

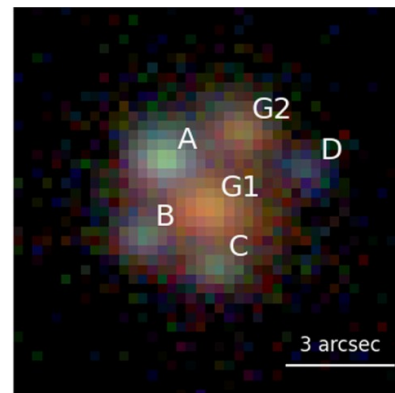
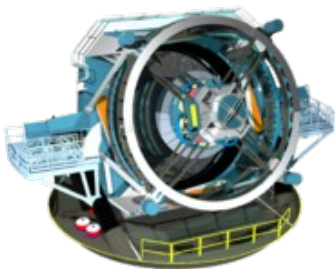


# Cosmology and stellar physics with strongly lensed supernovae

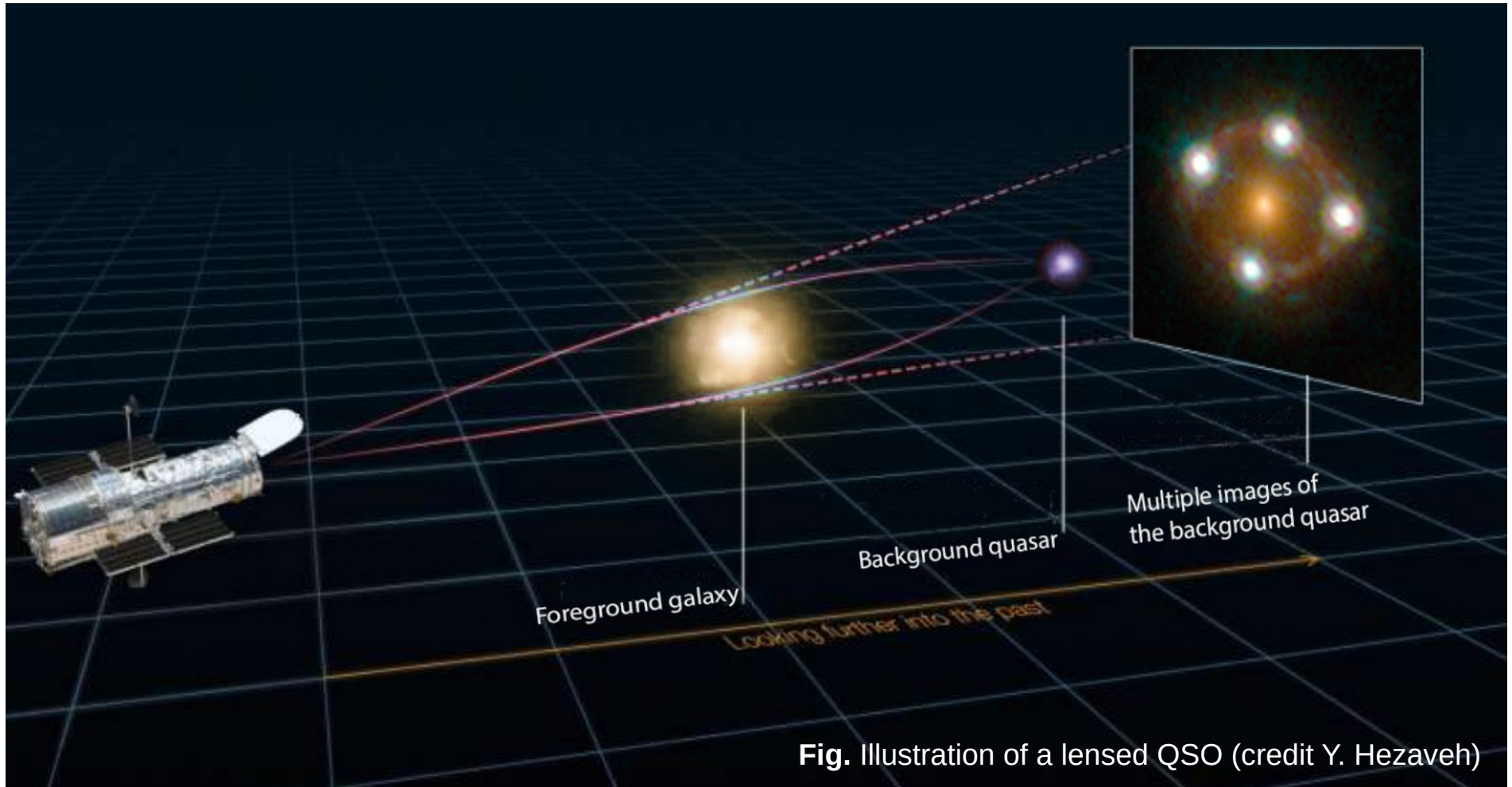
**Raoul Cañameras (LAM)** and HOLISMOKES coll.

Rubin LSST-France Meeting – LAPP Annecy

19 May 2026



# Time-delay cosmography



Strongly lensed time-variable sources (quasars, supernovae)

**Multiple images appear around the foreground lens galaxy *at different times***

# Ingredients for time-delay cosmography

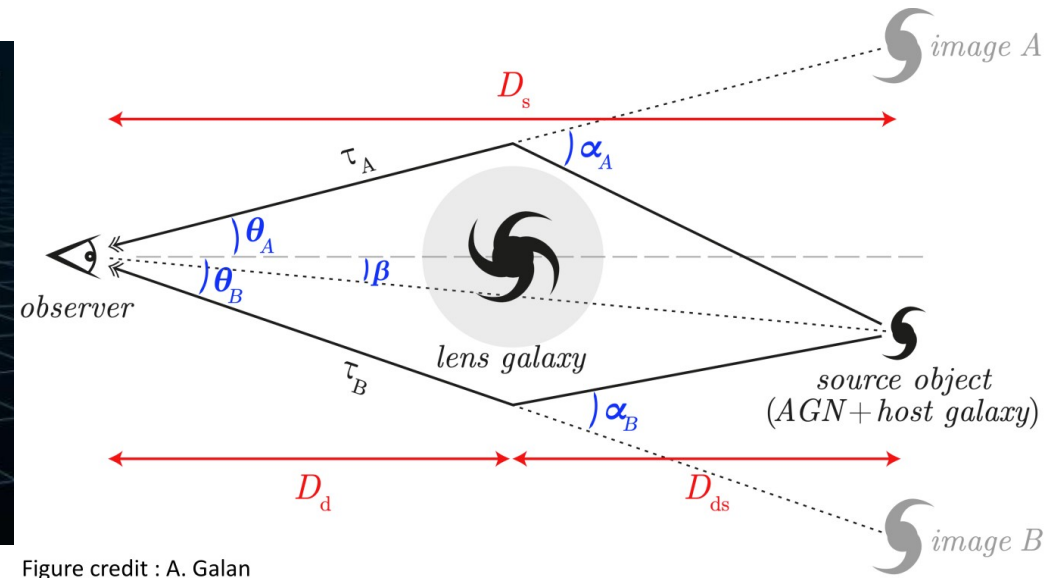
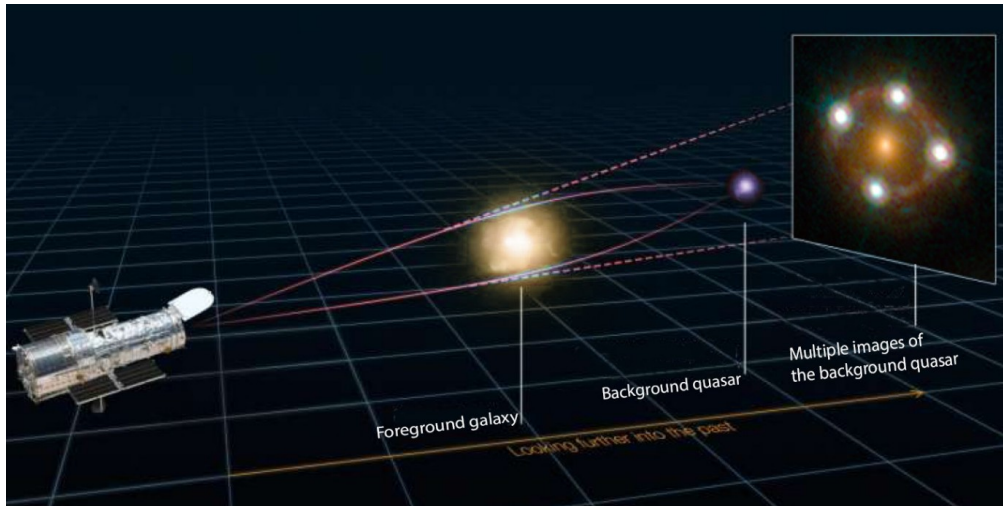
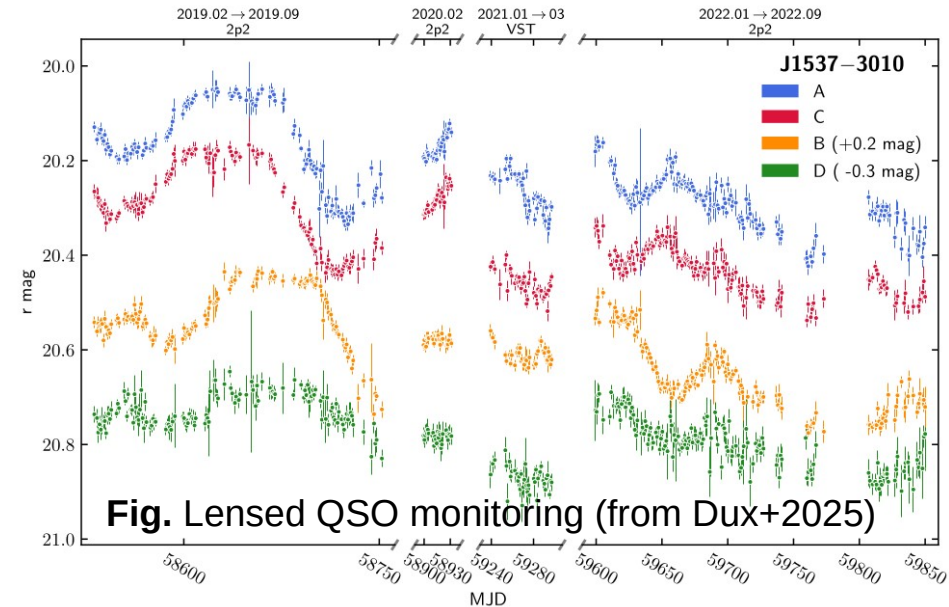
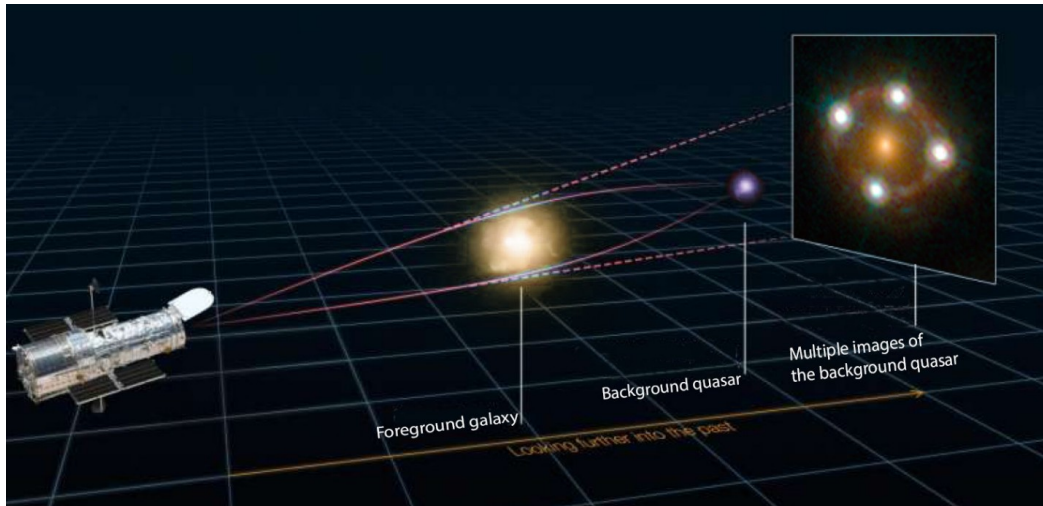


Figure credit : A. Galan

## Measurement of the time-delay distance

$$D_{\Delta t} = (1 + z_d) \frac{D_d D_s}{D_{ds}} \propto H_0^{-1}$$

# Ingredients for time-delay cosmography



- ① Time delays between lensed images with monitoring
- ② Strong lens modeling with high-resolution imaging
- ③ External convergence from the lens environment

$$D_{\Delta t} = \frac{c\tau_{AB}}{(1 - \kappa_{ext}) [\Phi(\theta_A) - \Phi(\theta_B)]}$$

# Measurements of $H_0$ through strong lensing time delays

## From lensed quasars to lensed supernovae

### Advantages:

SNe have characteristic light curves, enabling time-delay measurements.

Lens mass modeling is more straightforward, after SNe fade (quasars outshine other components; Ding et al. 2021).

SNe are standard candles (Foxley-Marrable et al. 2018).

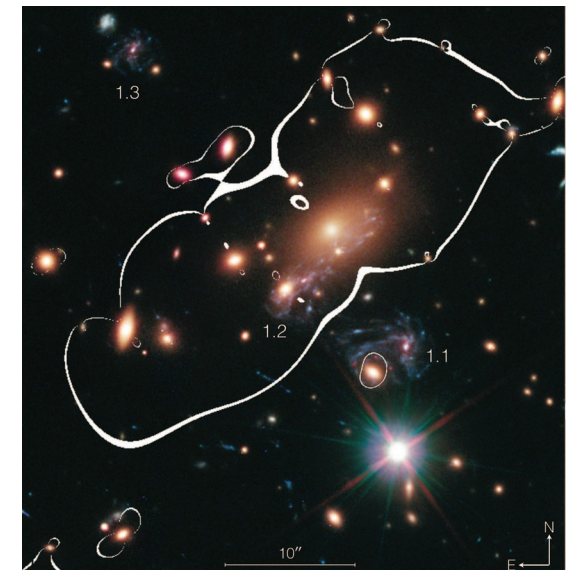
### Challenges:

Microlensing of SN by stars in the foreground lens.

Lensed SNe are very rare + short-lived.



