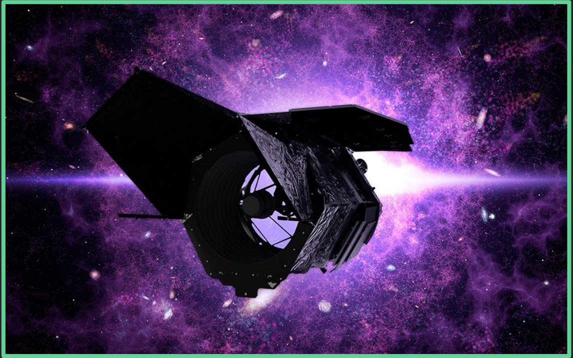
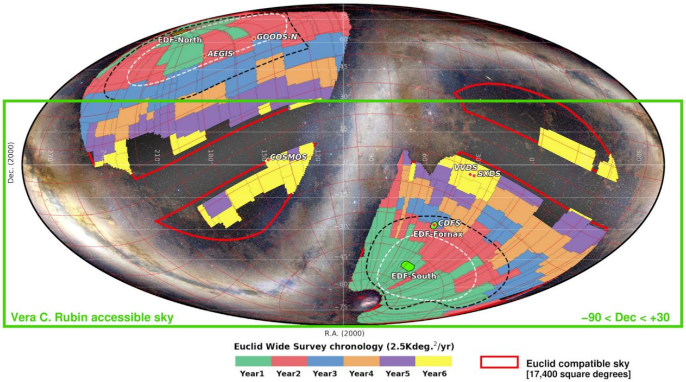
Scarlet2: Multi-survey pixel-level modeling to characterize transients and host galaxies

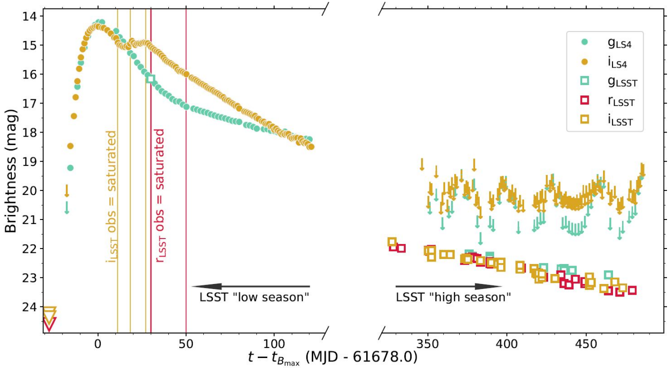


Charlotte Ward (Penn State)
with:
Peter Melchior
Gautham Narayan
Jennifer Li
Kendall Sippy
Veena Krishnaraj
Benjamin Remy
& many others!

RAPID Response 2026

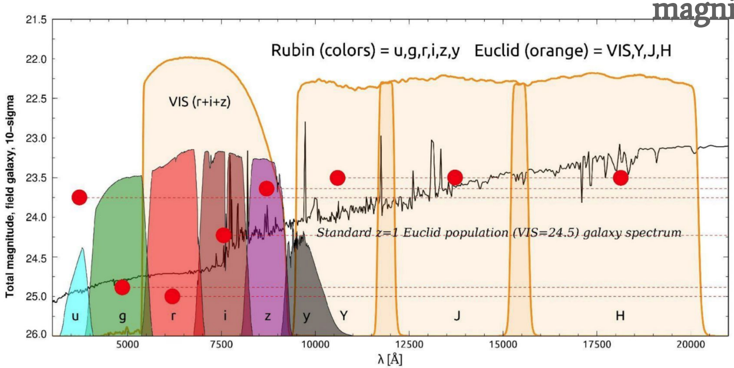
The combined strengths of next-generation surveys

