

~~Modelling Pair-instability~~ Supernovae

Stéphane Blondin (LAM)

Constraining Supernova Progenitors through Strong Lensing in the Rubin LSST Era

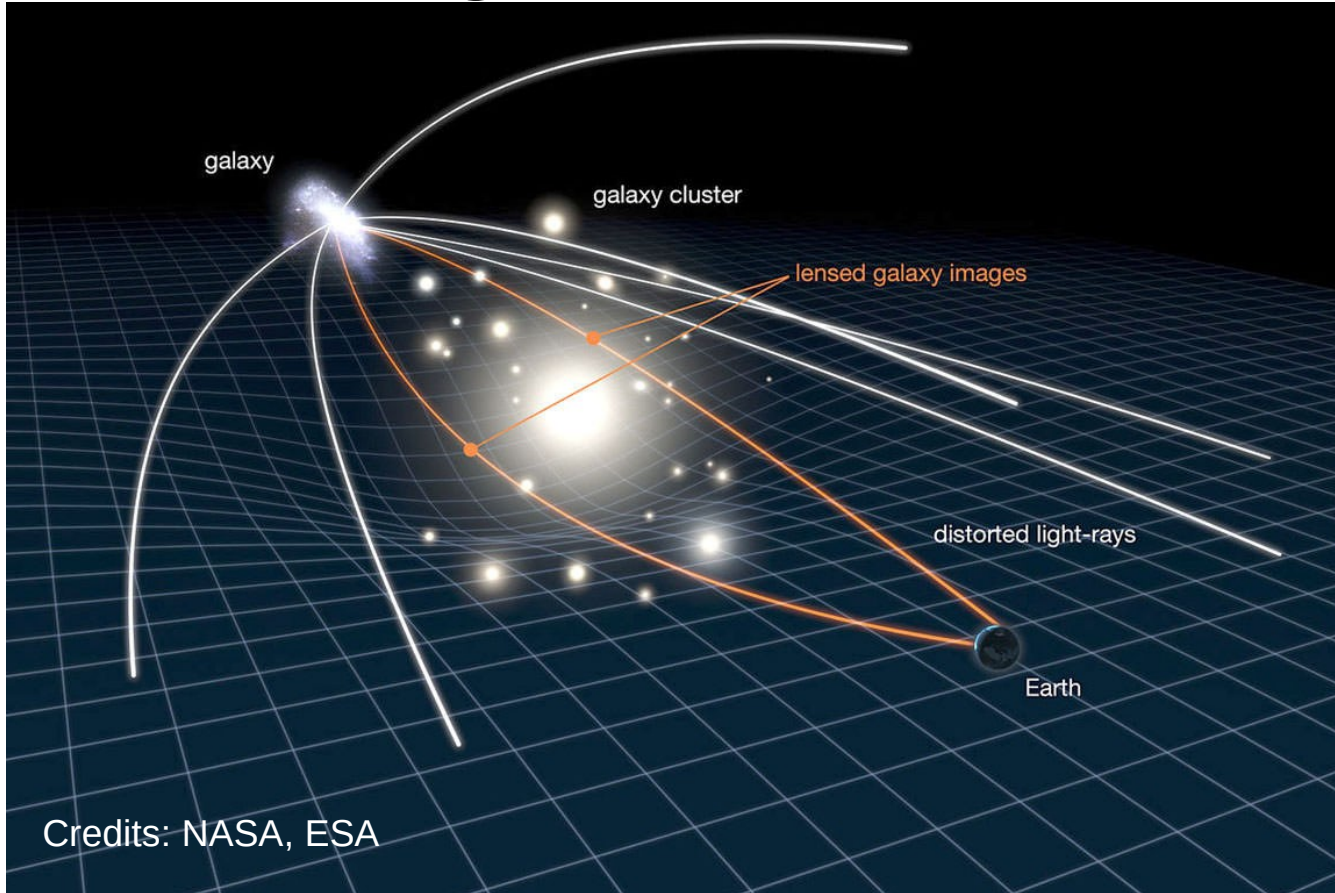
(proposed ANR-DFG project “SuperEarly”)

Stéphane Blondin (LAM)

Luc Dessart (IAP), Sherry Suyu (MPA/TUM), Stefan Taubenberger (MPA/TUM)

With some slide material “borrowed” from: Raoul Cañameras (MPA/TUM)

Strong Gravitational Lensing 101



Strong Gravitational Lensing 101

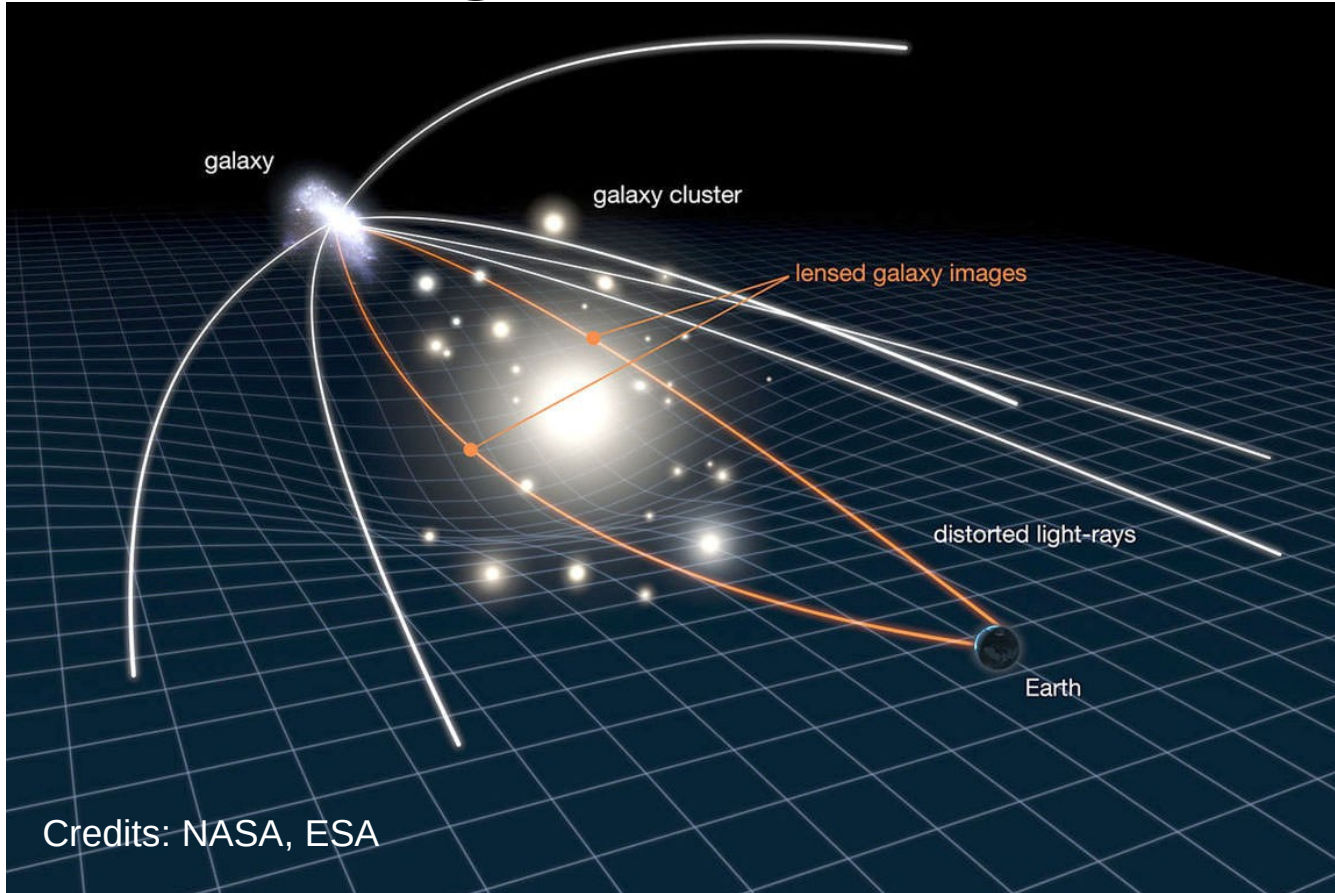
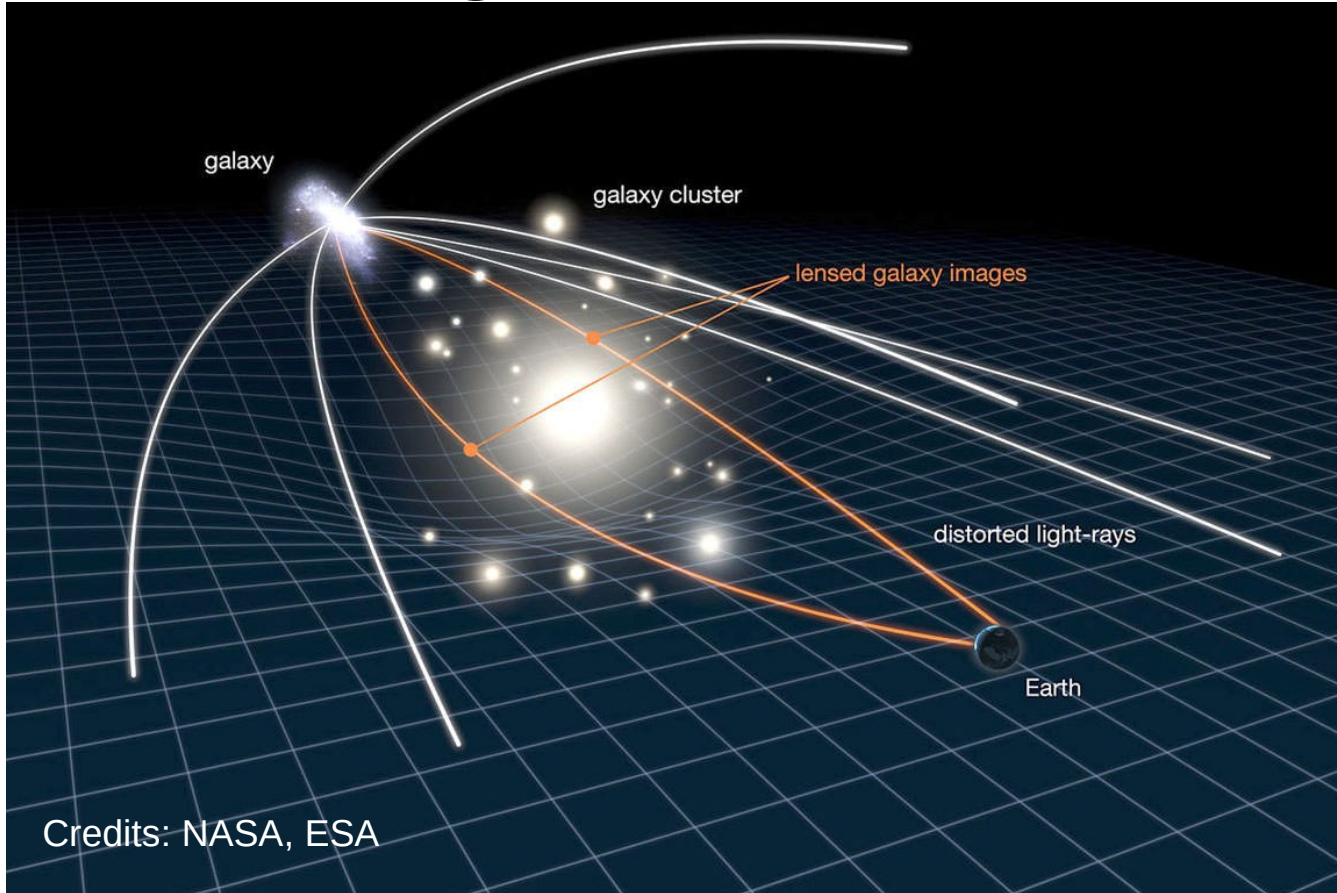