**SN iPTF16geu**  
(Goobar et al. 2017)



**SN Refsdal** (Kelly et al. 2015)

# Measurements of $H_0$ through strong lensing time delays

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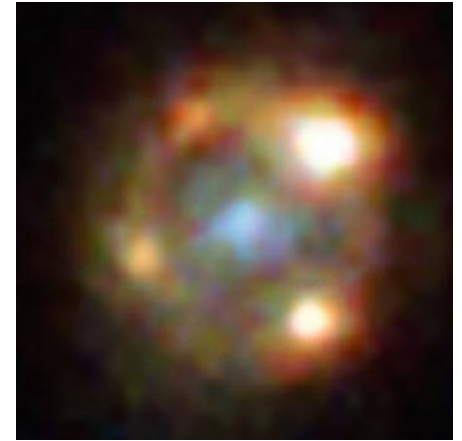
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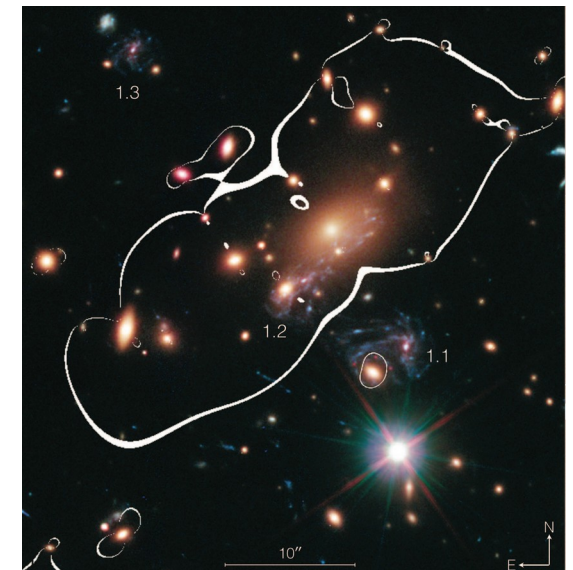
Microlensing of SN by stars in the foreground lens.

Lensed SNe are very rare + short-lived.

**Better precision on  $H_0$  (Suyu et al. 2020)**

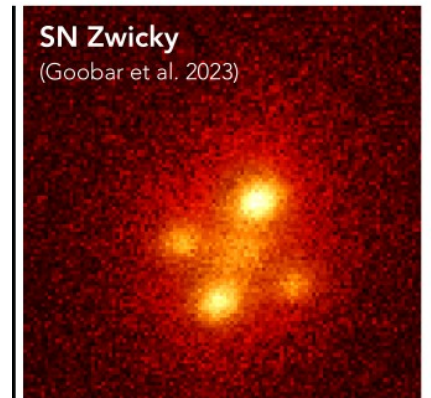
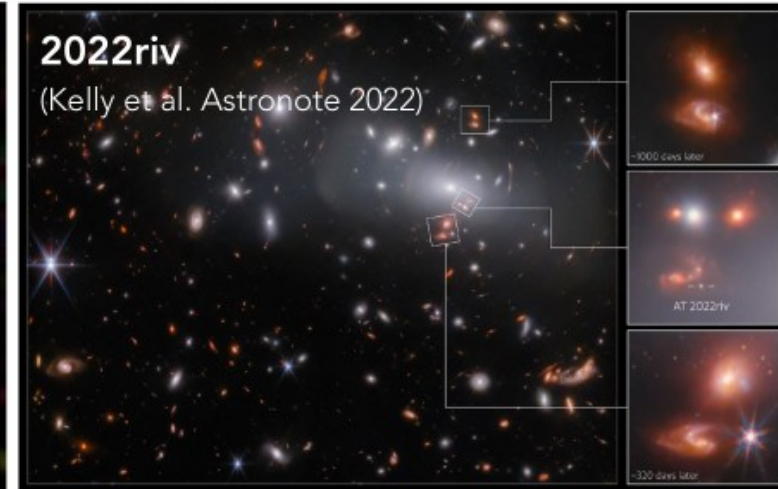
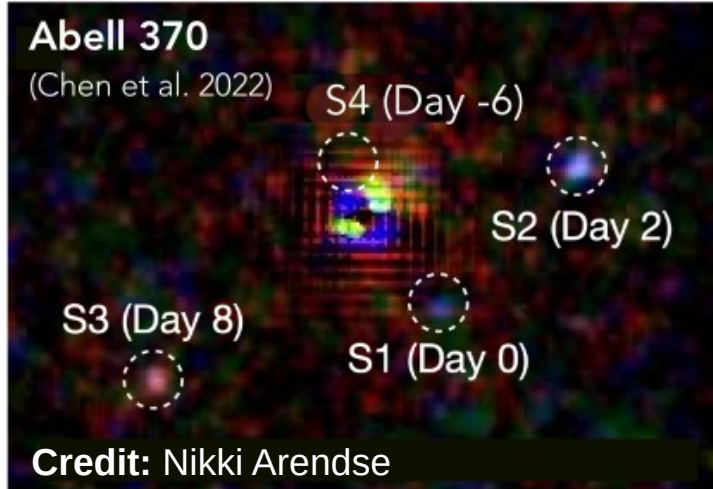
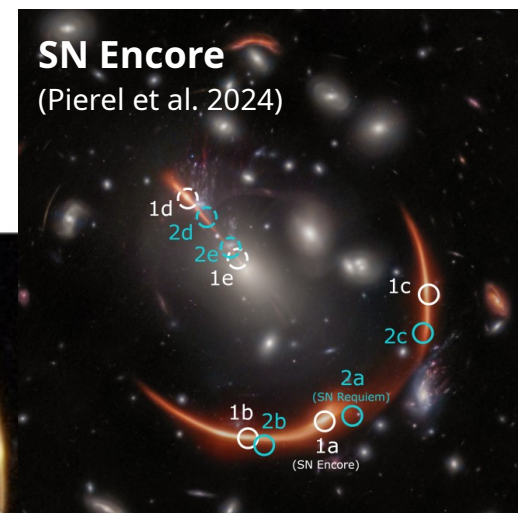
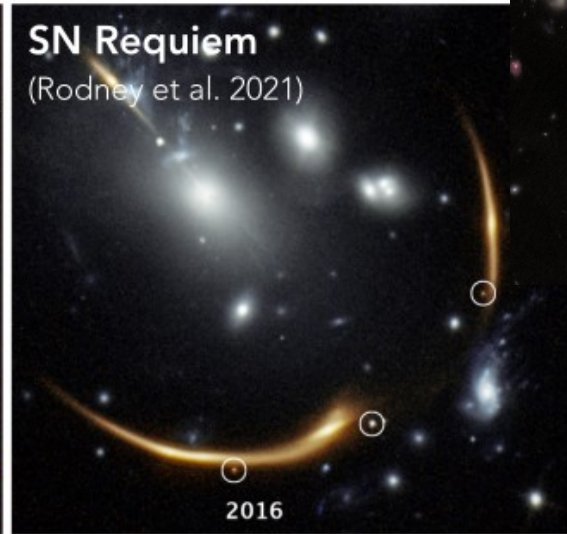
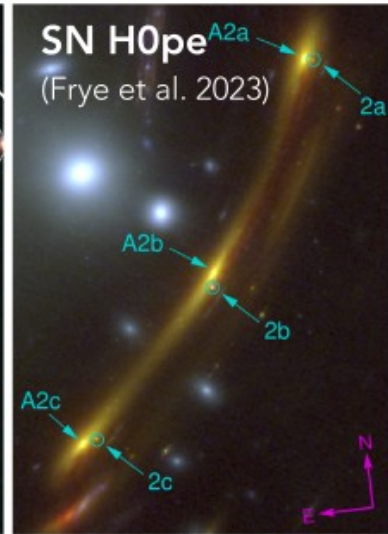
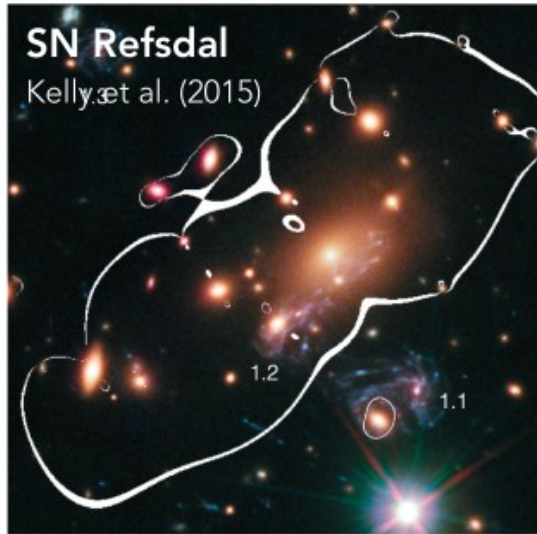


**SN iPTF16geu**  
(Goobar et al. 2017)



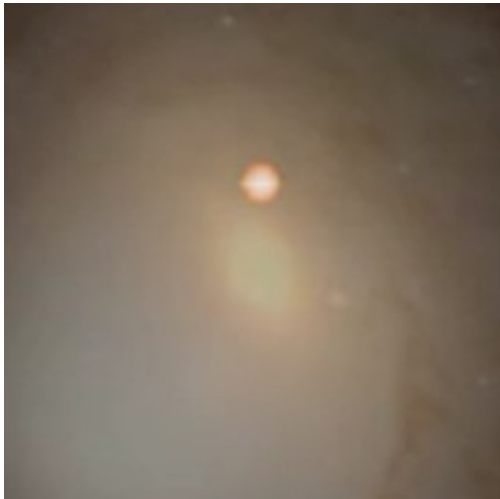
**SN Refsdal** (Kelly et al. 2015)

# Past lensed SN discoveries (< 2025)

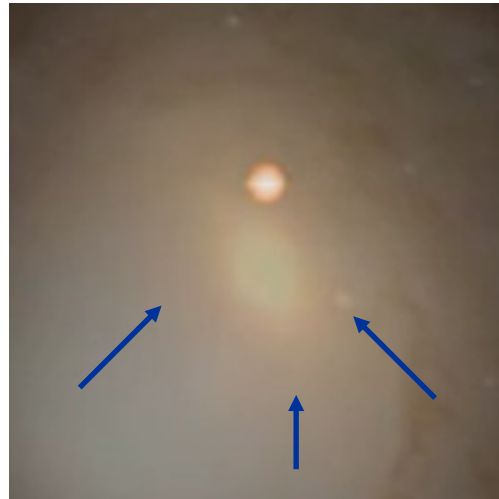


**Gold lensed SN sample best selected with Rubin LSST**  
(e.g. Huber et al. 2019, Arendse et al. 2024)

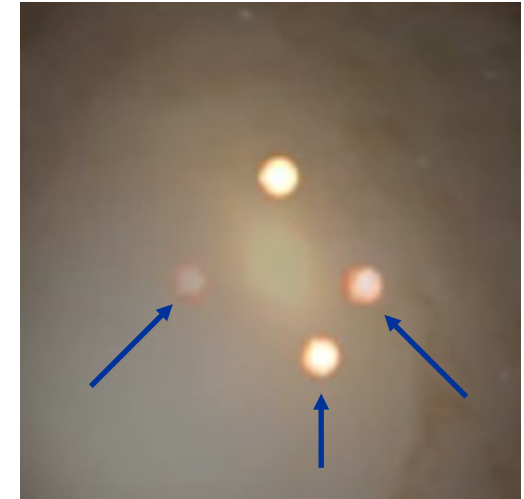
# Unveiling SN progenitors with lensed supernovae



Detect first SN image



Predict location/time of next SN image(s)



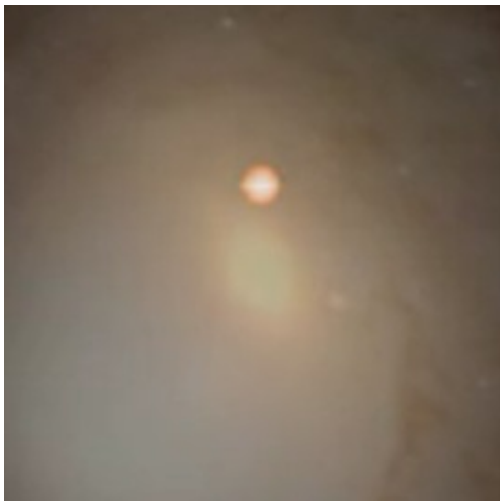
Observe early phase of next SN image(s)

## Lensed SNe allow to constrain SN progenitors

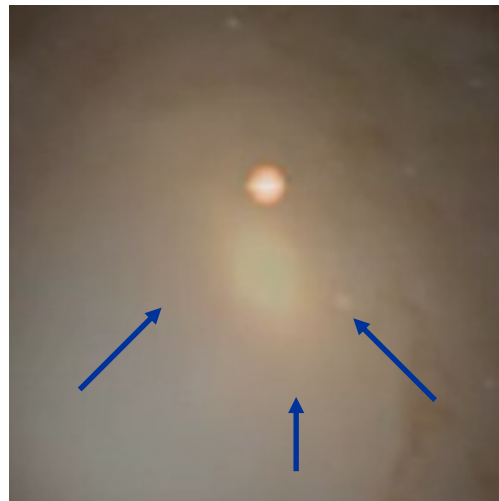
- Monitoring with 1-2m telescopes (ESO/MPG 2.2m, COLIBRI) + rapid ToO programs (MUSE, X-Shooter, etc)
- Rest-frame UV spectroscopy 1-2 days after explosion



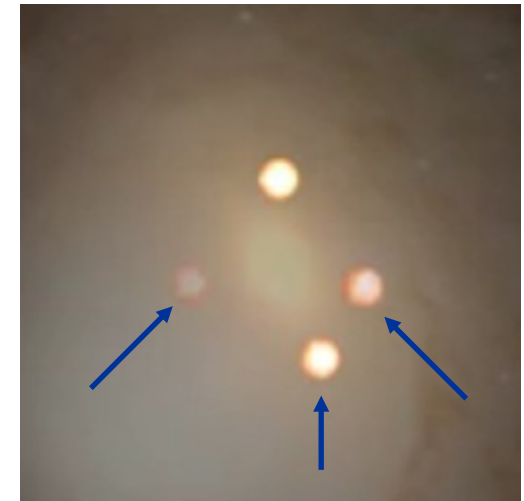
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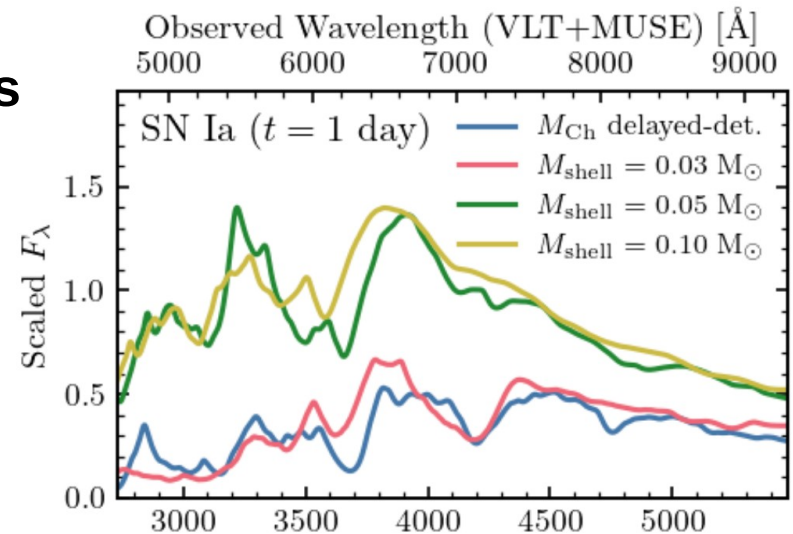
Predict location/time of next SN image(s)