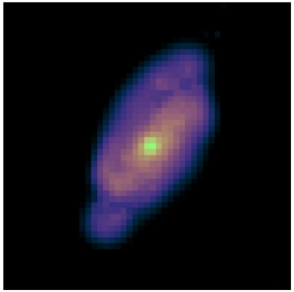


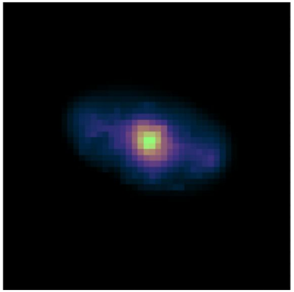


Aligned deep and wide surveys

Sensitivity to transient fluxes over 10 orders of magnitude





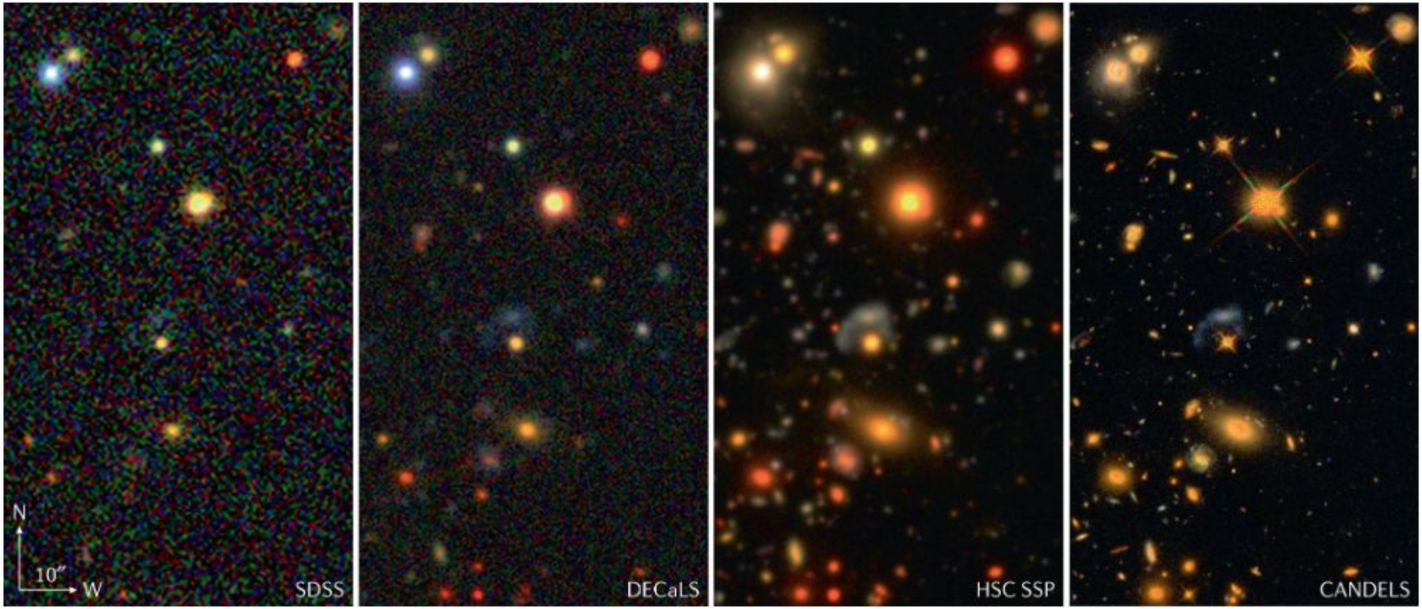


Optical/IR light curves and host SEDs

Resolved transient positions and host morphologies

The joint Rubin-*Euclid* data products

- **30-60% of galaxies in LSST coadds overlap with other galaxies** .
- 15% of sources will suffer from **'unrecognized' blending** with faint background sources and galaxy **photometry inaccurate at ~5% level** .
- **Correct host associations** needed for GW counterparts, hostless transients, gLSNe Ia identification.

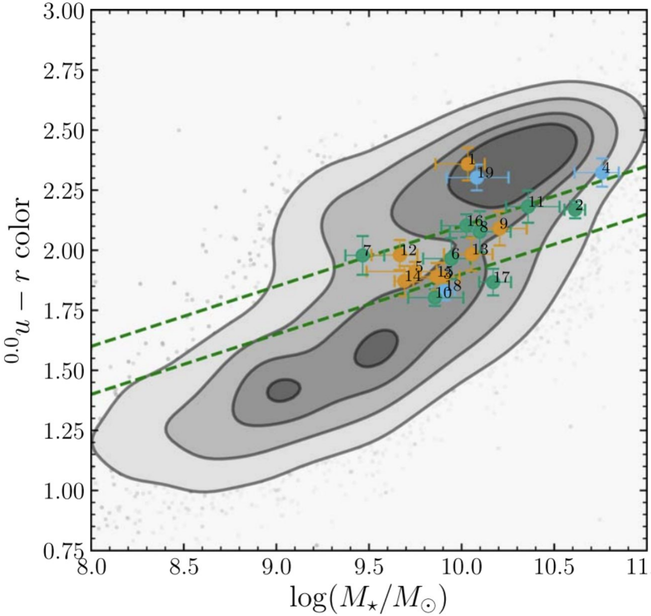


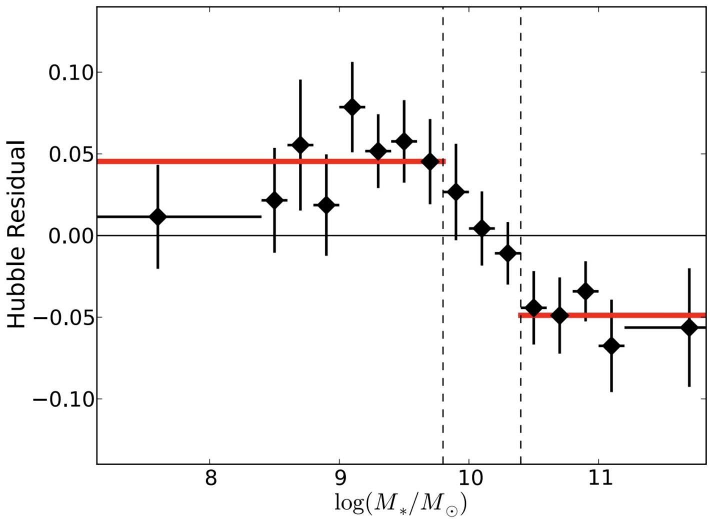
Melchior et al. (2018)

Multi-survey host galaxy characterization

Accurate host galaxy SEDs and morphology models will help us understand:

- Do **tidal disruption events prefer post-merger systems**?
- How does **host metallicity affect SNIa light curve shape**?
- What **environments are H-poor and H-rich superluminous supernovae** found in?