Illustration of a lensed SN event (credit S. More)

Strong Gravitational Lensing 101



Time delay:

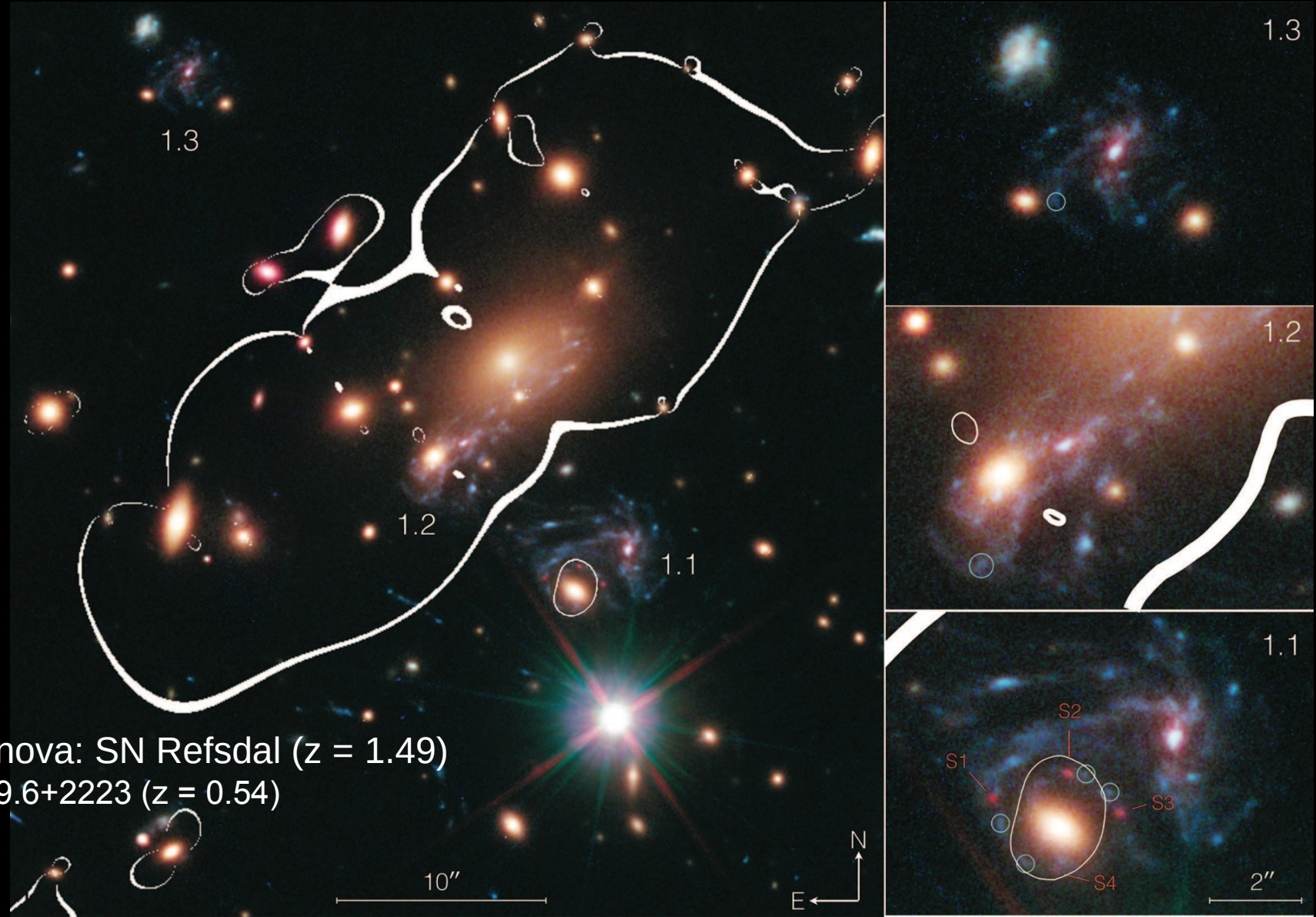
$$t = 1/c \times D_{\Delta t} \times \Phi_{\text{lens}}$$

Time-delay distance $\propto 1/H_0$



Illustration of a lensed SN event (credit S. More)

First lensed supernova: SN Refsdal ($z = 1.49$)
behind MACS J1149.6+2223 ($z = 0.54$)
(Kelly et al. 2015)



"Einstein cross"

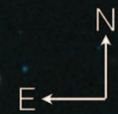
1.3

1.2

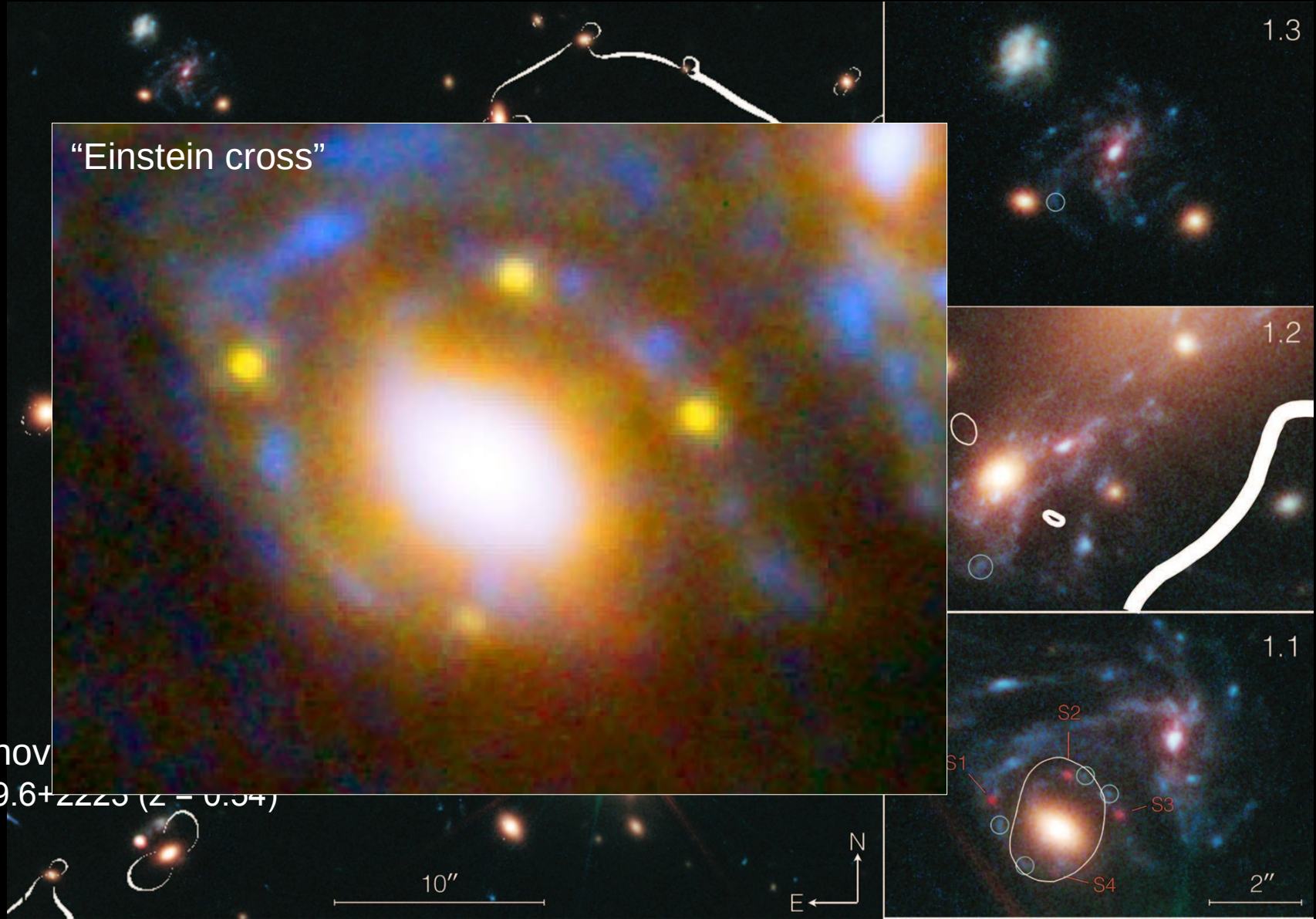
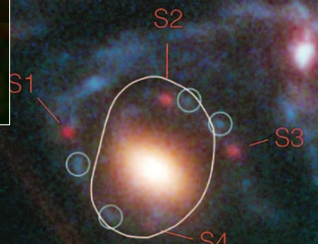
1.1