Observe early phase of next SN image(s)

## Lensed SNe allow to constrain SN progenitors

- Single degenerate, double degenerate or other scenarios for type Ia ?
- Newly funded project “SuperEarly”



Credit: Rest Wavelength at  $z = 0.7$  [Å]  
S. Blondin

# HOLISMOKES!

**H**ighly **O**ptimised **L**ensing **I**nvestigations of  
**S**upernovae, **M**icrolensing **O**bjects, and **K**inematics  
of **E**llipticals and **S**pirals

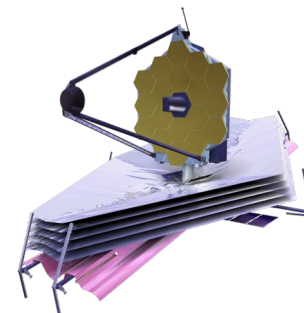
Suyu et al. 2020, A&A 644, 162 (HOLISMOKES I)

[www.holismokes.org](http://www.holismokes.org)



**Setup:** Sample of 20 mock lensed SN Ia from LSST with precise and accurate time-delay measurements

+ Spatially-resolved 2D stellar kinematics of the lens



→ Infer the time-delay distance and the angular diameter distance to the lens galaxy

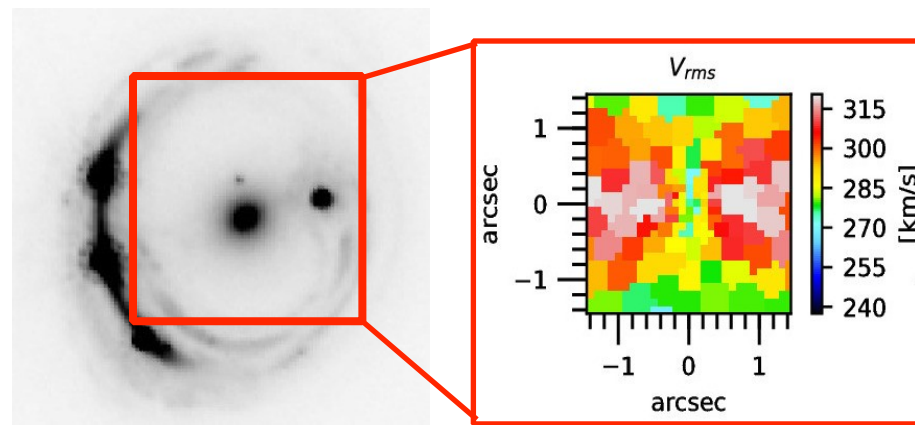
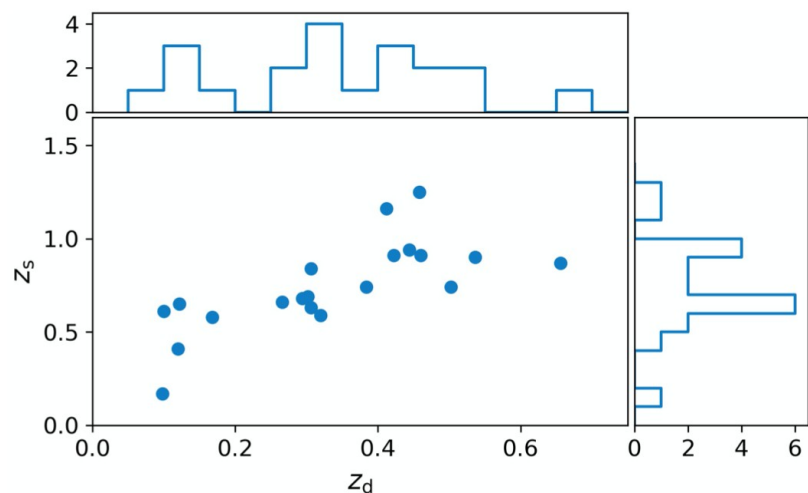


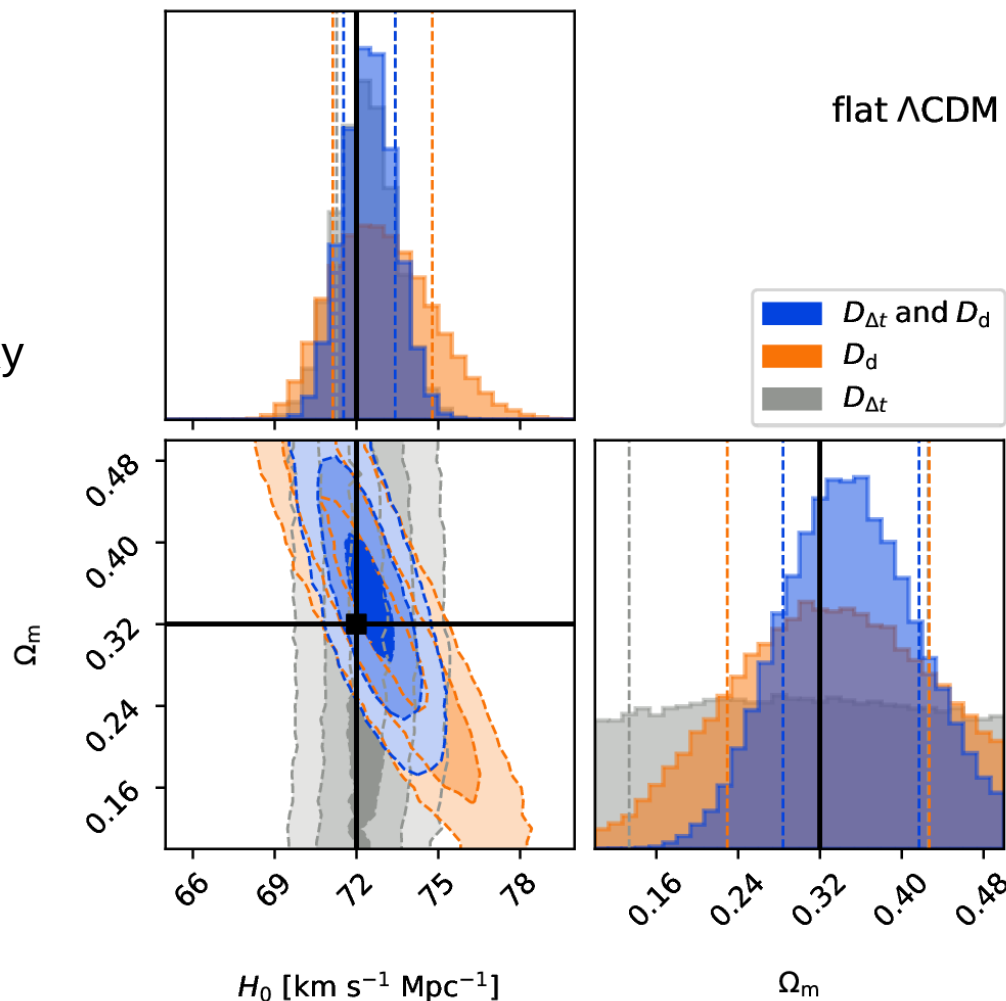
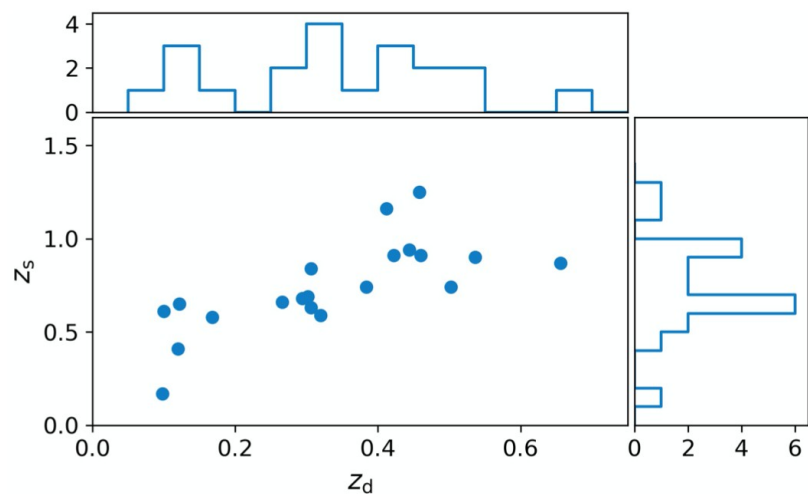
Fig. Example for quasar RXJ1131 (Yıldırım et al. 2020).

→ Anticipate  $H_0$  constraints with 1.3% precision in flat  $\Lambda$ CDM from this sample

Suyu, Huber, Cañameras et al. 2020 (HOLISMOKES I)

**Setup:** Sample of 20 mock lensed SN Ia from LSST with precise and accurate time-delay measurements

→ Infer the time-delay distance and the angular diameter distance to the lens galaxy



→ Anticipate  $H_0$  constraints with 1.3% precision in flat  $\Lambda$ CDM from this sample

# Strategies for finding lensed supernovae

Cañameras et al. 2020, 2021, 2024 (HOLISMOKES II, VI, XI)

**First option → Monitoring static strong lenses**

**Identify all static strong lenses and wait for a SN to explode in the background hosts**

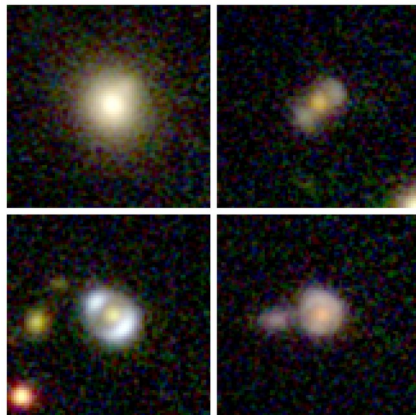
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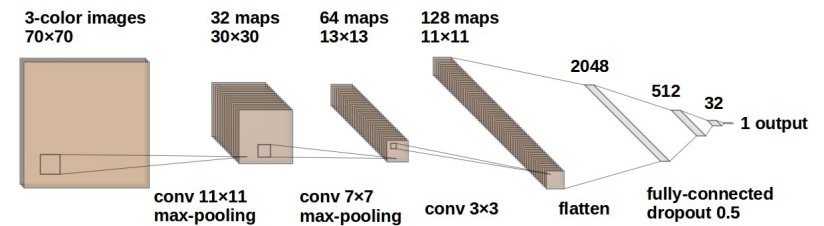
- Supervised Deep Learning classification to cope with huge data volume
- Realistic lens simulations for higher classification accuracies



$10^5$  lens simulations



$10^5$  negative examples



# Strategies for finding lensed supernovae

Cañameras et al. 2020, 2021, 2024 (HOLISMOKES II, VI, XI)

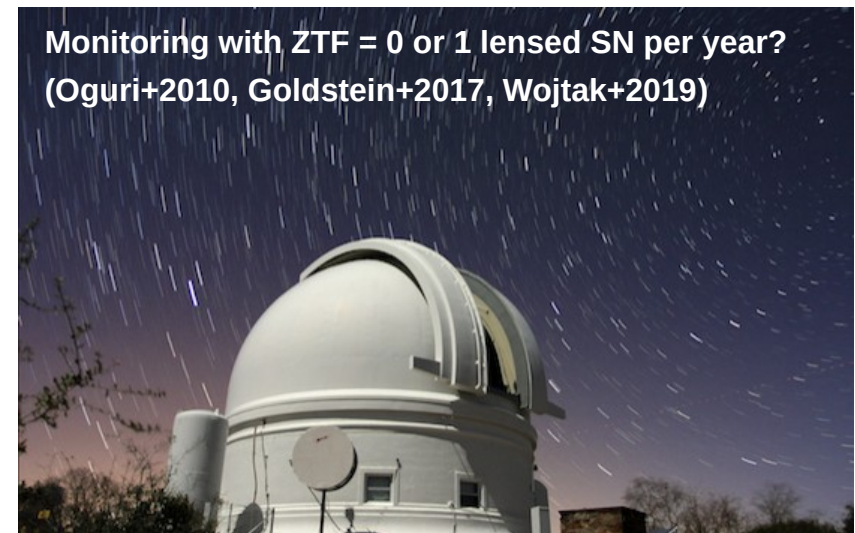
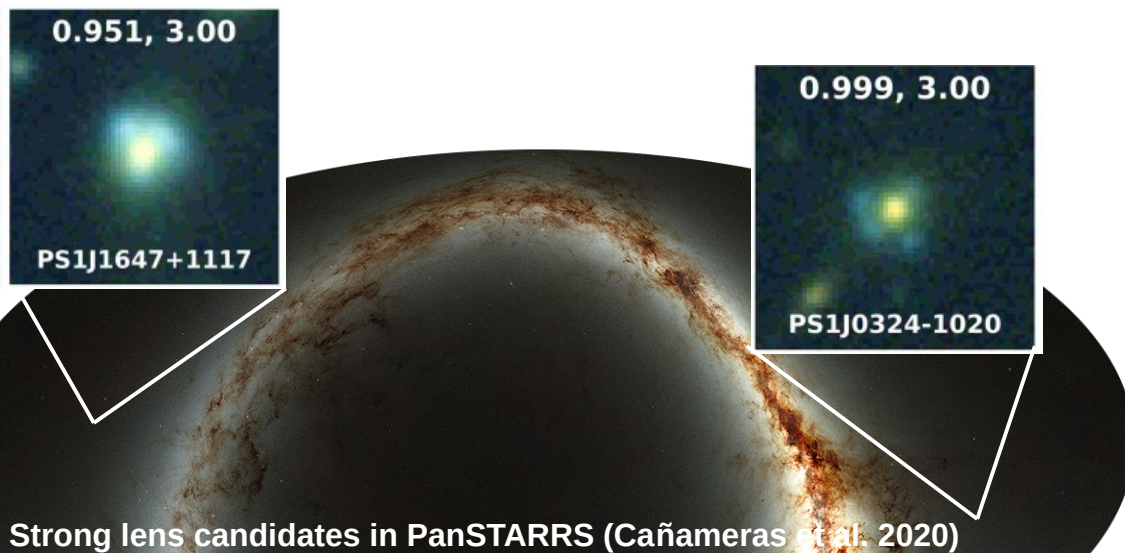
## First option → Monitoring static strong lenses