Childress et al. (2013)

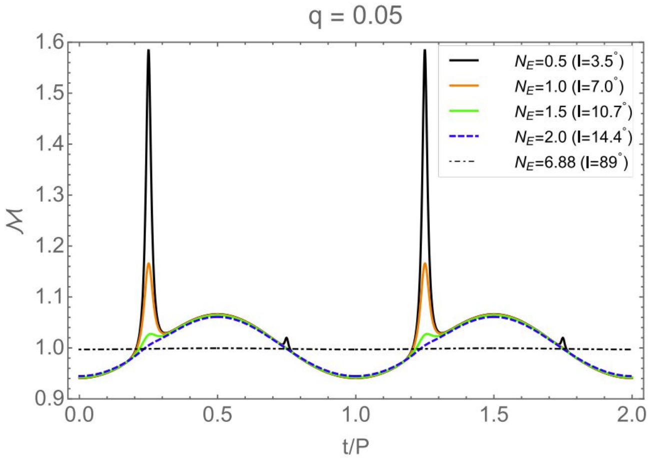
Hammerstein et al. (2021)

Multi-survey photometry

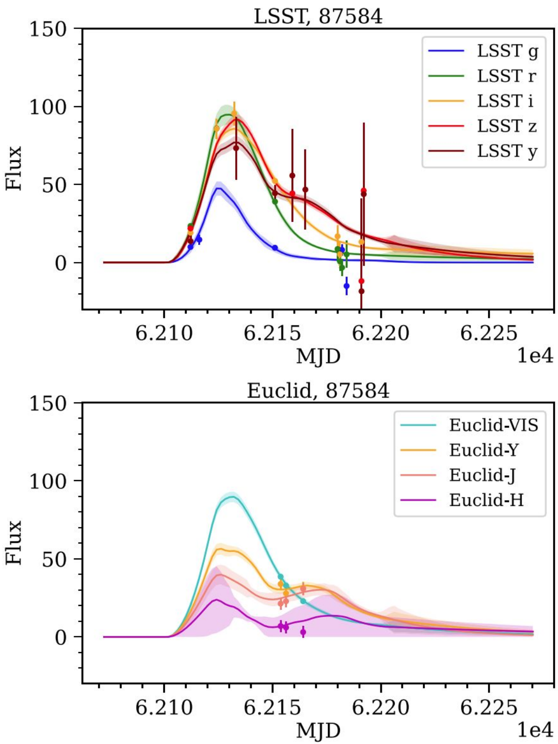
High cadence, long baseline optical + IR light curves to study:

- Repeating tidal disruption events;
- Supernova light curve shape and dust reddening;
- Variability of 'changing-look' AGN;
- Self-lensing flares in SMBH binaries.

And we want to **avoid issues from reference image mismatch**, especially for AGN!

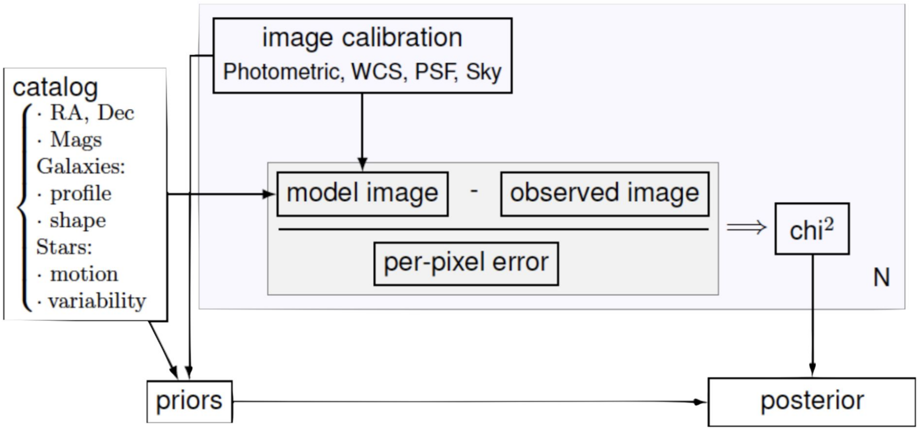


D'Orazio et al. (2018)