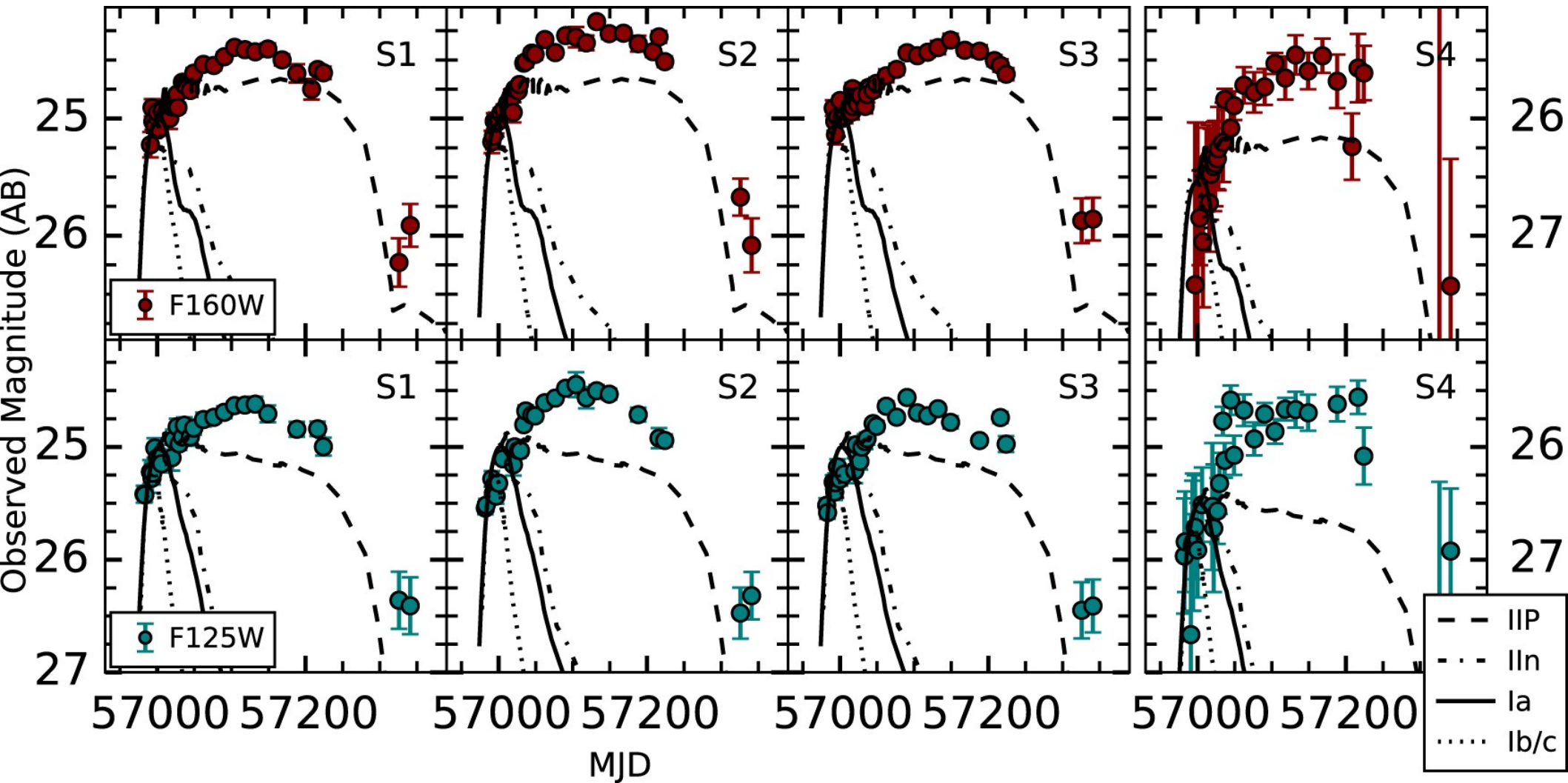
First lensed supernovae
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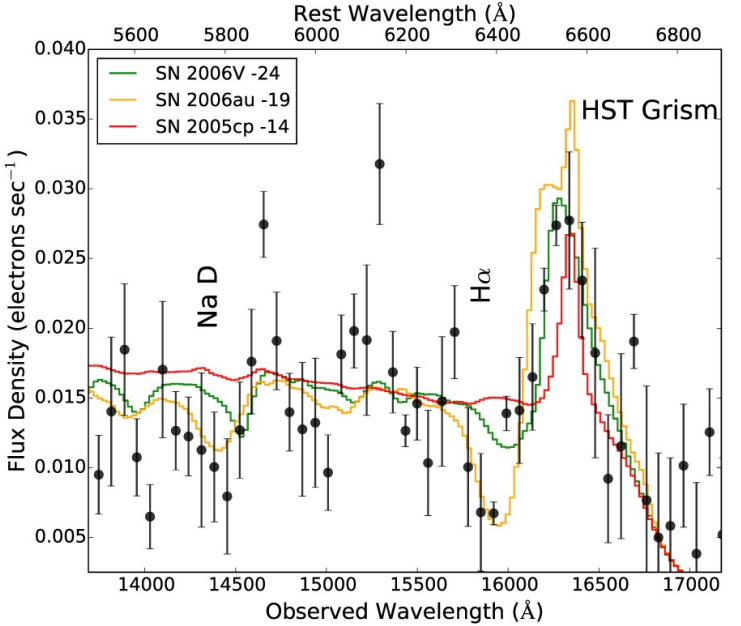
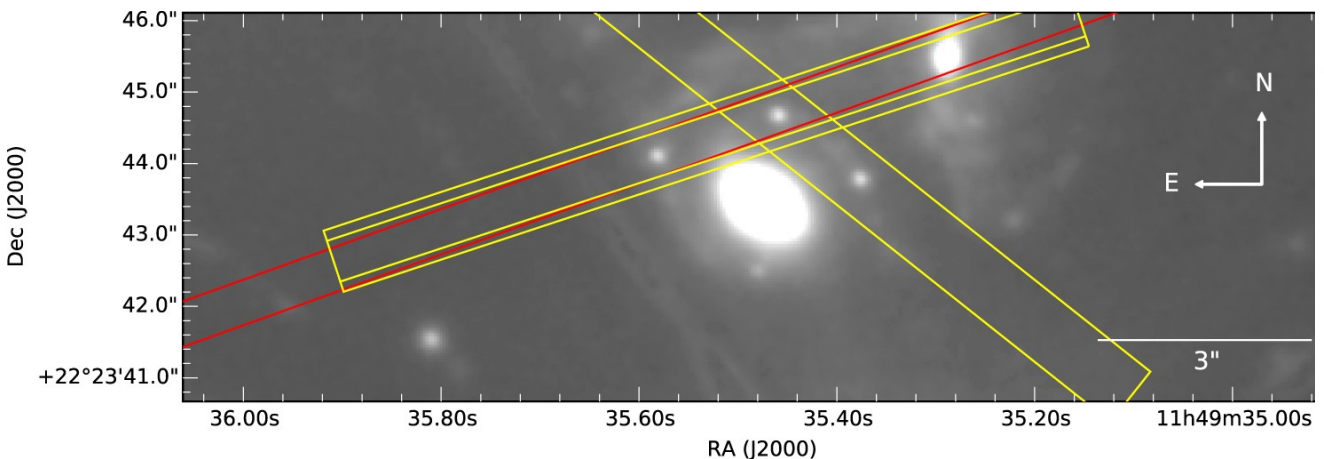
10"



2"