### Identify all static strong lenses and wait for a SN to explode in the background hosts

- Supervised Deep Learning classification to cope with huge data volume
- Realistic lens simulations for higher classification accuracies

From 3 billion sources from Pan-STARRS  $3\pi$  survey → to few 1,000 static lens candidates

→ All-sky classification in the North with PanSTARRS + ZTF alert monitoring



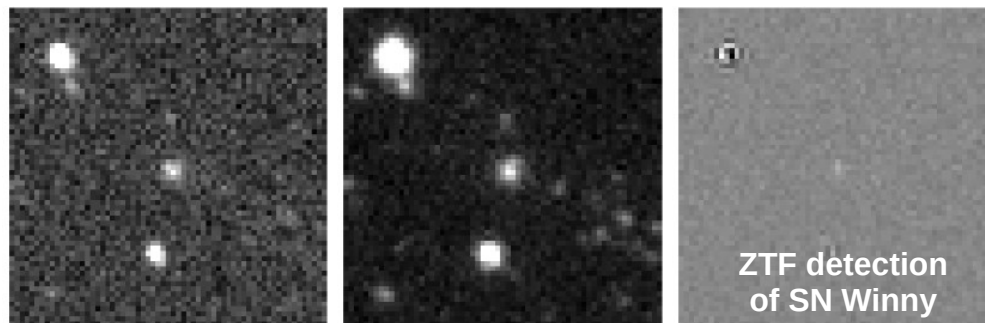


# Discovery of SN Winny

Taubenberger, Acebron, Cañameras,  
et al. 2025, A&A acc. (HOLISMOKES XIX)

## SN 2025wny (ZTF25abnjznp, GOTO25gqt) detection history

- First detected by ZTF on 2025-08-27
- Detected by GOTO on 2025-09-01  
→ First report to TNS by GOTO coll.  
<https://www.wis-tns.org/object/2025wny/discovery-cert>

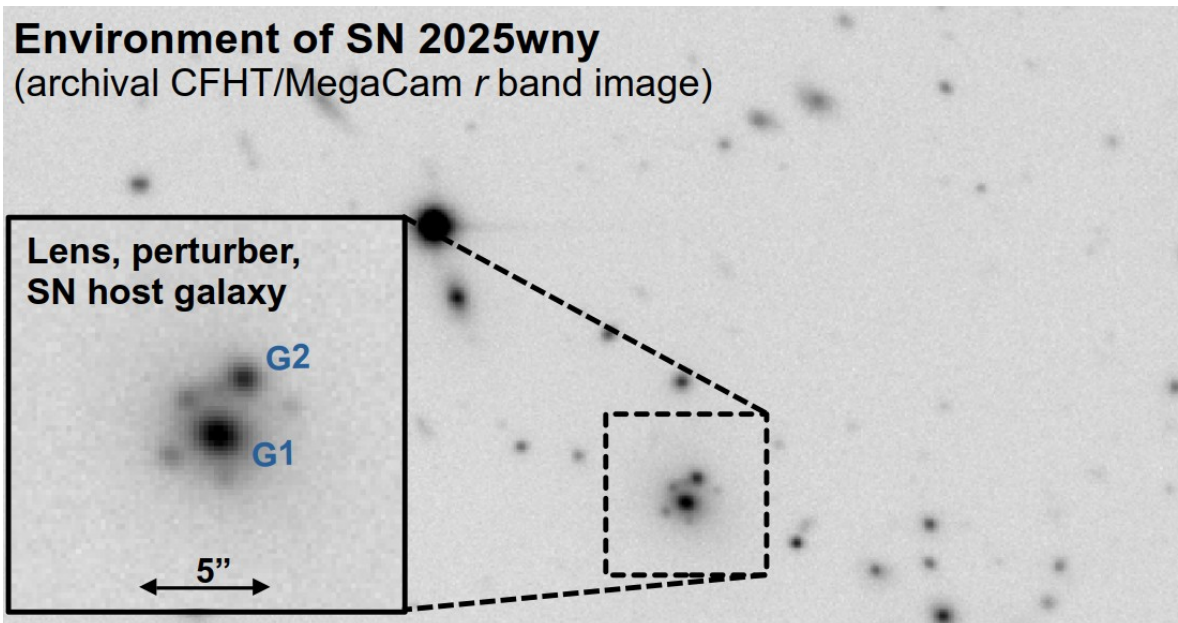


- **Appears in our daily monitoring of public ZTF alerts**

→ 1.2" away from PanSTARRS  
strong lens candidate from paper II

→ **Is that really a lens? Yes !**

+ G1 at  $z_{\text{spec}} = 0.3754$  from DESI



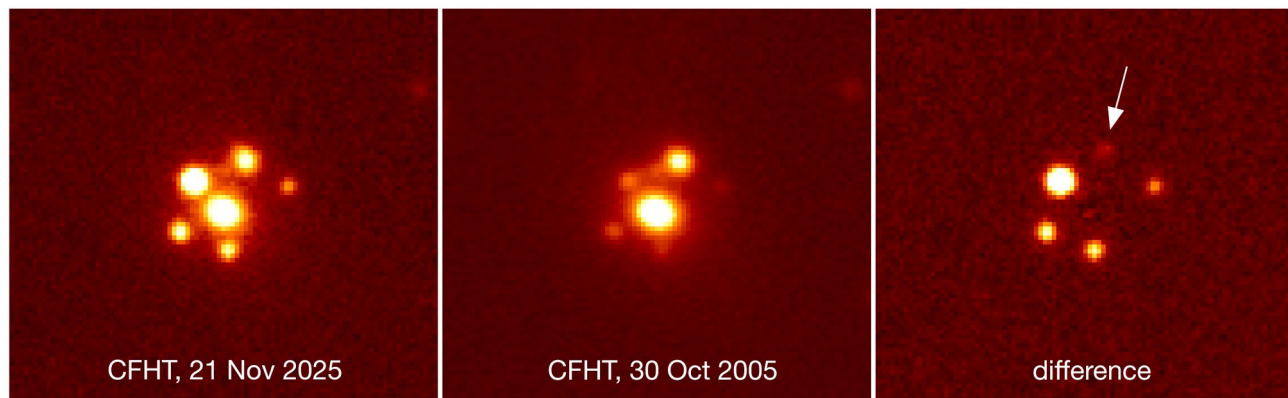
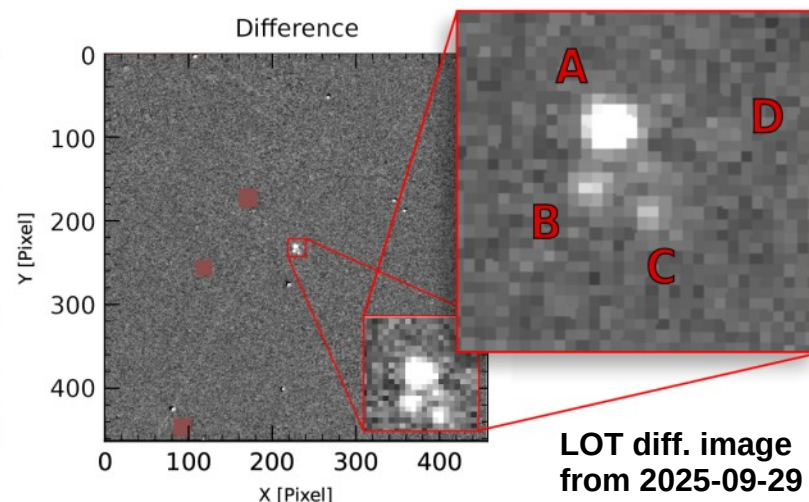


# Discovery of SN Winny

Taubenberger, Acebron, Cañameras,  
et al. 2025, A&A acc. (HOLISMOKES XIX)

## SN 2025wny (ZTF25abnjznp, GOTO25gqt) detection history

- First detected by ZTF on 2025-08-27
- Appears in our monitoring of ZTF alerts  
→ Is the SN in the source/foreground ?  
**Multiple images confirmed with Lulin obs. !**
- Start follow-up campaign in early Oct. 2025
- **Fifth image from CFHT** on 2025-11-21  
→ AstroNote 2025-330 (Taubenberger+2025)





# Spectroscopic typing of SN Winny

Taubenberger, Acebron, Cañameras,  
et al. 2025, A&A acc. (HOLISMOKES XIX)

## Redshift and typing of SN Winny

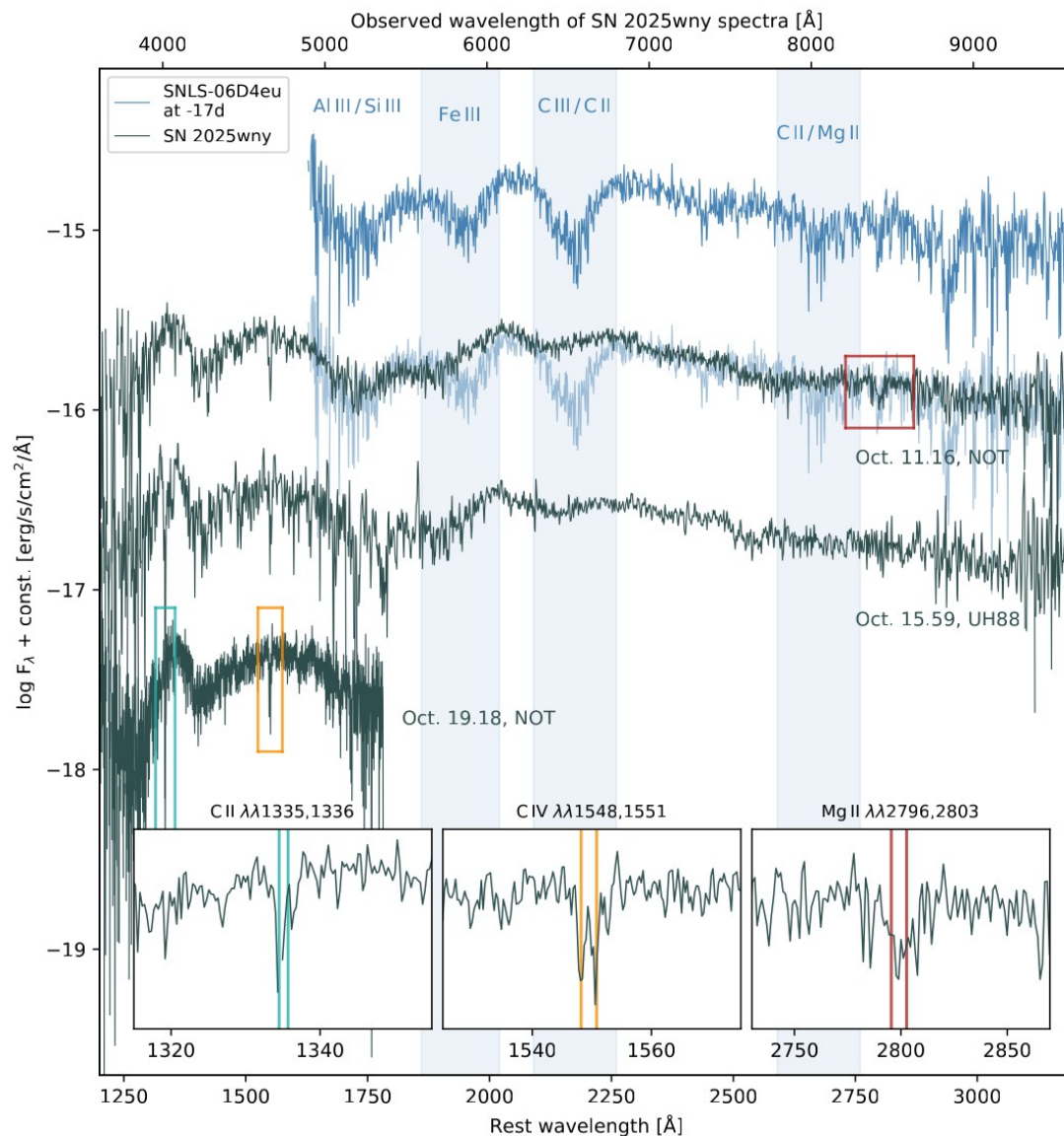
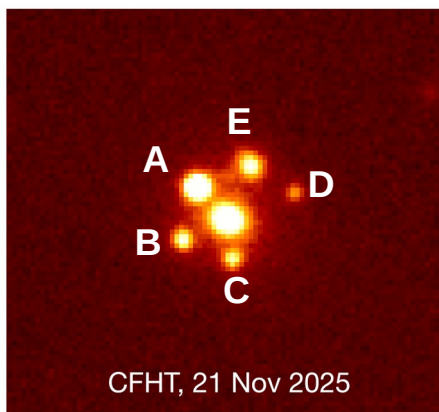
- Slit spectroscopy from NOT and UH88

$$z_{\text{SN}} = 2.008 \pm 0.001$$

+ High ejecta temperatures >17,000 for several RF weeks + Weak spectral lines

**The first confirmed lensed SLSN-I**

- See also independent follow-up with NOT and Keck (Johansson+25)