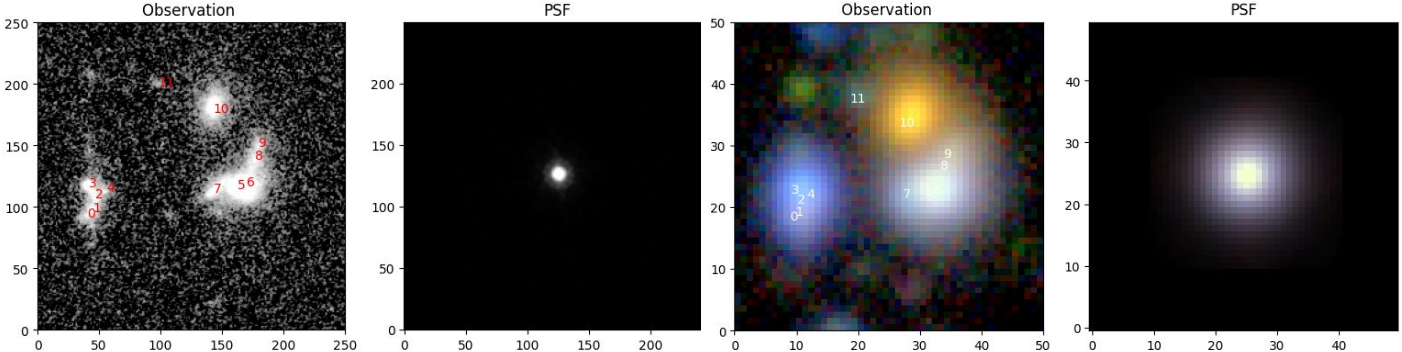


Rubin and Euclid: Bailey et al. (2023)

Joint detection and multi-resolution modeling



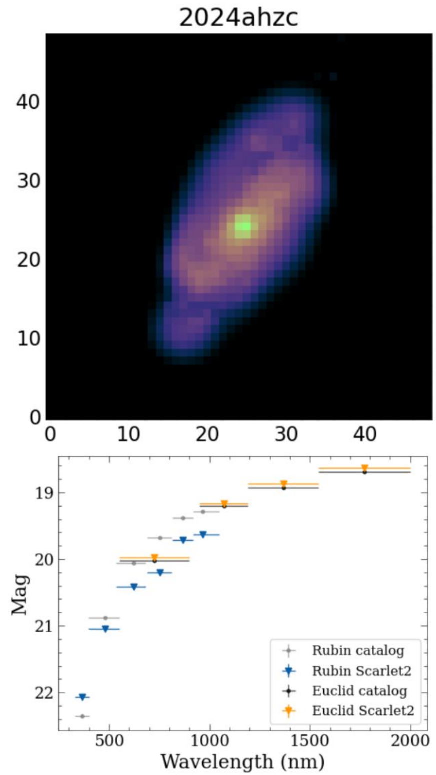
Lang (2018)



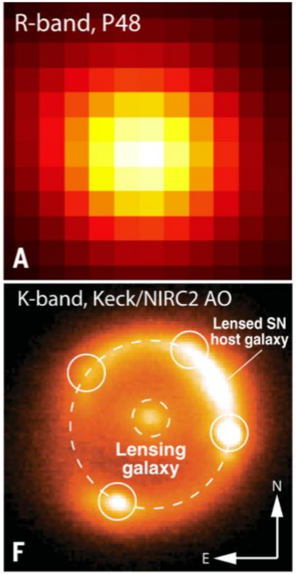
Melchior, Ward et al. (submitted to JOSS)

Why use multi-resolution scene modeling for transients?

- Use all available deep imaging to **identify faint background host galaxies, get improved photo-z's, and resolve substructures within host galaxies** .
- Measure transient fluxes across surveys or from a single image **without reference images.**
- **MCMC sampling** on parameters like source positions and host shapes.
- **Extract photometry from multi-epoch ground-based imaging that is highly blended** – anchored on a space-based image.
- **Precise SNIa photometry** via treatment of SED-dependence of PSF.



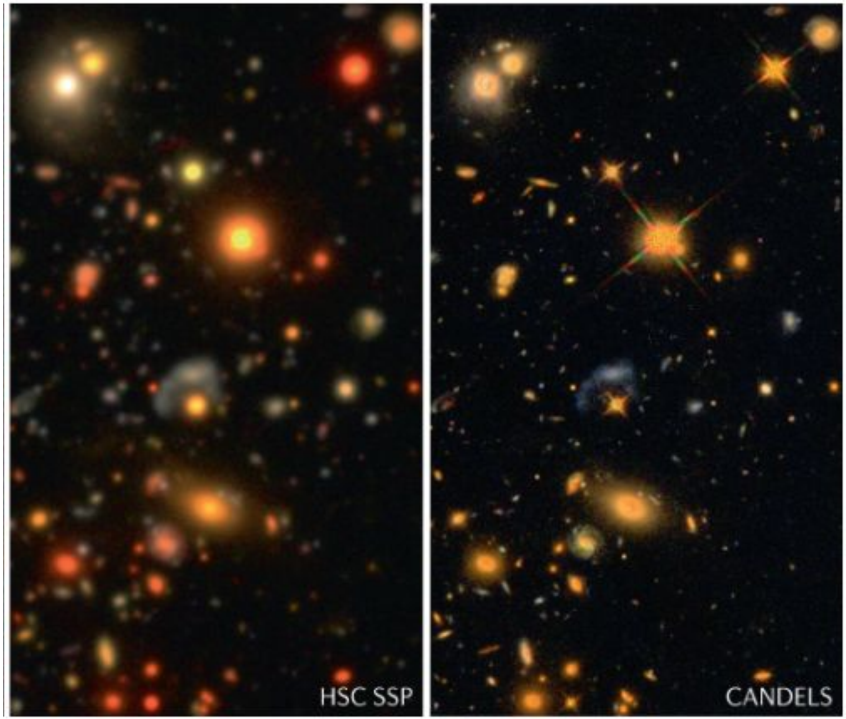
Ward et al. (in prep)