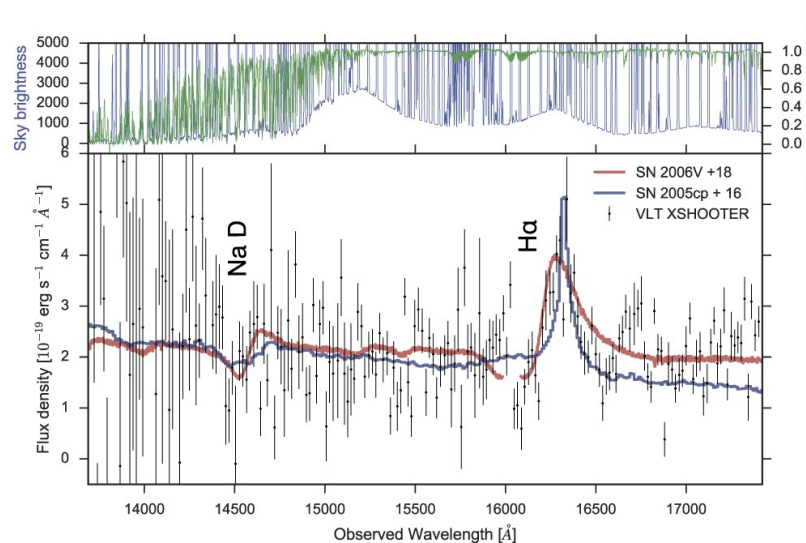




... and spectra! (HST Grism + VLT/XSHOOTER)

Na I D absorption + clear H α P-Cygni profile

Kelly et al. (2016)

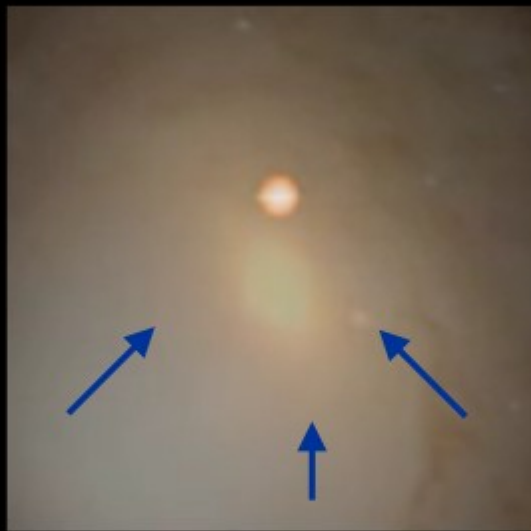


Lensed SN follow-up

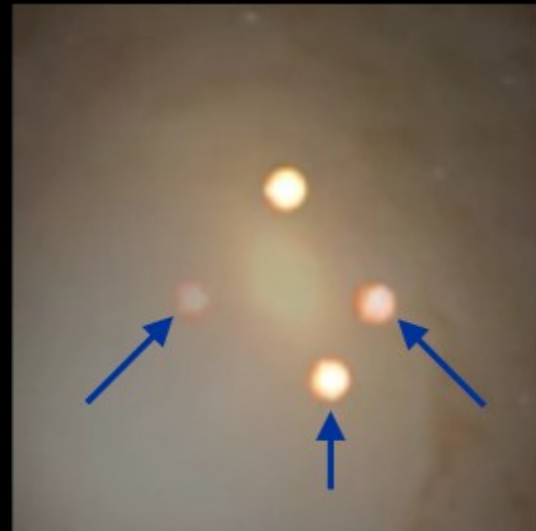
Monitor field of a detected lensed (high-redshift) SN to catch its reappearance within $\sim 1\text{-}2\text{d}$ from explosion: access to **early times** + **rest-frame UV**



Detect first
SN image



Predict location/time
of next SN image(s)



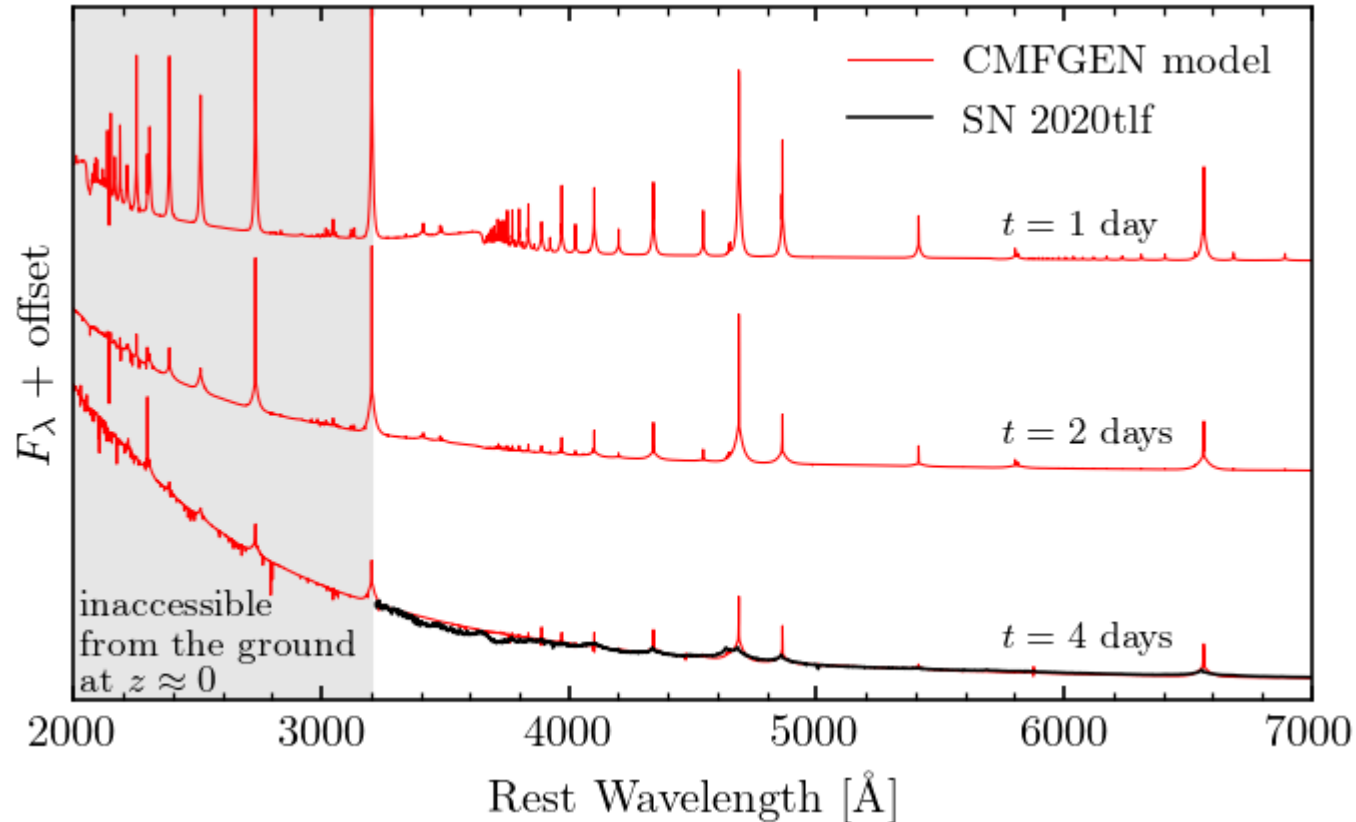
Observe early phase
of next SN image(s)

Early times + rest-frame UV *spectra*

Facility/Project	early times	rest-frame UV	spectroscopy	high-redshift
This proposal (lensed SNe) <i>(LSST + VLT/MUSE)</i>	yes	yes	yes	yes
Low-redshift surveys <i>(e.g., ZTF, YSE, ATLAS)</i>	yes	no	yes (with additional follow-up)	no
<i>Hubble Space Telescope</i>	no	yes	yes	yes
<i>Swift</i> satellite	yes	yes	no (grism only*)	no

* feasible only for targets < 15 mag and of limited use due to the very low resolution

