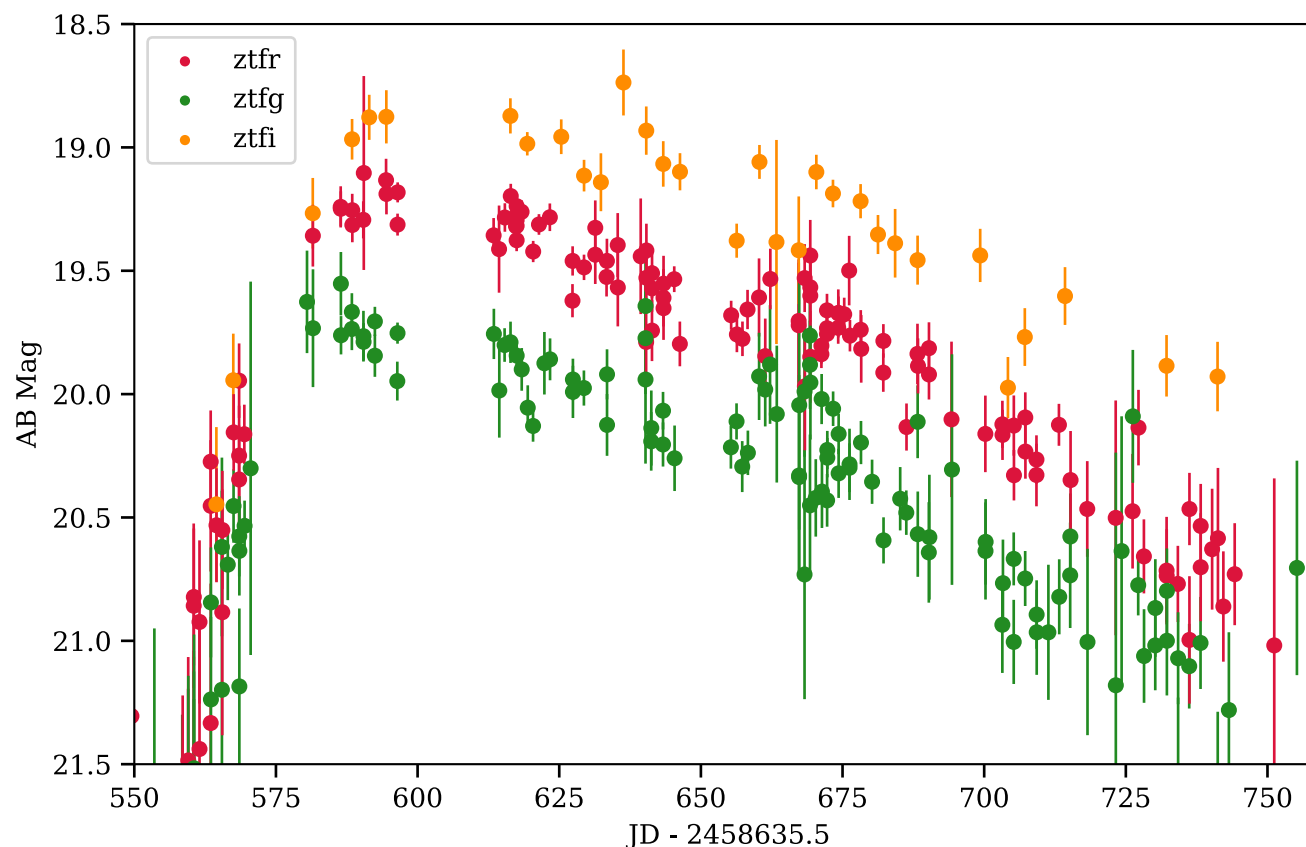


# Contaminants – TDEs

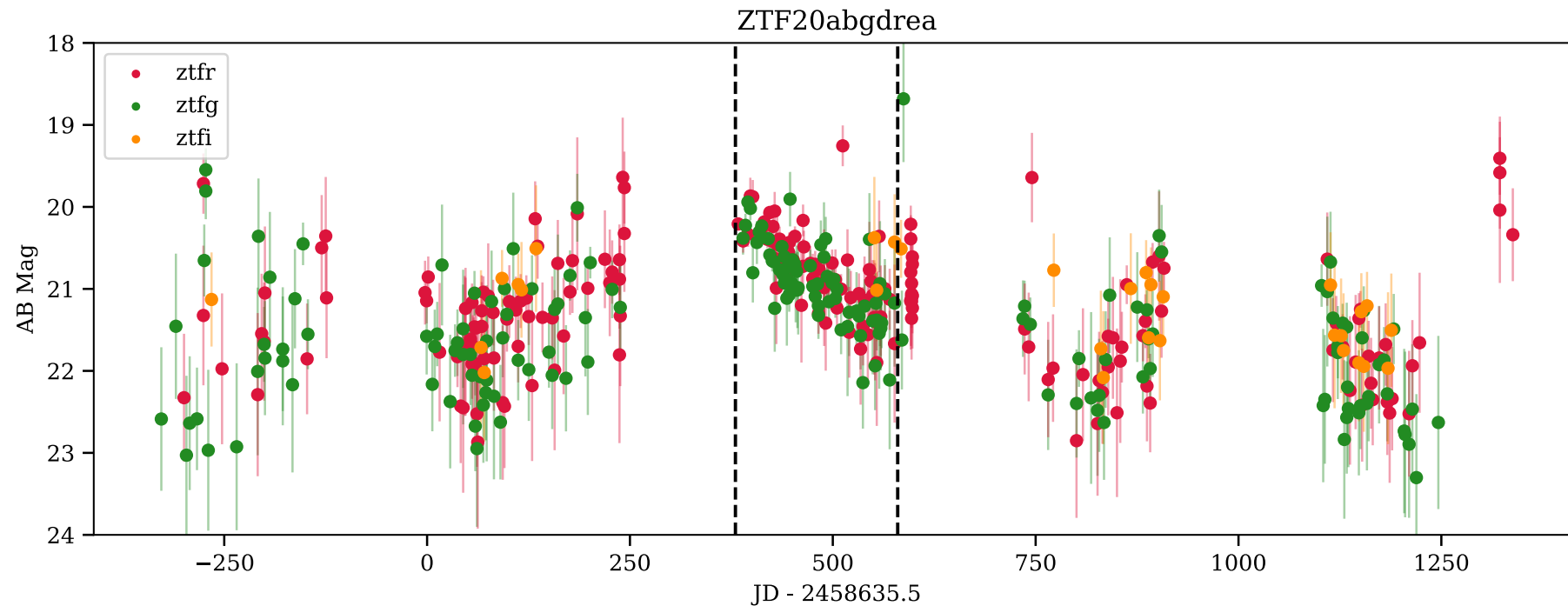
TDE can be confused because they...

- can also be bright
- are close to core of galaxy
- can be red

However, we can distinguish them by light curve shape.



# Contaminants – AGN



Passed all cuts, in a candidate lens system, but has long-term variability ☹️