Goobar et al. 2017

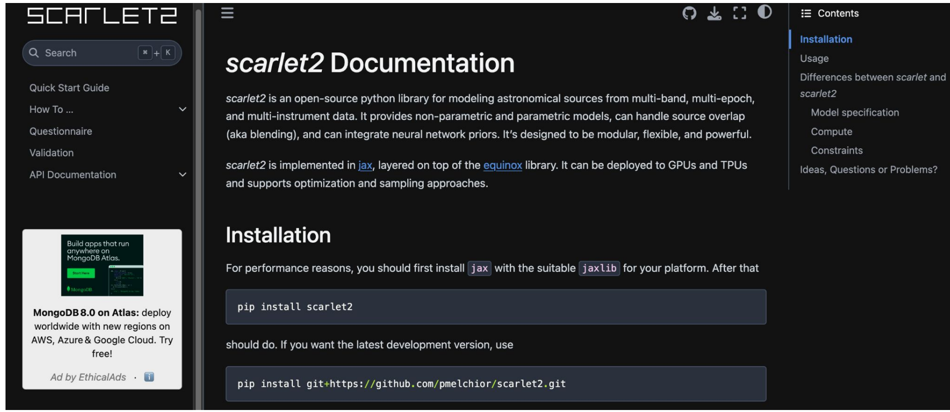
New challenges for multi-resolution modeling

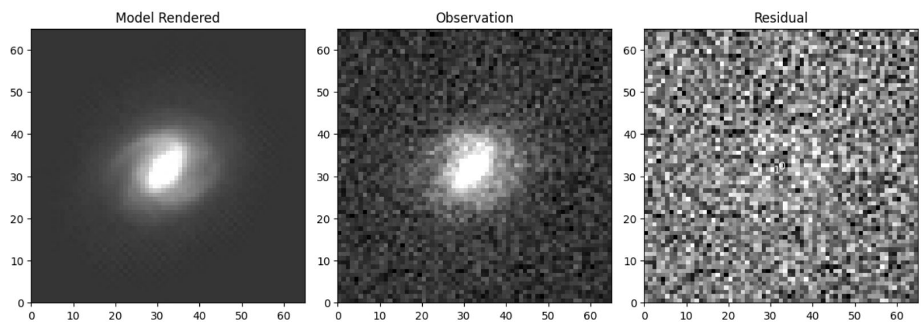
- Complex galaxy shapes seen in space-based imaging require **non-parametric morphology models.**
- Non-parametric galaxy models **need machine-learning priors** for stable fitting.
- The source densities at Rubin depths require **GPU-acceleration** .
- We need the speed to model **variable sources across 1000s of multi-epoch images.**



Scarlet2: A new approach to multi-resolution modeling

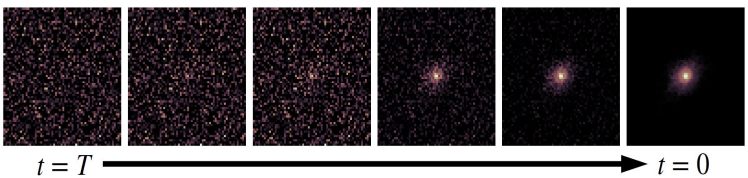
- **Fully differentiable.**
- **Non-parametric galaxy morphology** models.
- Data-driven priors on galaxy morphology provided by **score-based neural networks** .
- Written in **jax for GPU-compatibility** .
- Transient and variable source models.
- https://scarlet2.readthedocs.io/en/latest/