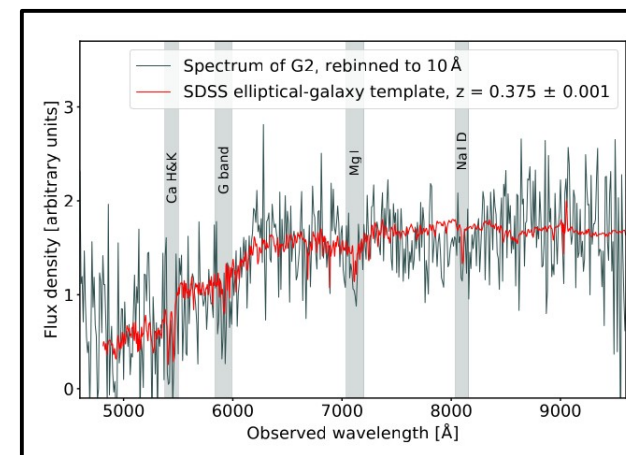
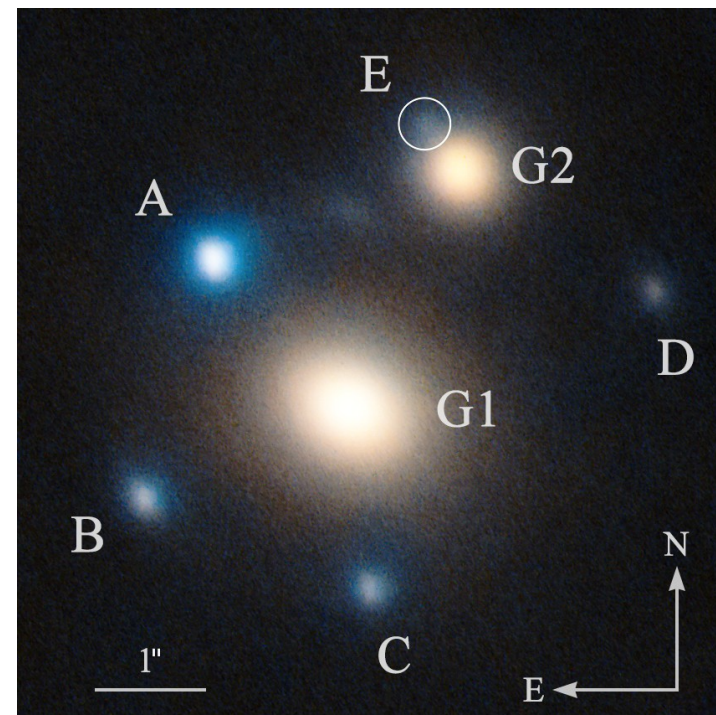
# Strong lens modeling

Ecker, Schweinfurth, et al. 2026,  
A&A sub. (HOLISMOKES XX)



## High-resolution AO imaging from LBT in J+K bands

- SN images positions as constraints (mas-level accuracy)
- Parametric mass models explored using independent codes:
  - Lenstronomy (Birrer & Amara 2018)
  - GLEE (Suyu & Halkola 2010; Suyu et al. 2012)
- Best-performing model:
  - G1: Singular Isothermal Ellipsoid (SIE)
  - G2: Singular Isothermal Sphere (SIS)
  - external shear





# Strong lens modeling

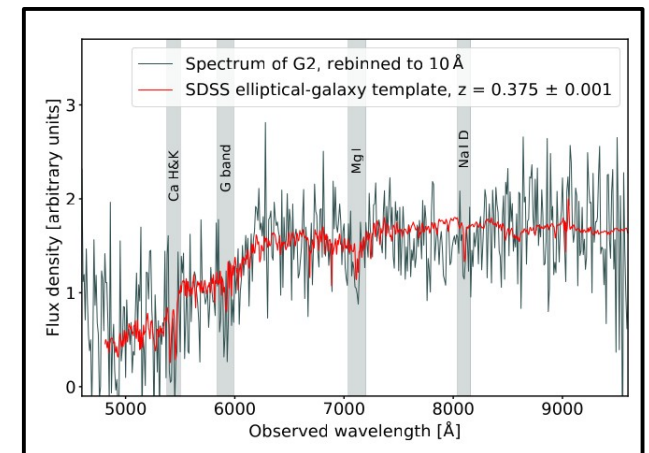
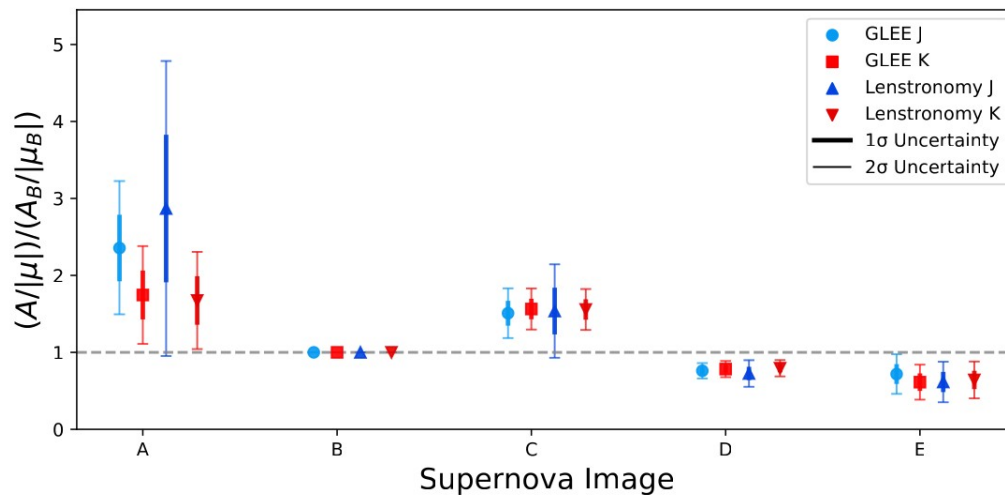
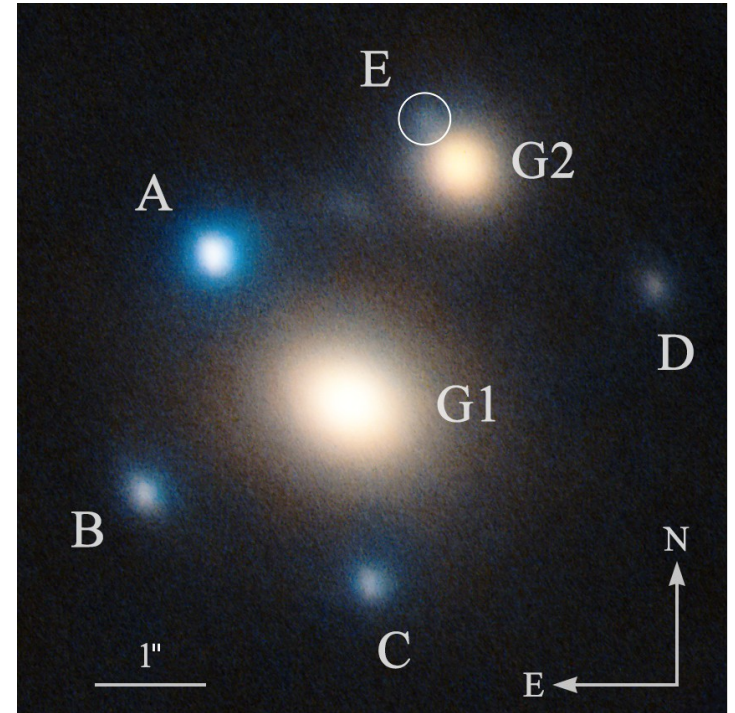
Ecker, Schweinfurth, et al. 2026,  
A&A sub. (HOLISMOKES XX)



## Lens modeling with two foreground galaxies at $z=0.375$

- Recover image positions with  $\text{rms}_i = 0.0012'' - 0.0025''$
- Consistent to  $< 2\sigma$  with indep. Keck model (Storfer et al. 2026)
- Predicted magnifications range from  $\sim 1.6$  (E) to  $\sim 10$  (A)

→ Possible micro- or milli-lensing effects ?



**Paves the way to future cosmography-grade models**



# Photometric monitoring

Taubenberger, Acebron, Cañameras, et al. 2025, A&A acc. (HOLISMOKES XIX)

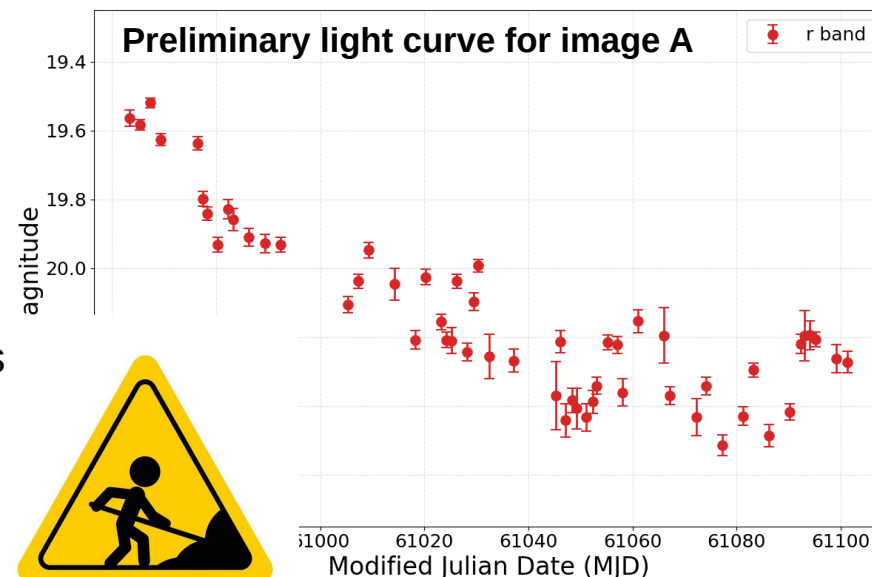
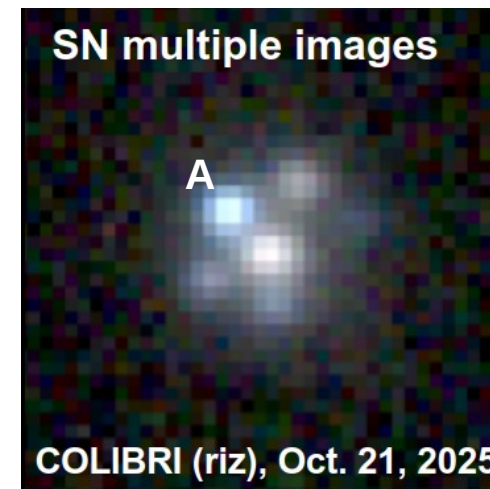


## Monitoring with COLIBRI, LOT, Maidanak, Wendelstein

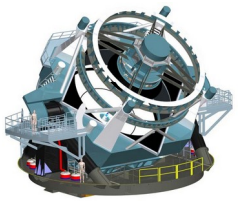
- Deep, high-cadence follow-up is key for cosmography
- COLIBRI monitoring = 75 epochs in *riz* bands since Oct 15 !
  - Excellent cadence for time-delay measurements

## Light curve extraction

- With lightcurver+STARRED (Michalewicz et al. 2023)
  - Preserve subpixel information across epochs
- **Two-channel multi-epoch deconvolution**
  - (a) variable point sources
  - (b) static extended background
- Separate analysis per telescope + combine light curves



**Next = Final time delays with microlensing**



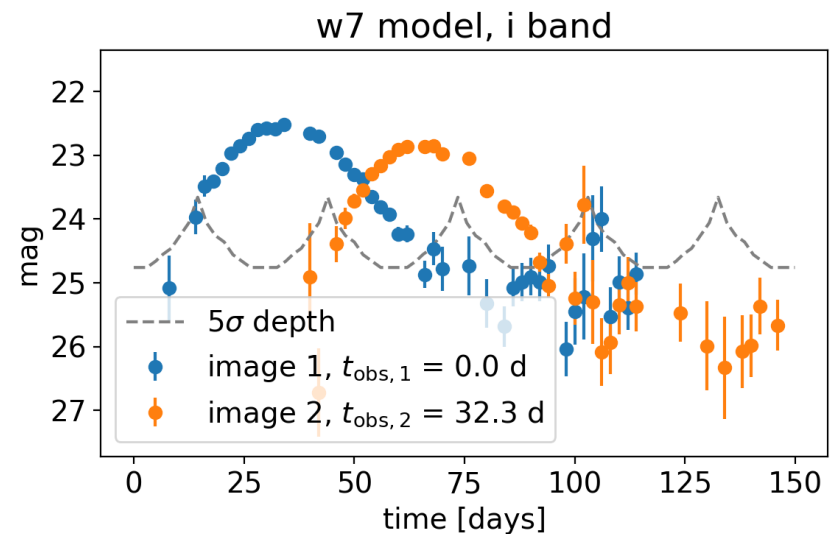
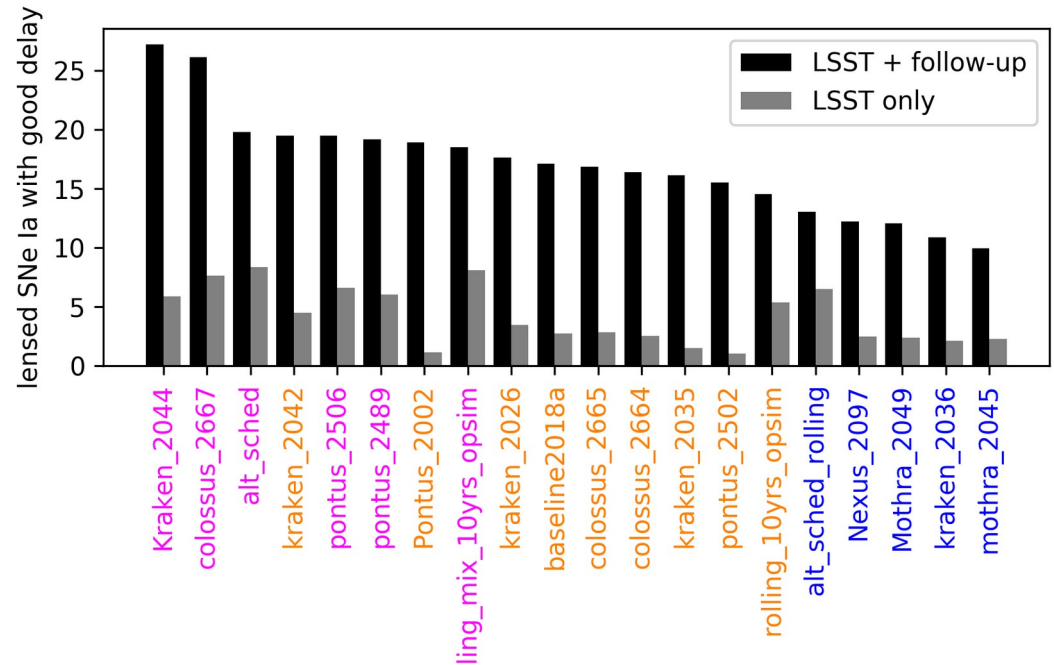
# The future of lensed SNe with Rubin

→ Hundreds of lensed SNe expected during the 10-year LSST (Wojtak+19)

- Gold sample of 5 lensed SNIa / year with early detection and mag < 22.5 (Arendse+24)

→ Deep, high-cadence follow-up imaging is key for precise and accurate time delays