Early times + rest-frame UV spectra



Early interaction with CSM
in a normal Type II SN

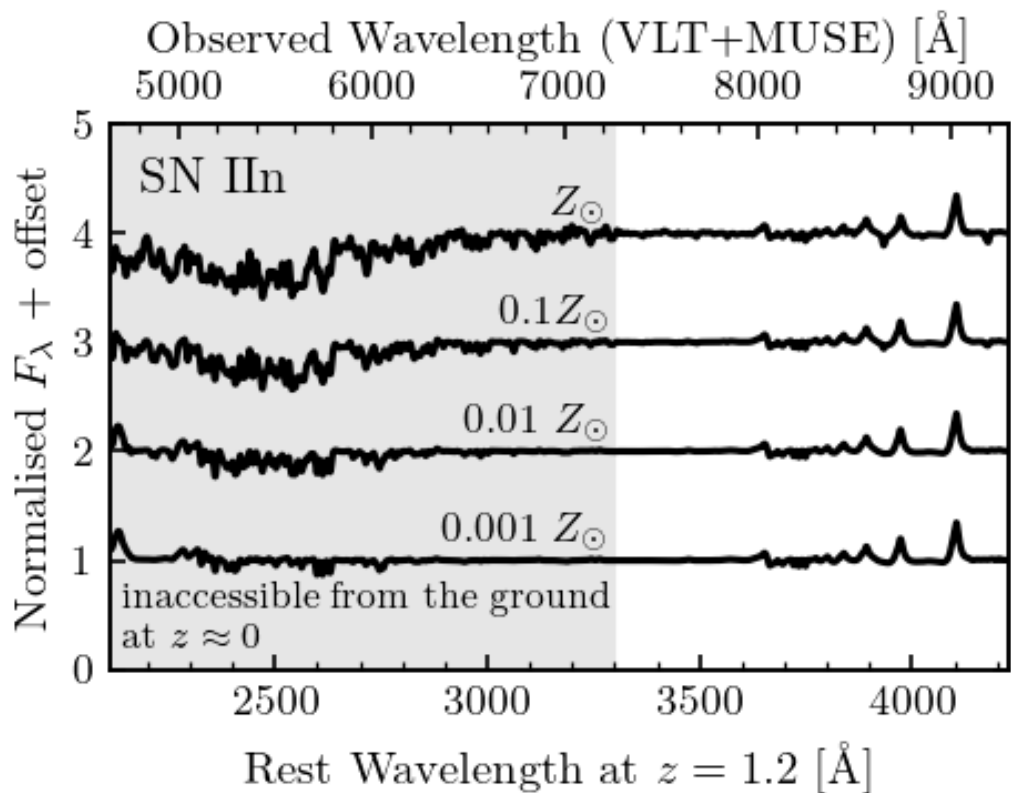
$$M_{\text{RSG}} = 15 M_{\text{sun}}$$

$$dM/dt = 0.01 M_{\text{sun}} / \text{yr}$$

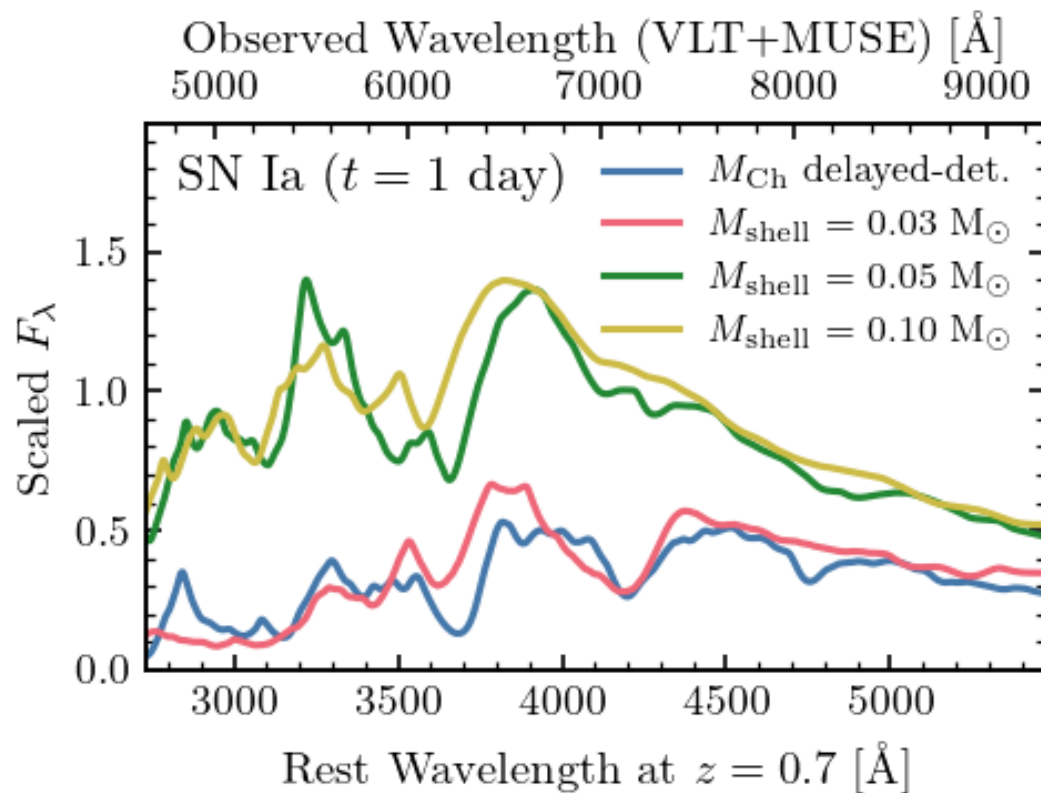
$$r_{\text{CSM}} = 6 \times 10^{15} \text{ cm}$$

Early times + rest-frame UV spectra

SN IIn at different metallicities



SN Ia from different explosion models

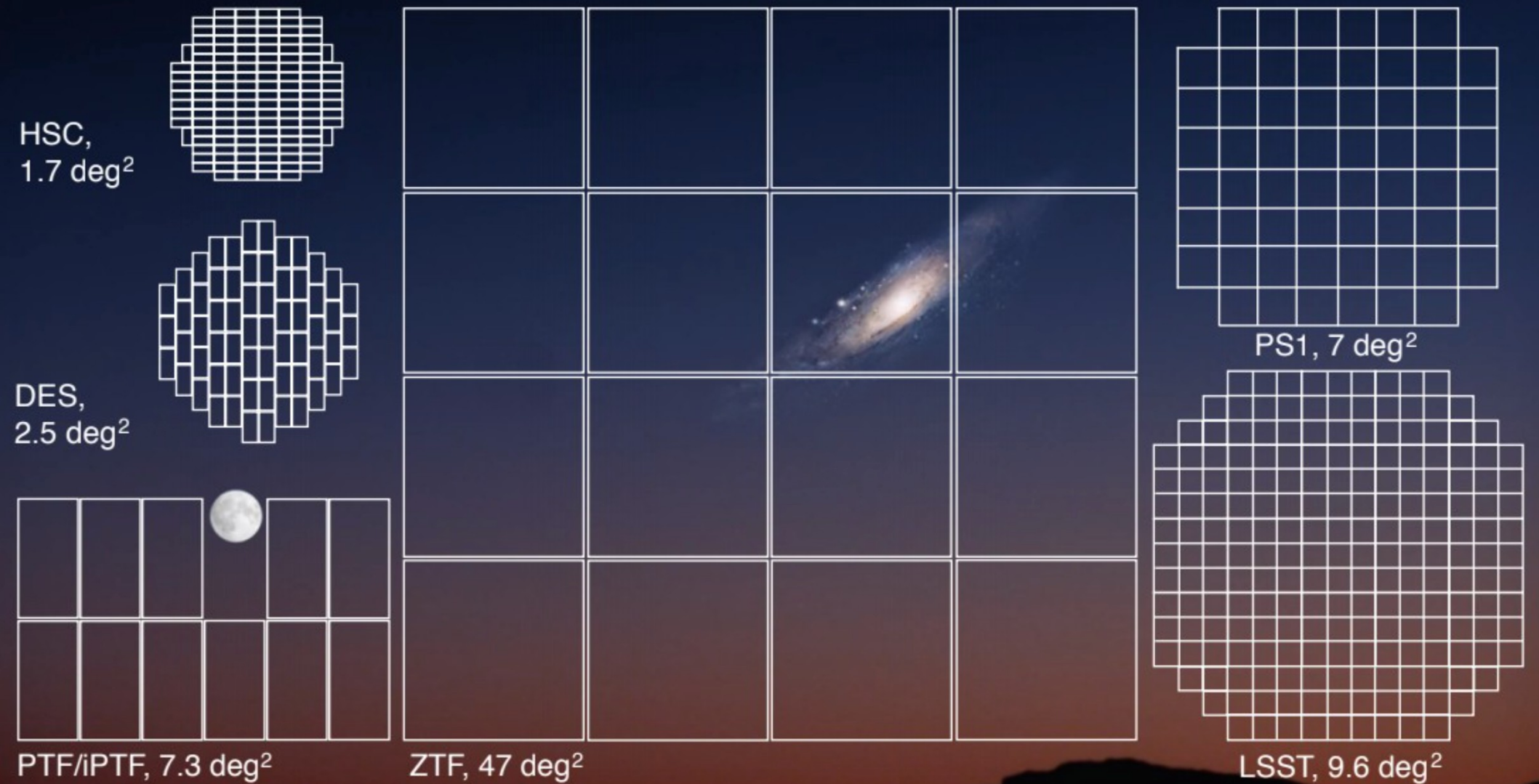


HOLISMOKES!

Highly Optimised Lensing Investigations of
Supernovae, Microlensing Objects, and
Kinematics of Ellipticals and Spirals

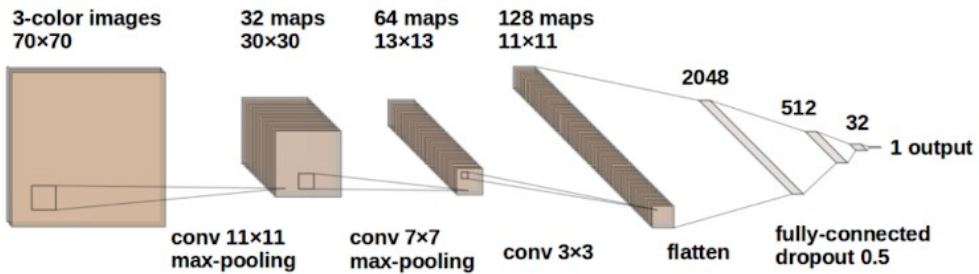
Suyu et al. 2020, A&A 644, 162 (HOLISMOKES I)