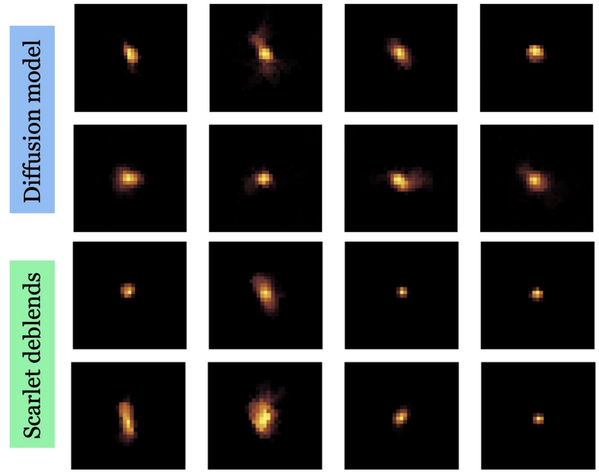


Non-parametric galaxy models with score-based NN priors

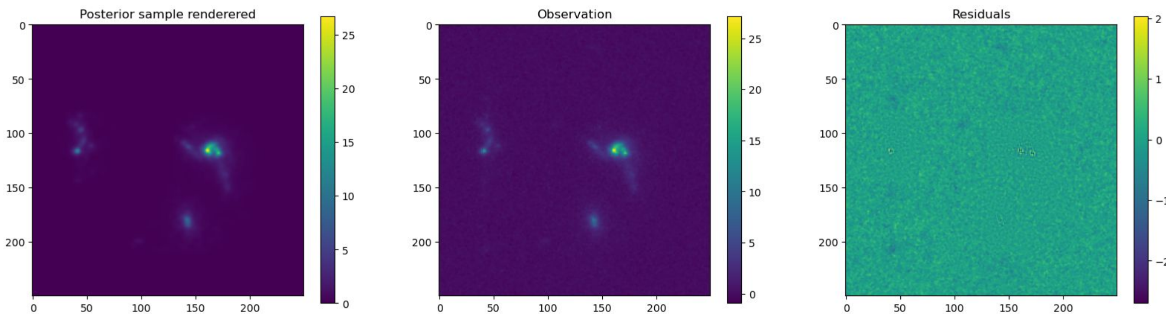
- A neural network is trained to reverse the diffusion process.
- We are developing a library of priors on galaxy images from HSC, ZTF, and simulated HST-resolution imaging.



box size 32^2

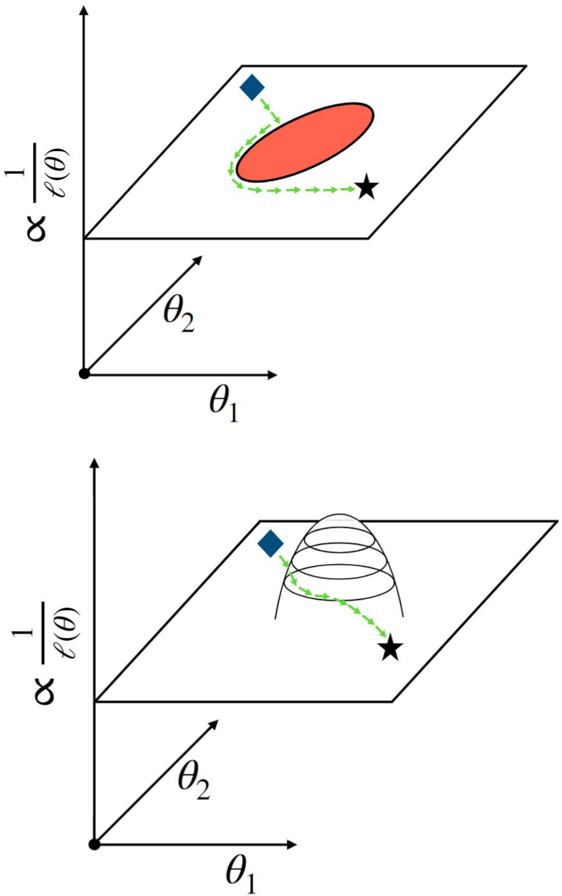


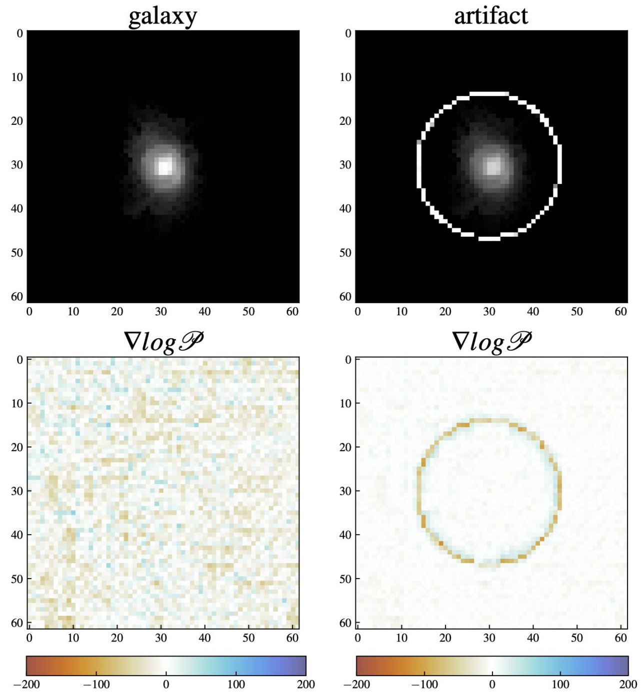
Sampson, Melchior, Ward et al. (2024)



Remy et al. (in prep)