- e.g. MPG/ESO 2.2m, COLIBRI



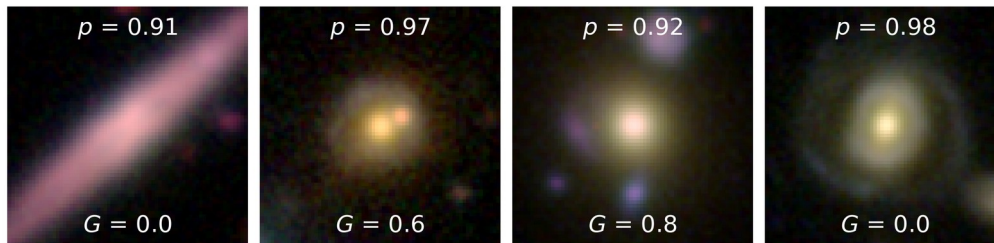
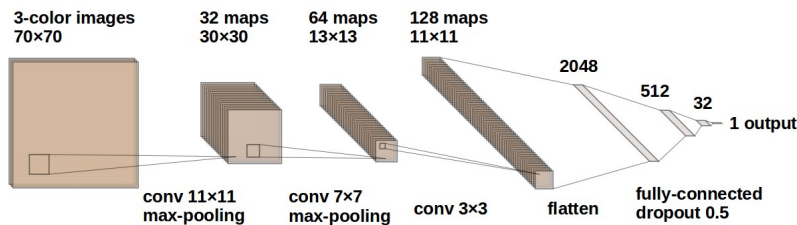
Credit: Huber et al. 2019

## First option → Monitoring static strong lenses

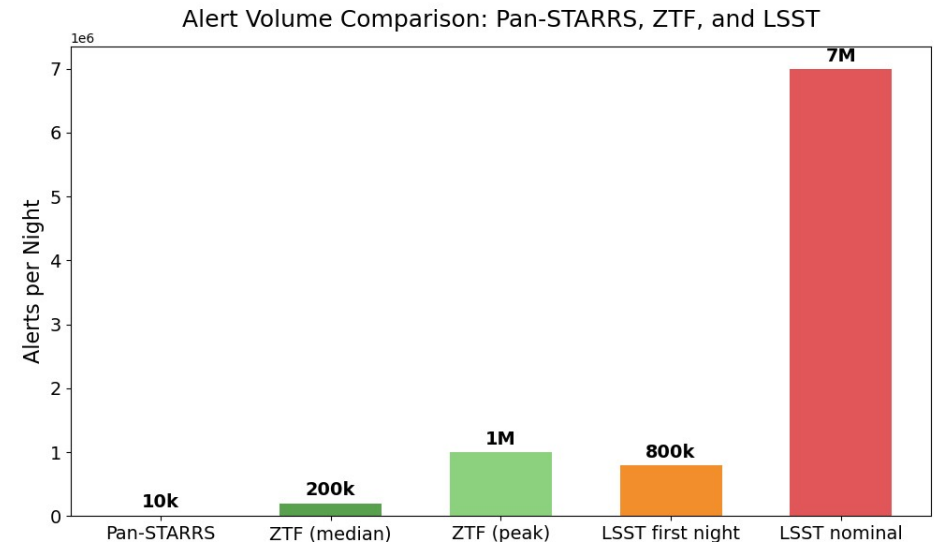
Identify all static strong lenses and wait for a SN to explode in the background hosts

- Supervised Deep Learning classification to cope with huge data volume

About 7 million alerts per night expected → Need to lower CNN contamination rates



False positives from CNN selection in Subaru/HSC



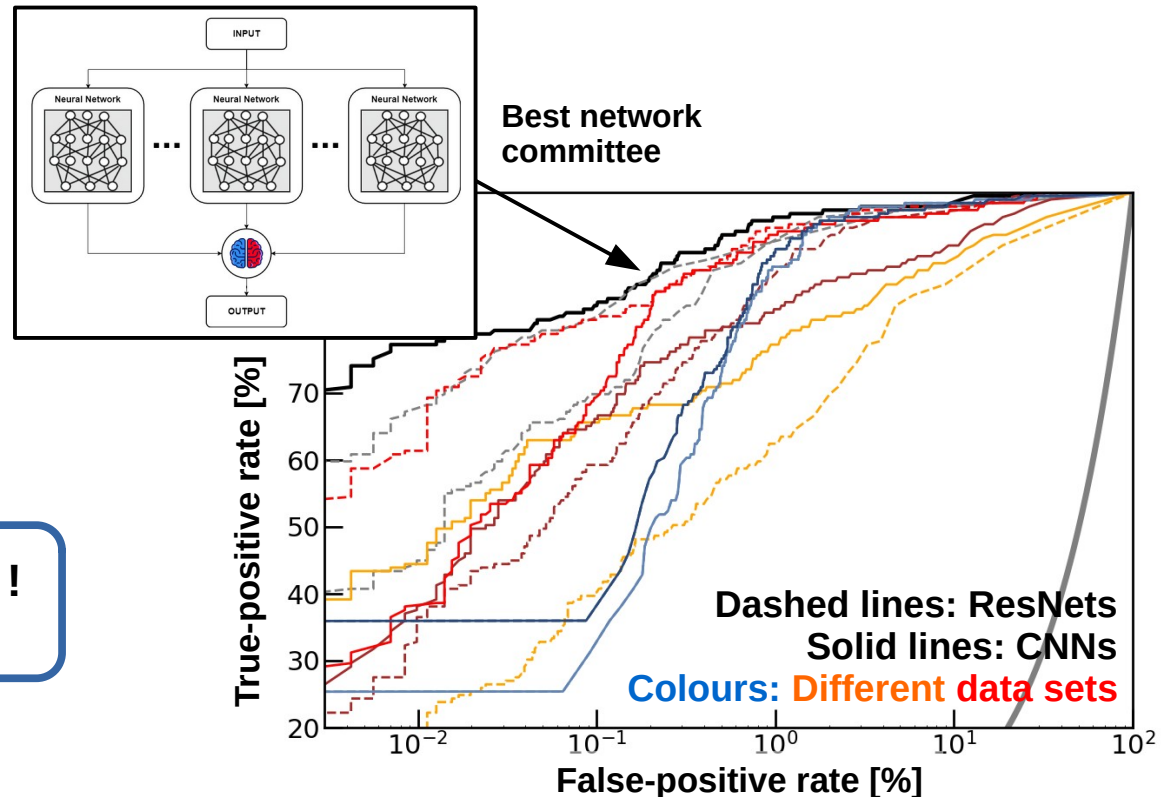
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Identify all static strong lenses and wait for a SN to explode in the background hosts

- Supervised Deep Learning classification to cope with huge data volume

About 7 million alerts per night expected → Need to lower CNN contamination rates

- (1) Fine-tuning training set content
- (2) optimisation of ResNet architectures
- (3) construction of network committees



**False-positive rates down to 0.01% !**  
(Cañameras et al. 2024)



# Finding lensed supernovae from LSST

Cañameras et al. 2020, 2021, 2024 (HOLISMOKES II, VI, XI)



**First option → Monitoring static strong lenses**

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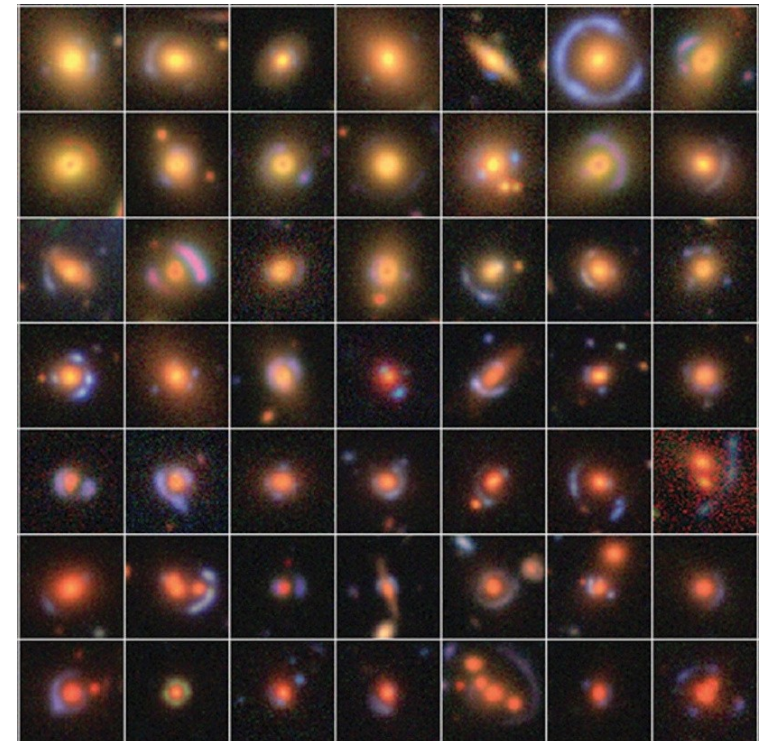
→ **Proof of concept:** >600 candidates in HSC

(Cañameras et al. 2021; Shu, Cañameras et al. 2022; Schuldt, Cañameras et al. 2025a, 2025b, see figure)

+ Reproduce selection on LSST DR1 stacks

+ Complementary cross-match with Euclid strong lenses

→ Euclid DR1 standard project



# Finding lensed supernovae from LSST

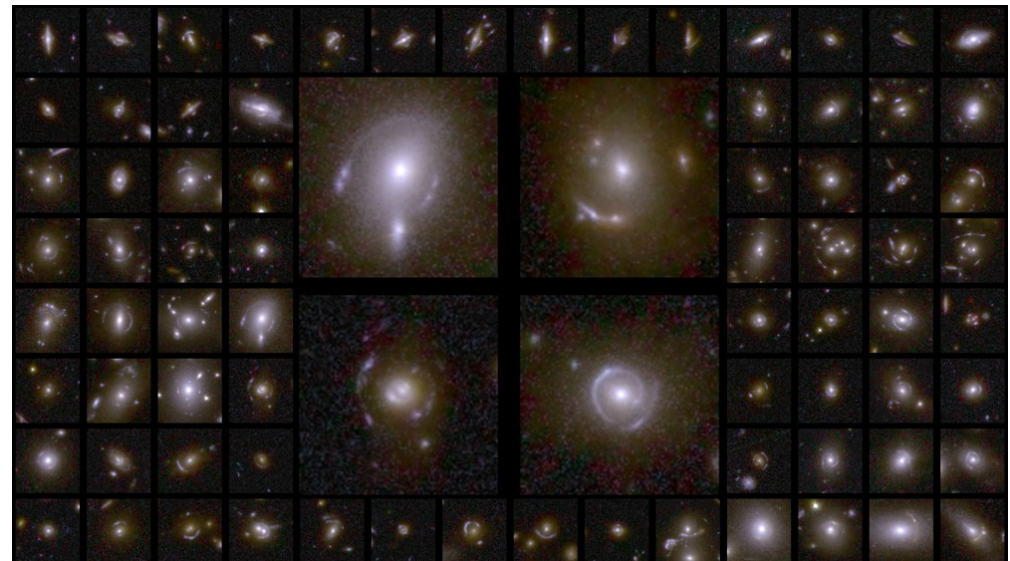
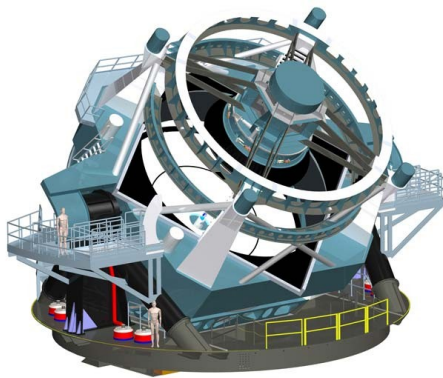
Cañameras et al. 2020, 2021, 2024 (HOLISMOKES II, VI, XI)

First option → Monitoring static strong lenses

Identify all static strong lenses and wait for a SN to explode in the background hosts

- Supervised Deep Learning classification to cope with huge data volume

All-sky catalog to monitor the Rubin LSST alerts

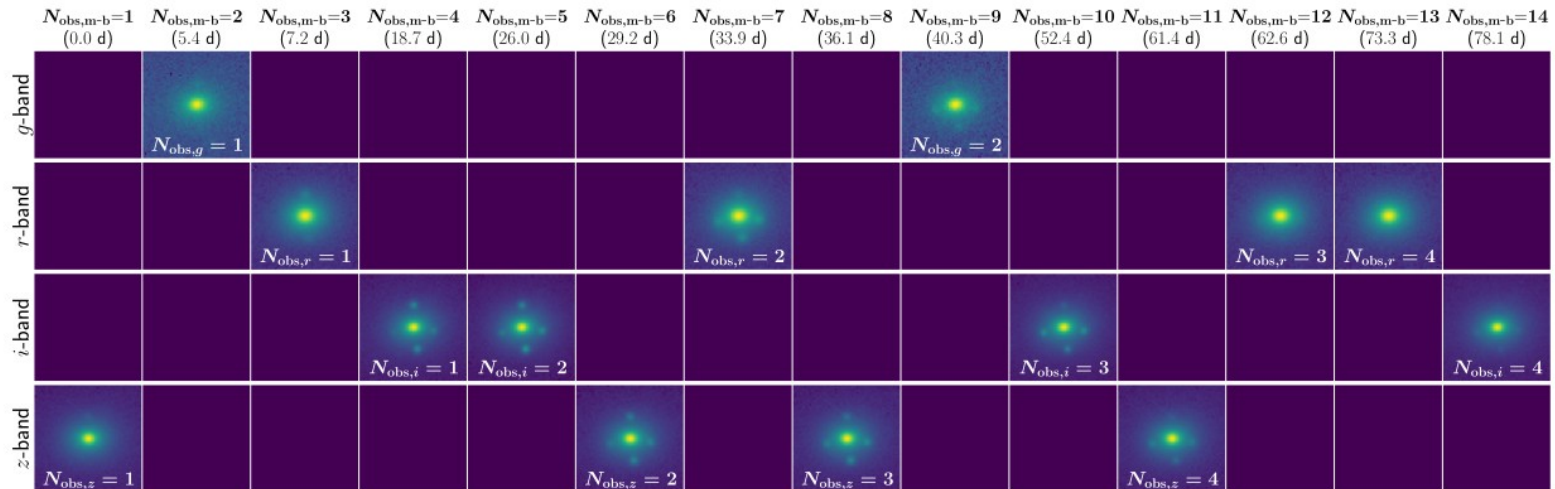
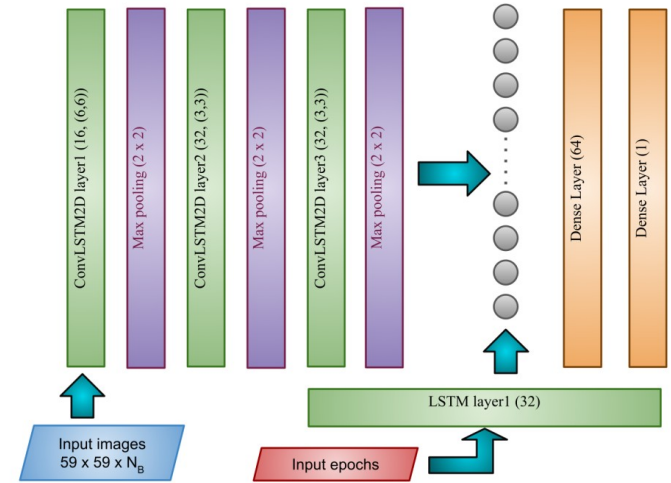