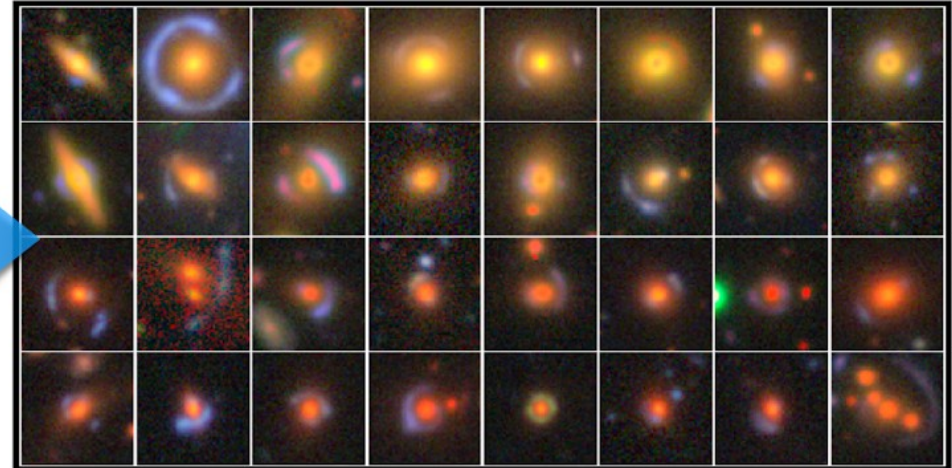


Finding Lensed Supernovae (1)

CNN architecture



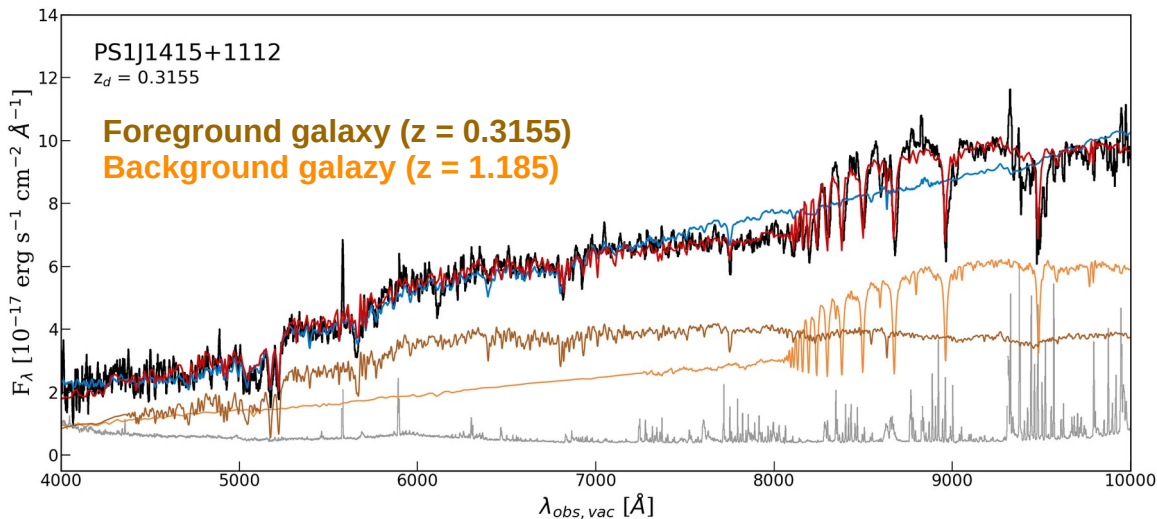
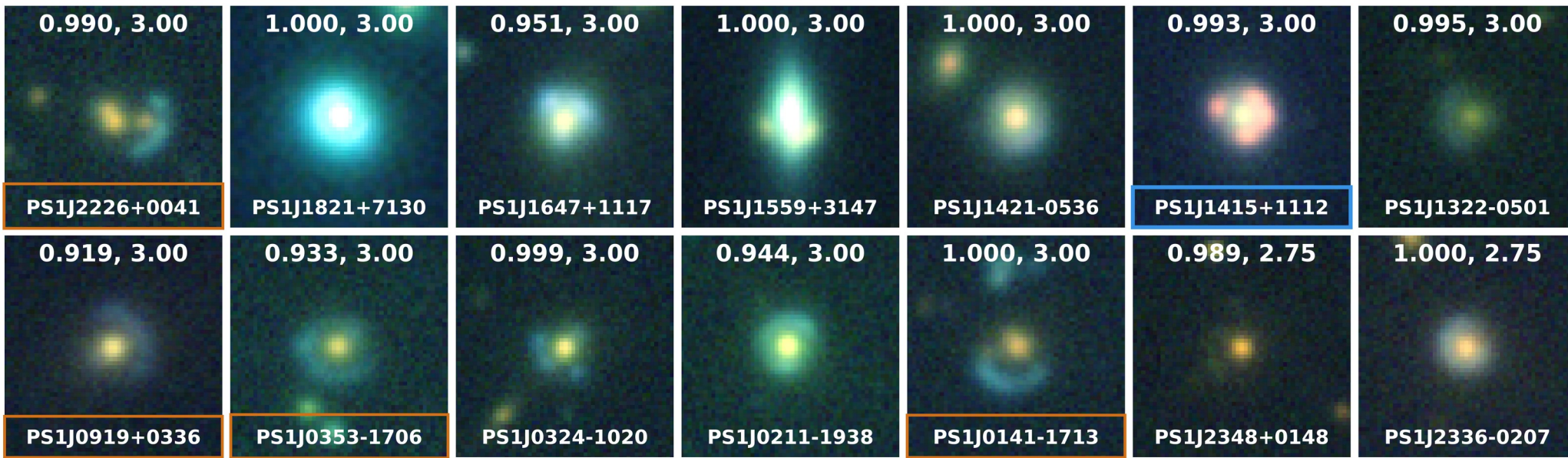
Mock catalogue (HST + HSC)



Find lensed galaxies that could serve as potential SN hosts (ZTF, Pan-STARRS, HSC*)

*Subaru Hyper-Suprime-Cam (HSC) Survey

Cañameras et al. (2020, 2021)

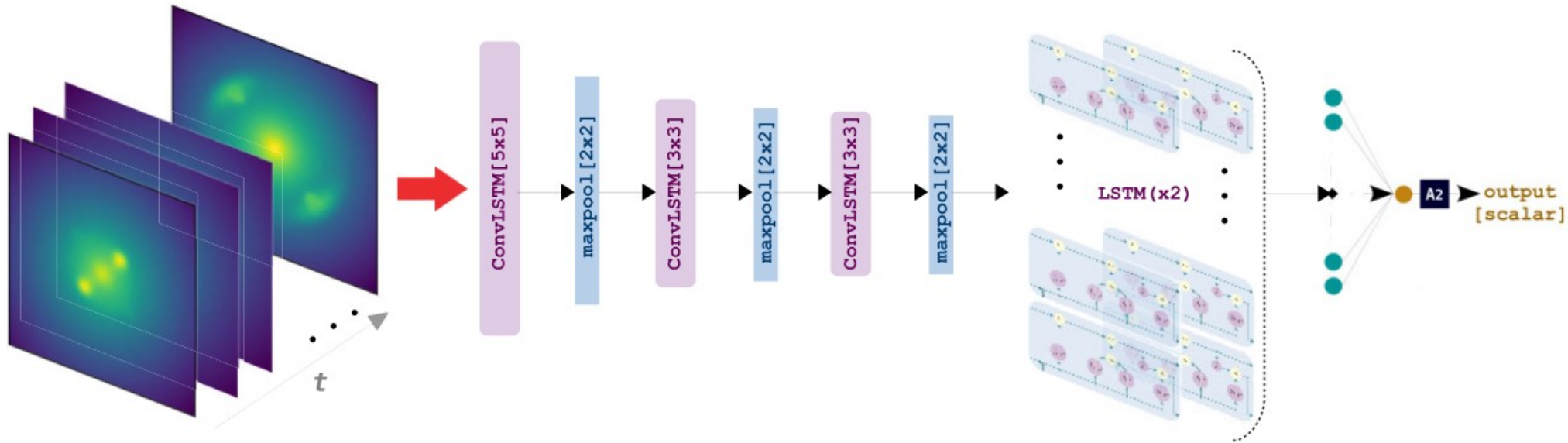


It works!

330 new lens candidates in Pan-STARRS
 430 new lens candidates in HSC

Cañameras et al. (2020, 2021)

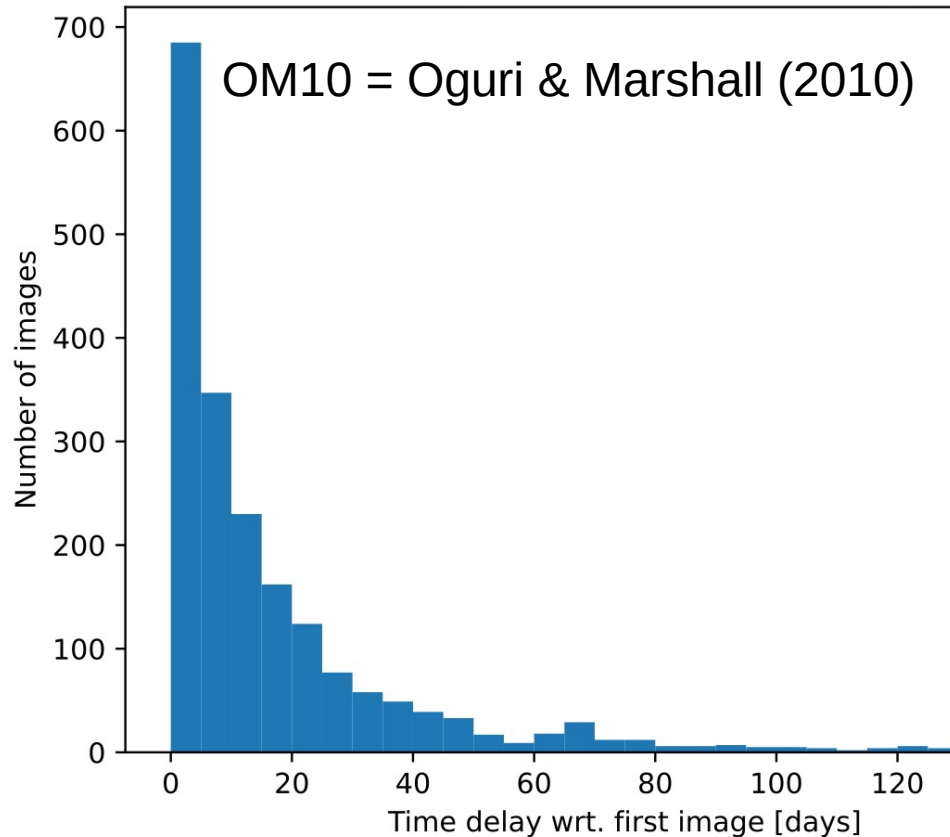
Finding Lensed Supernovae (2)