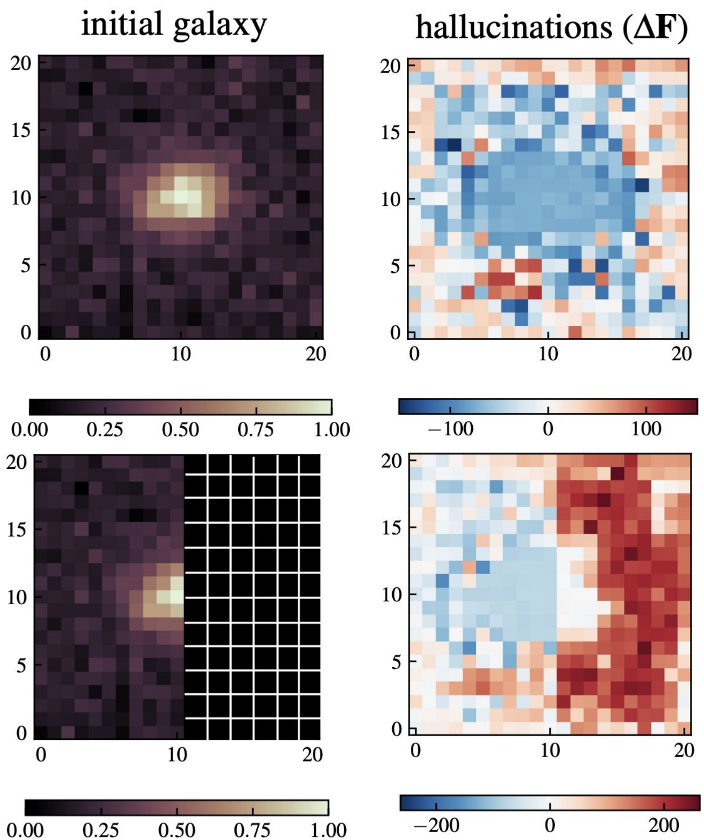
How priors are incorporated into deblending





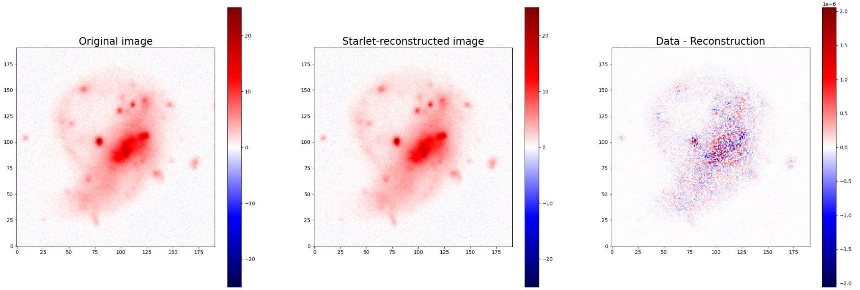
Sampson, Melchior, Ward et al. (2024)

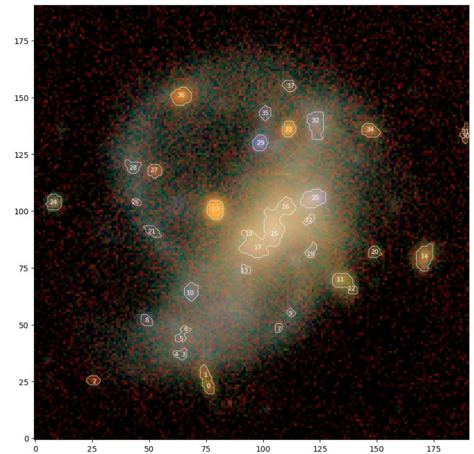
Prior dependence shown via hallucination scores

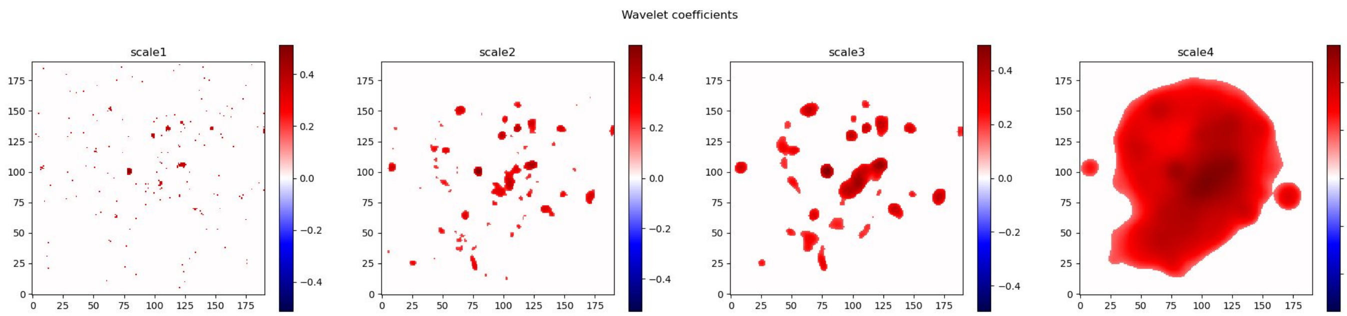


Sampson, Melchior, Ward et al. (2024)