Euclid Q1 lenses (ESA/Euclid/Consortium Euclid/NASA)

## Second option → Direct classification of lensed SNe using spatio-temporal information

### → Deep-learning classification of image time-series

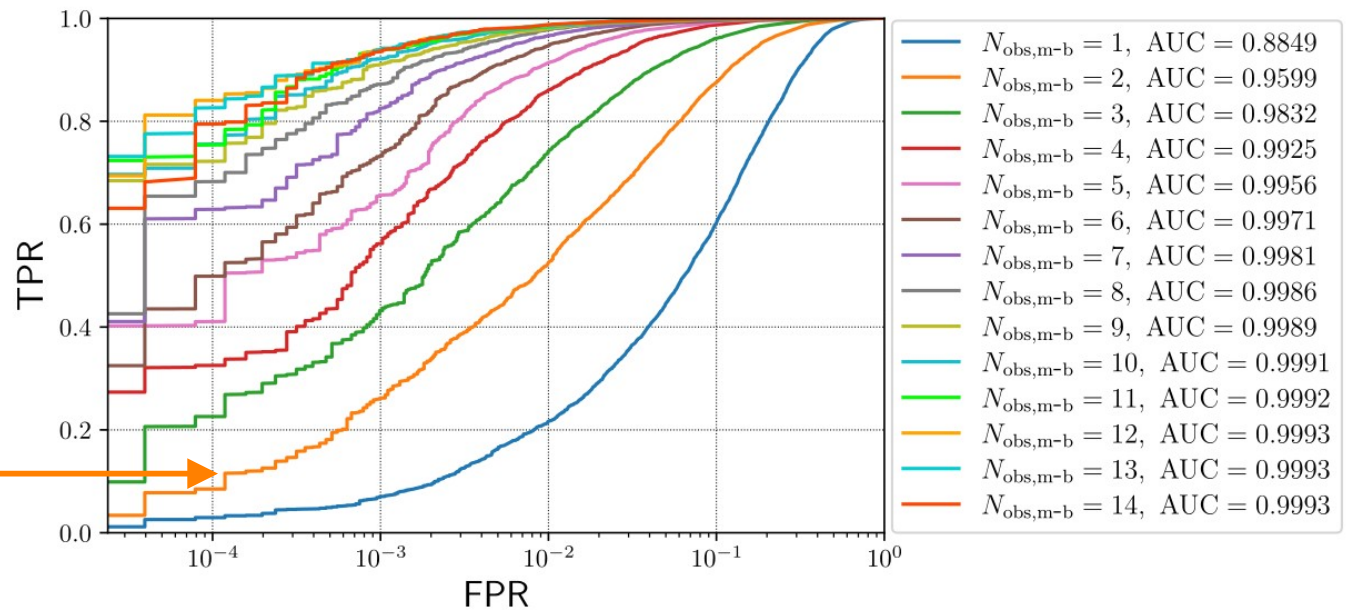
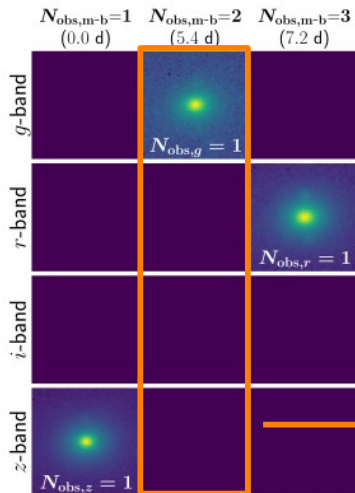
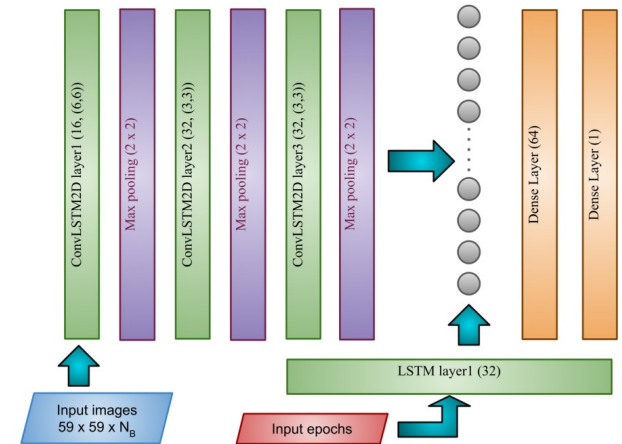
- Train a convLSTM model (Shi et al. 2015)
  - positives (lensed SN Ia mock image time-series)
  - negatives (SNe Ia in LRGs/Spirals + HSC variables)
- Data from HSC transient survey (Yasuda et al. 2019)
- Binary score predictions at each time stamp



## Second option → Direct classification of lensed SNe using spatio-temporal information

### → Deep-learning classification of image time-series

- Train a convLSTM model (Shi et al. 2015)
  - positives (lensed SN Ia mock image time-series)
  - negatives (SNe Ia in LRGs/Spirals + HSC variables)
- Multiband scenario with padding
- Binary score predictions at each time stamp

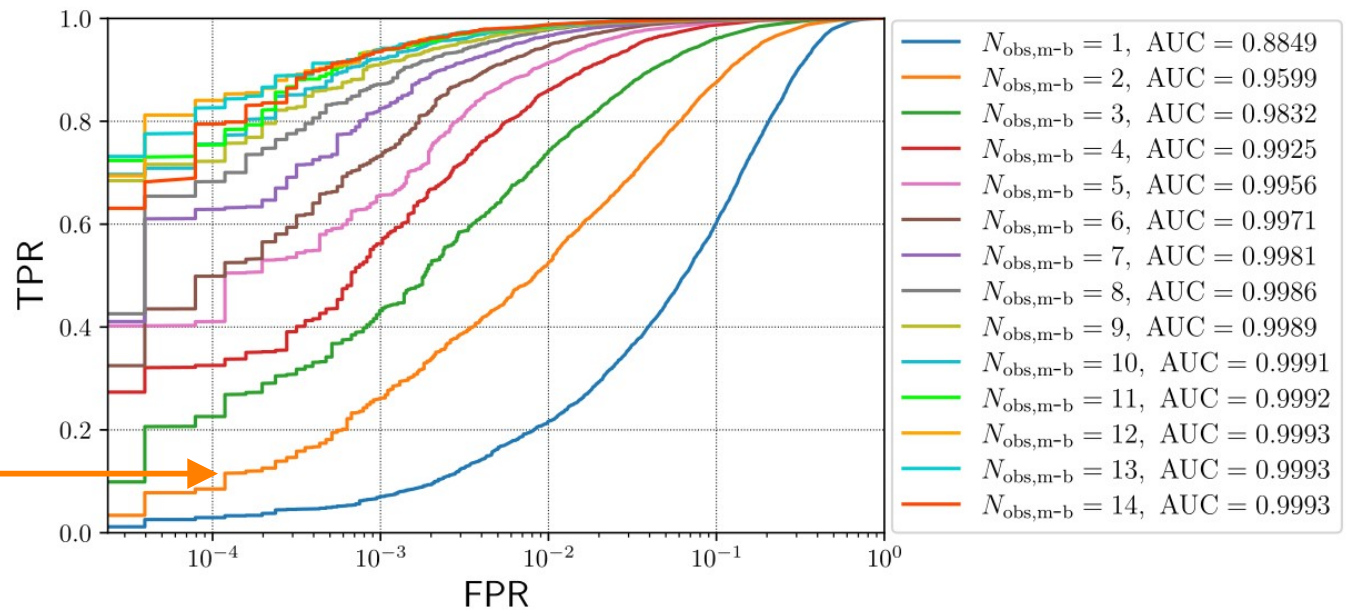
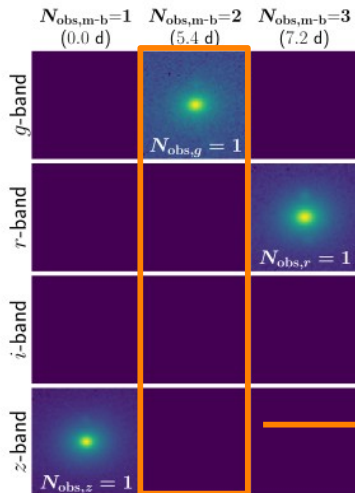
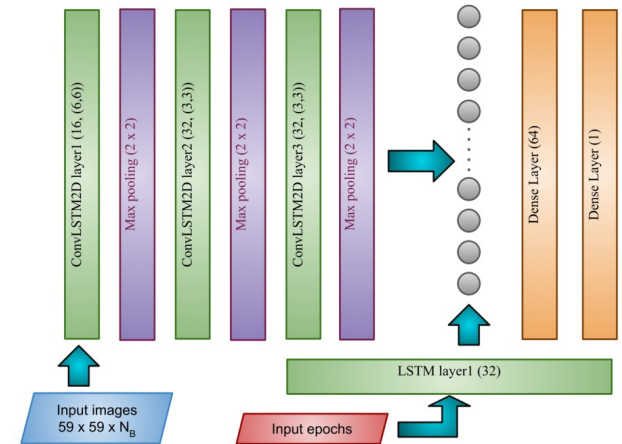


## Second option → Direct classification of lensed SNe using spatio-temporal information

### → Deep-learning classification of image time-series

- Train a convLSTM model (Shi et al. 2015)
- Multiband scenario with padding

**Promising proof of concept  
+ retrain with Rubin LSST data**





## Lensed SNe for cosmology and SN progenitors

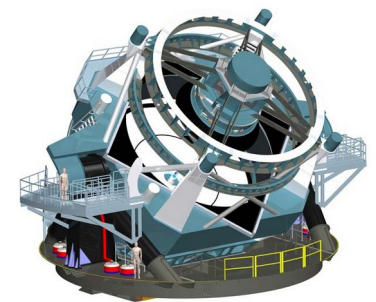
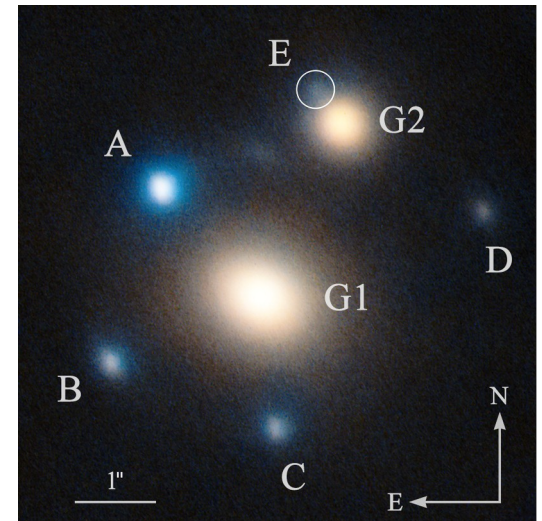
- Anticipate  $H_0$  constraints with 1.3% precision in flat  $\Lambda$ CDM in LSST era
- Rapid follow-up enables early-phase SN studies (rest-frame UV)

## SN Winny (SN 2025wny) at $z = 2.008$

- The first confirmed strongly lensed superluminous supernova
- Offers rare access to early-universe SLSN UV/optical physics
- Strong lens models + On-going photo- & spectroscopic monitoring

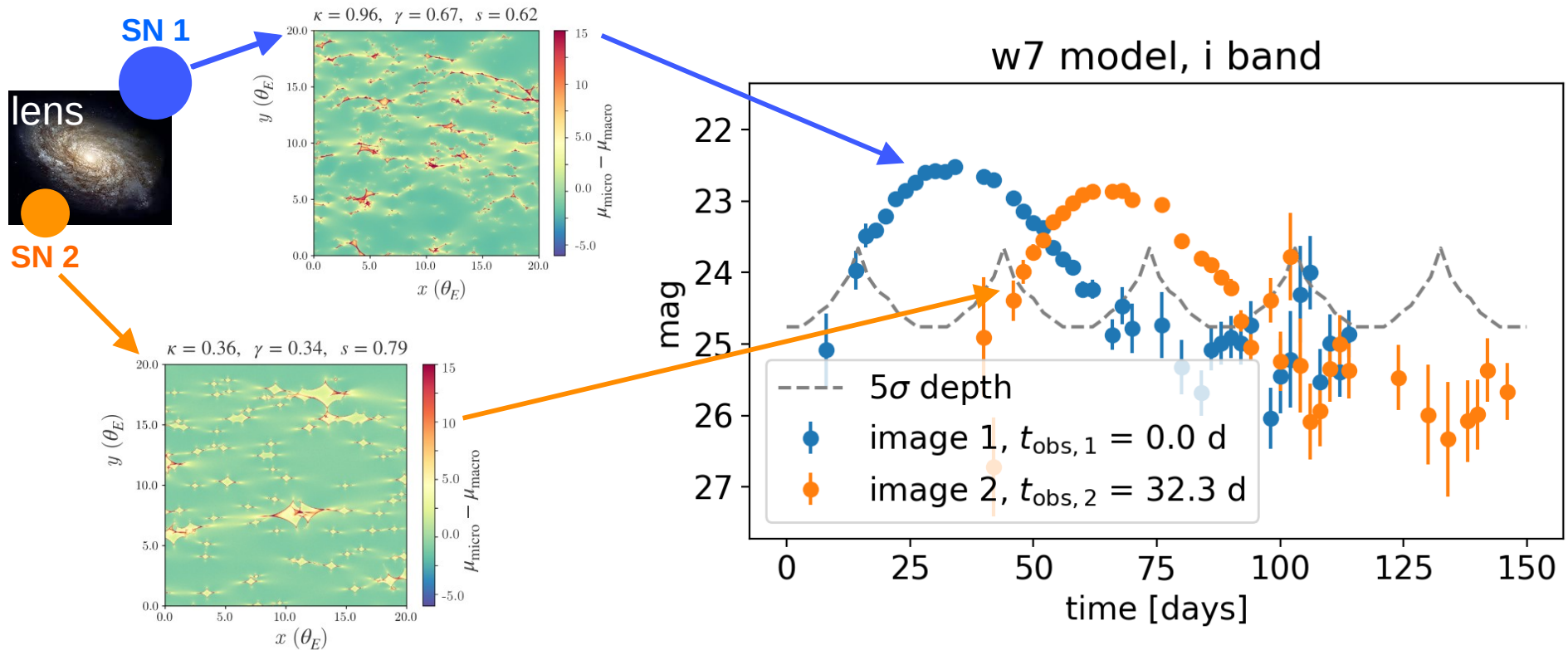
## Bright future for lensed SNe with Rubin LSST