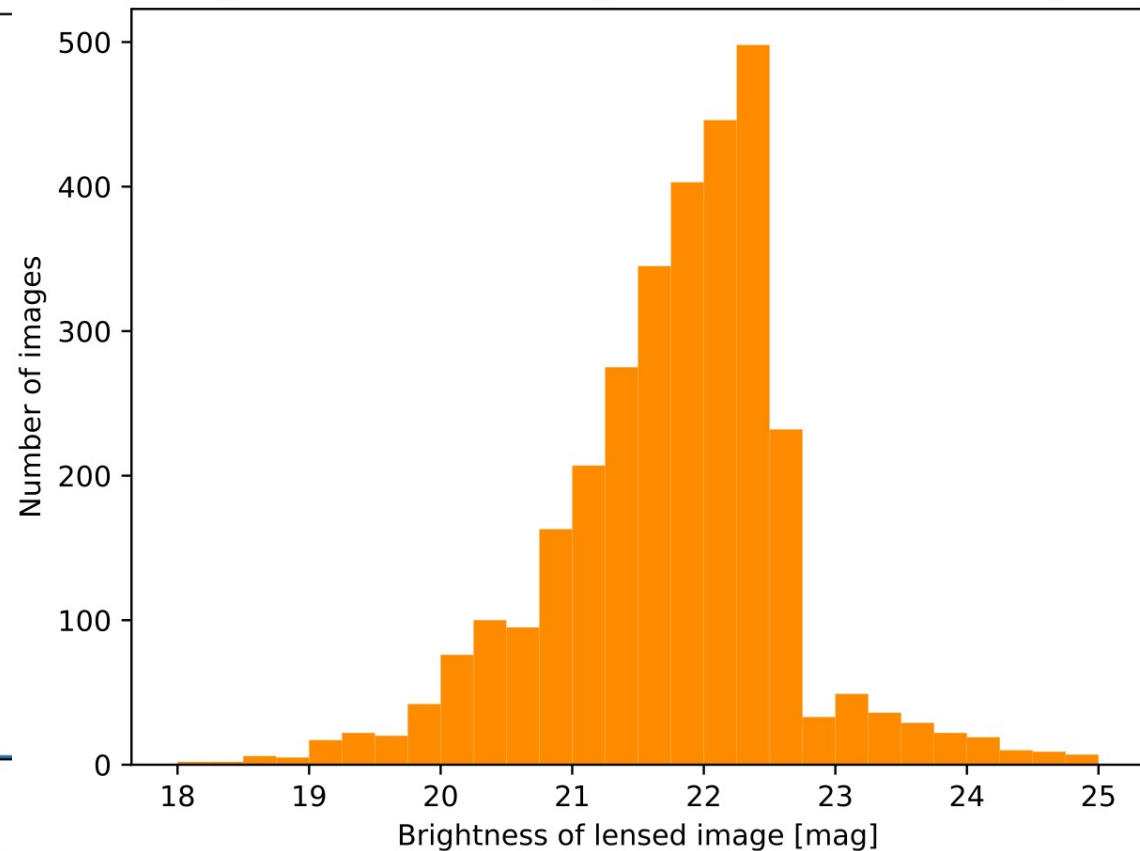
Find lensed transients in multi-epoch observations
(currently being trained on HSC data)