- New deep learning algorithms for selection in alert streams
- Time delays require external high-cadence monitoring
- Promising method to infer time delays with spectroscopy





Huber et al. 2024 (HOLISMOKES XII)

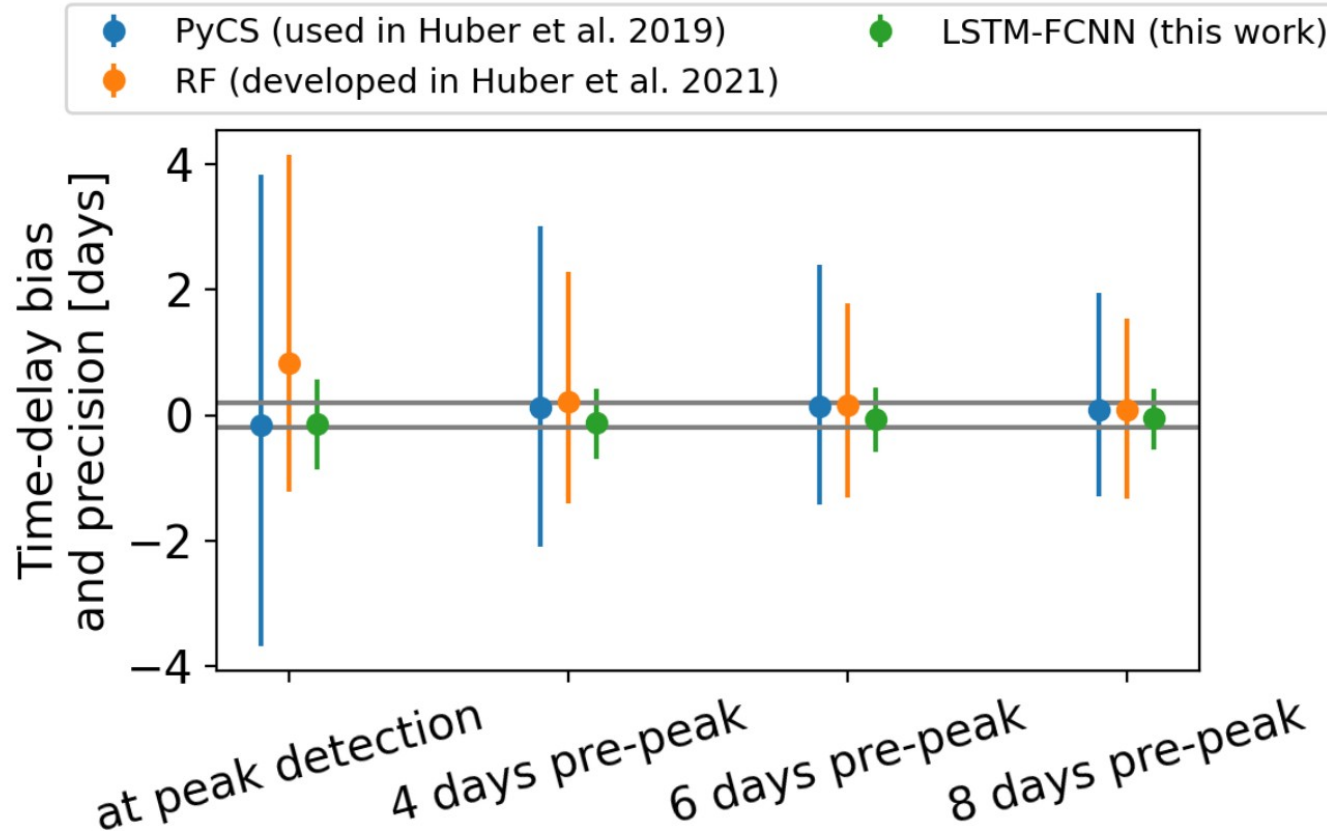


- **Training data** : 400000 lensed SNe Ia light curves from 4 SN models with microlensing
- **Test data** : 40000 lensed SNe Ia from (a) 4 SN models, (b) SNEMO15 (Saunders et al. 2018)

→ **Long Short-Term Memory (LSTM) network to separate intrinsic SN variability from extrinsic microlensing variability**

# Time delays with machine learning

Huber et al. 2024 (HOLISMOKES XII)



→ Delays bias free with uncertainties <0.7 days → factor 3 increase in precision

→ Need to detect first image at peak at latest + needs to be extended to SLSNe

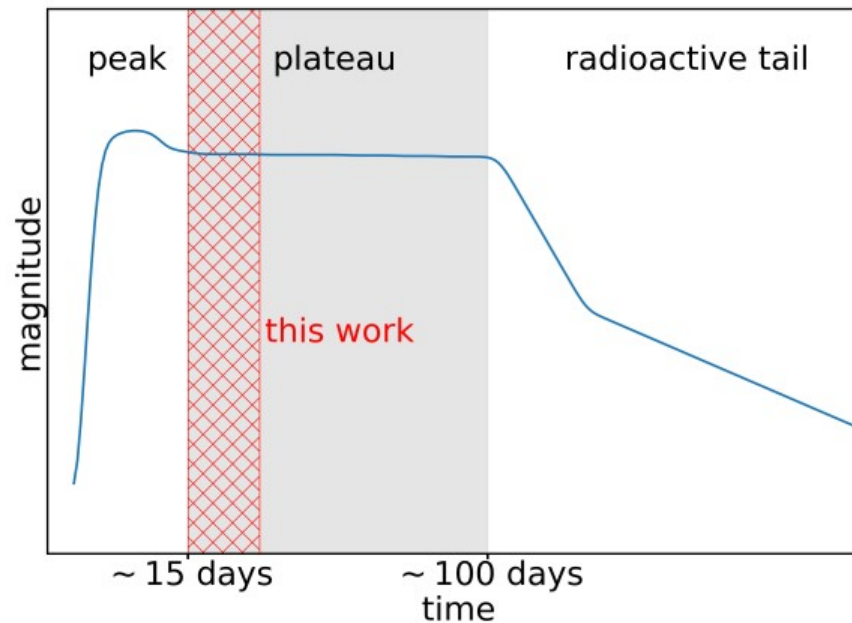


# Time delay through spectra

Bayer et al. 2021, 2025b (HOLISMOKES V, XVII)

*Can we use spectra to measure time delays for type II SNe?*

- Models of SN 1999em within plateau phase and effect of microlensing
- Light/color curves lack strong variations for time delays (in contrast to SNe Ia)



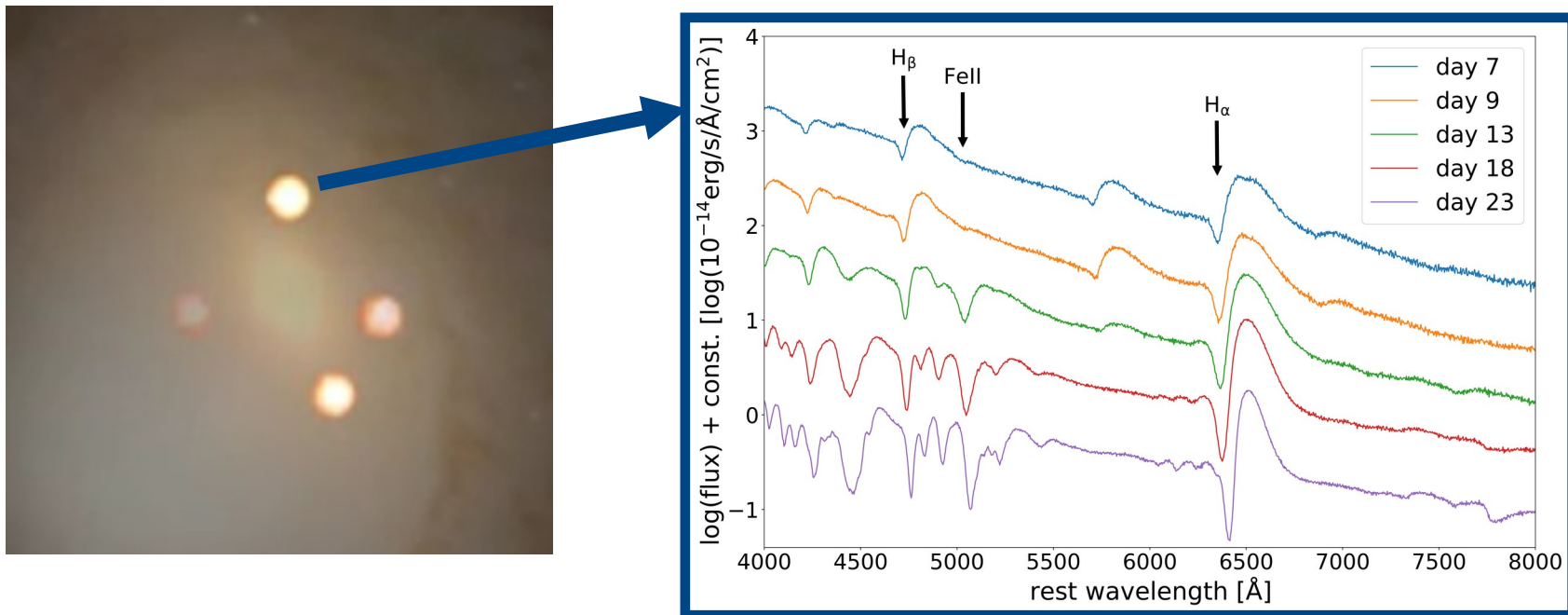
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- Light/color curves lack strong variations for time delays (in contrast to SNe Ia)

**→ Use spectral evolution to retrieve phase and infer time delays**





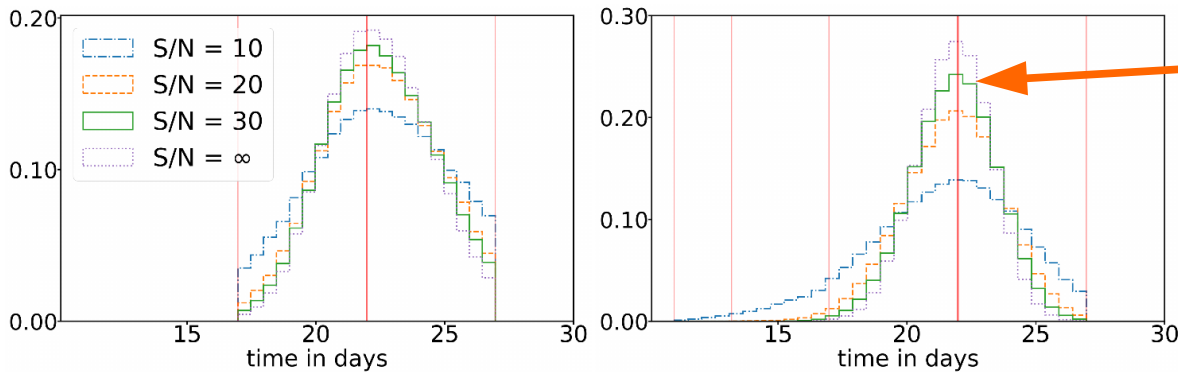
# Time delay through spectra

Bayer et al. 2021, 2025b (HOLISMOKES V, XVII)

*Can we use spectra to measure time delays for type II SNe?*

- Focus on two images, various spectrum S/N, constraints from line centroids

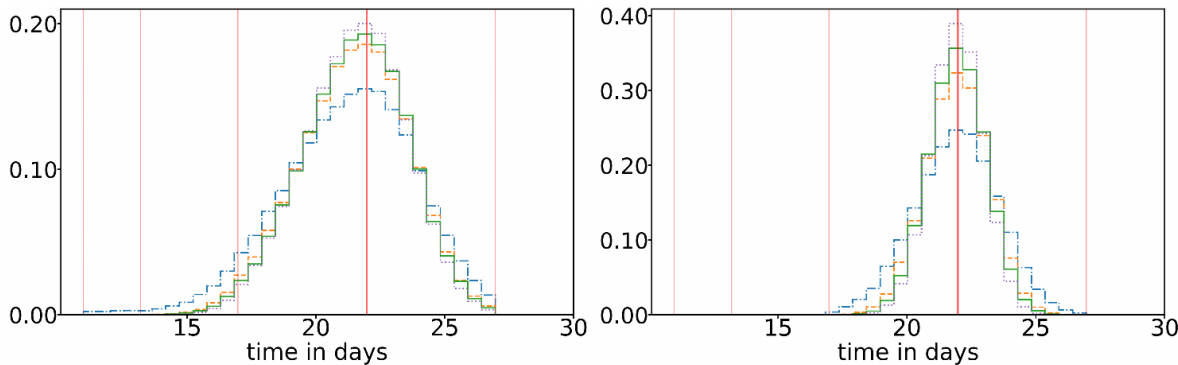
**Promising approach →  $1\sigma$  uncertainty  $< 2$  days from a single spectral feature**



(a) Retrieved phase using the absorption line of Fe II

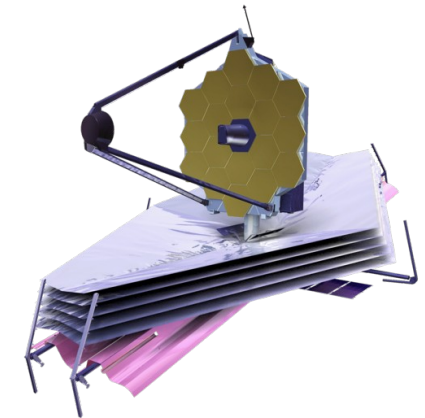
(b) Retrieved phase using the absorption line of H $\alpha$

Input of 22.0 days



(c) Retrieved phase using the absorption line of H $\beta$

(d) Retrieved phase combining all three absorption lines



**Feasible in a few minutes with JWST**