Expected rates in VRO LSST

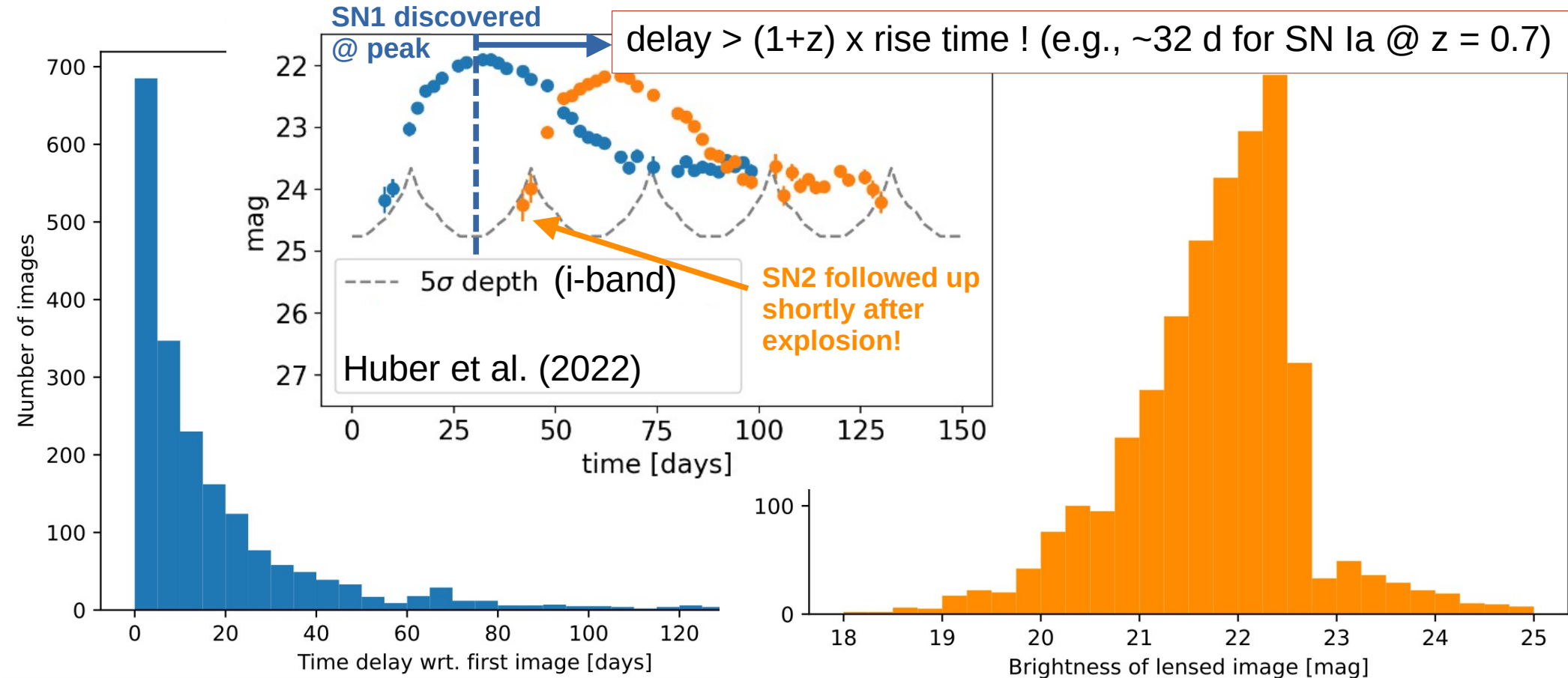
Time delays in the full OM10 catalogue



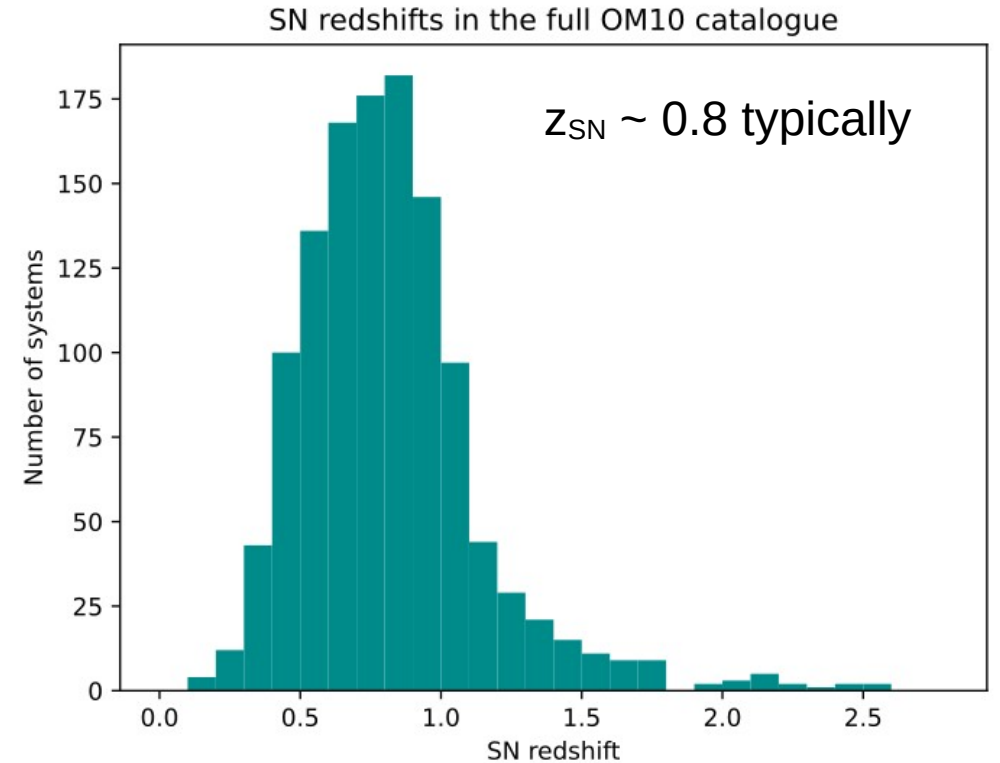
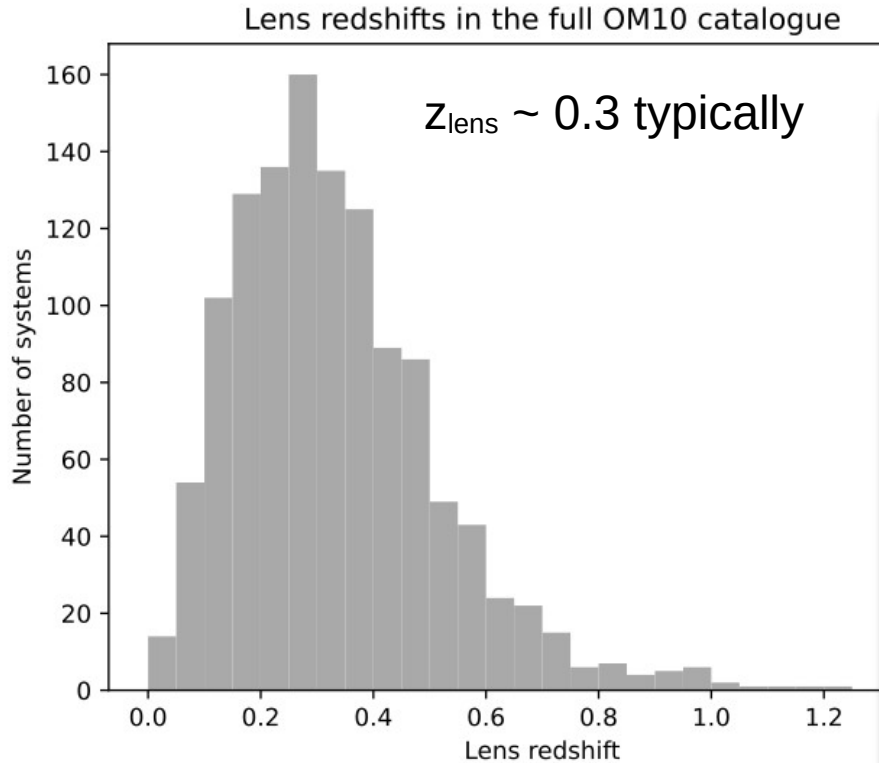
Brightness of lensed images in the full OM10 catalogue



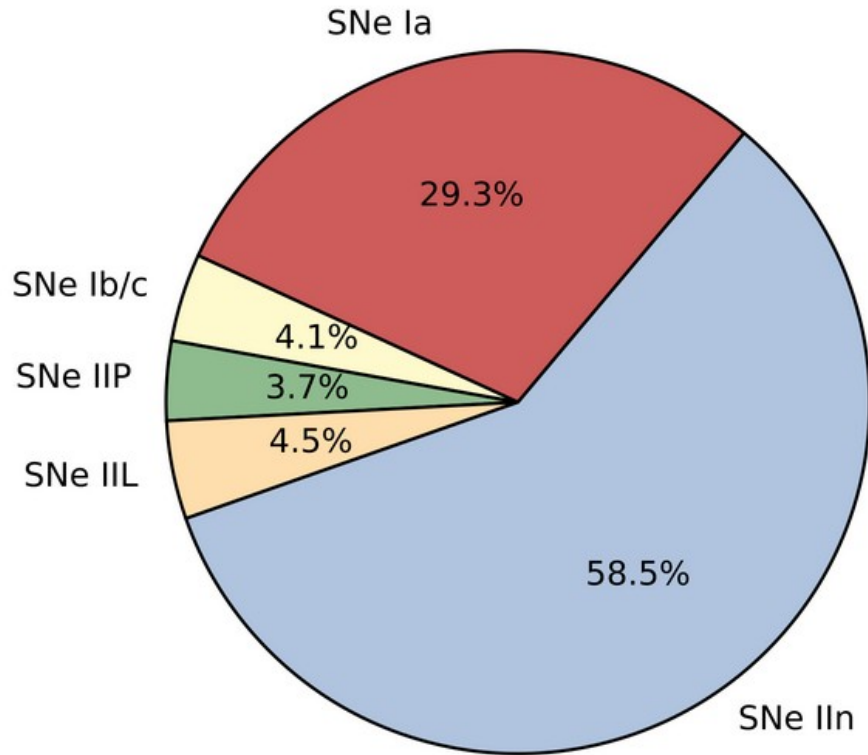
Expected rates in VRO LSST



Expected rates in VRO LSST



Expected rates in VRO LSST

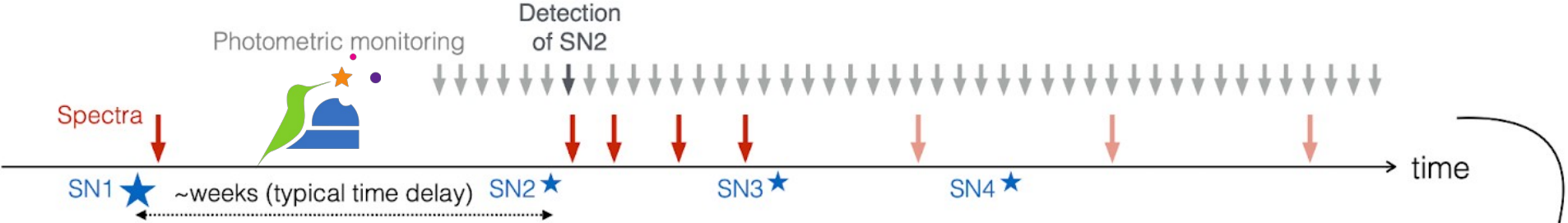


Wojtak et al. (2019)

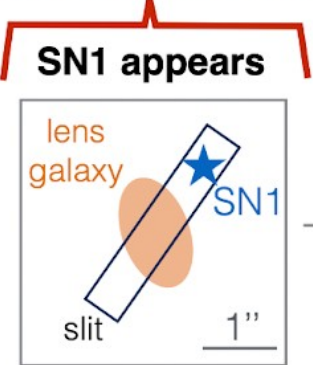
SN Type	Mean redshift	<i>N</i> per year *
IIIn	~1.2	~3
Ia	~0.7	~1

* suitable for early-time spectroscopy

SuperEarly Observing Strategy

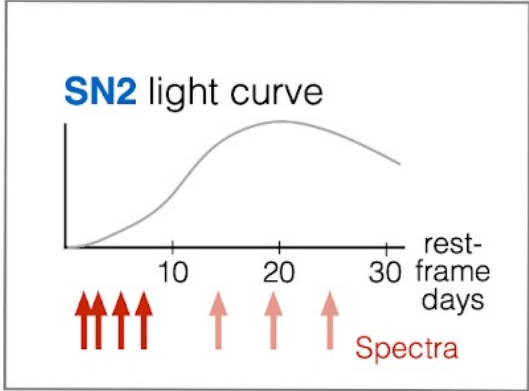
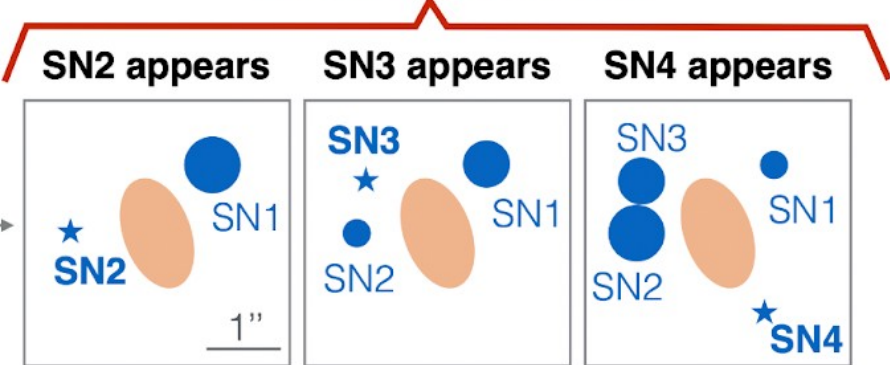


FORS2 observation



Classification spectrum:
 → z_{lens} and z_{SN}
 → SN type & phase

MUSE observations



Summary

- Strong lensing offer a unique possibility to study the earliest phases of SNe in the rest-frame UV
- LSST will discover 100-200 lensed SNe
- ~ 1 SN Ia and ~ 3 SN IIn per year suitable for early-time spectroscopy (VLT+MUSE)
- COLIBRI can be used for monitoring the reappearance of trailing SN images