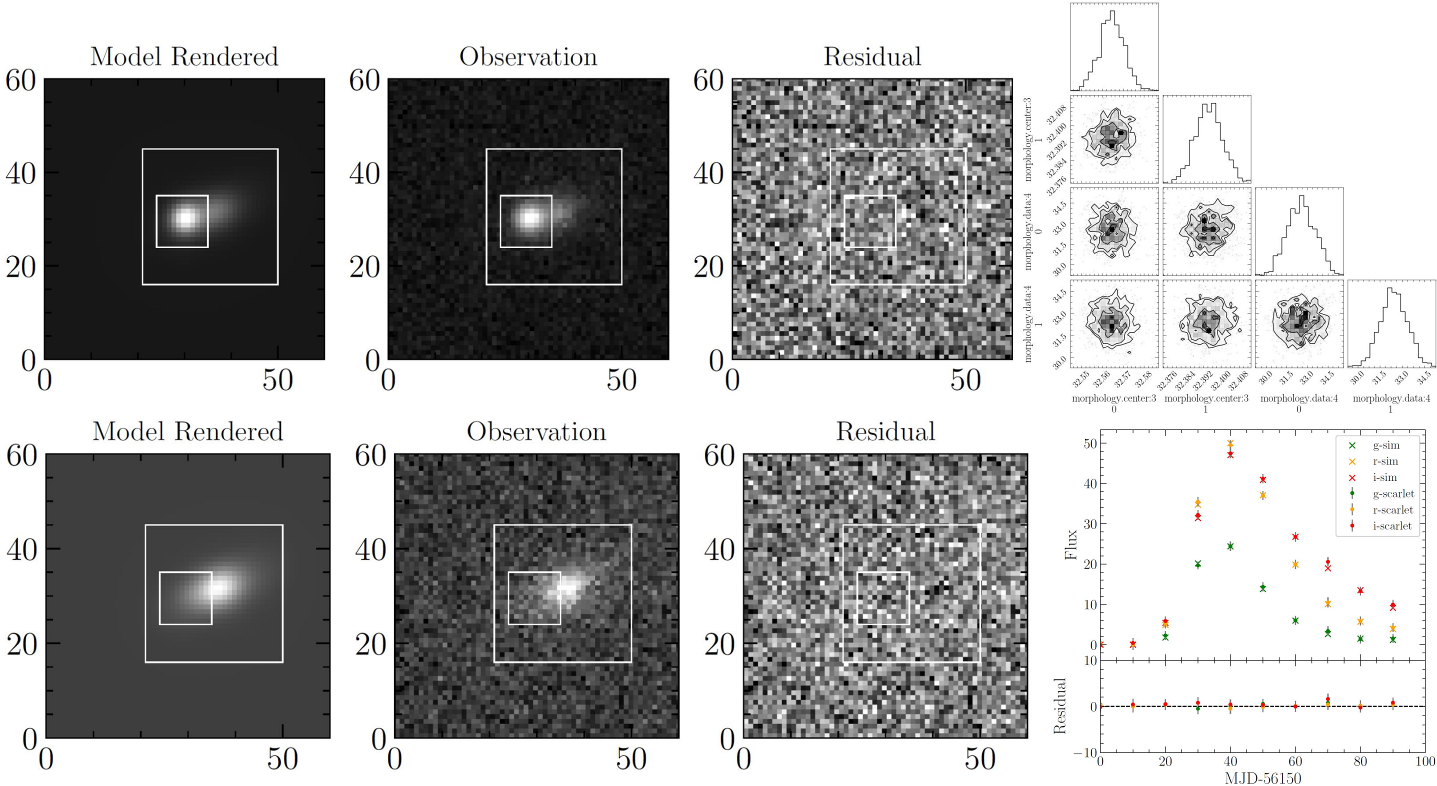
Wavelet decomposition for multi-resolution source detection and fitting







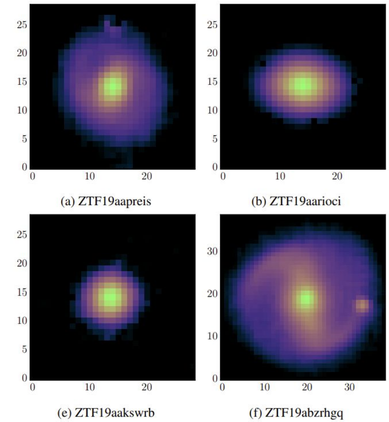
Deblending static and variable sources

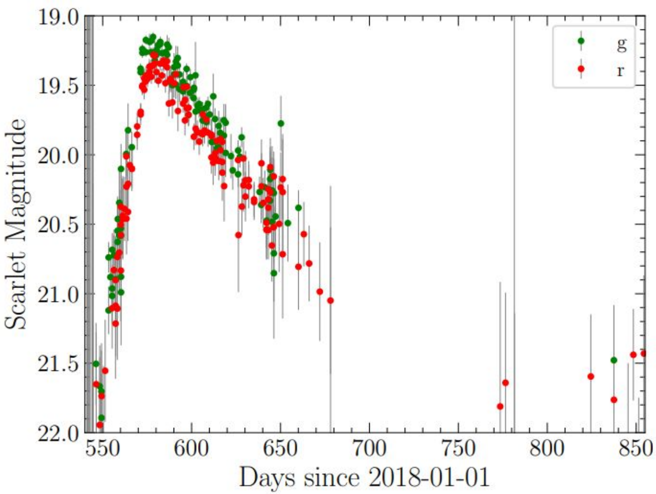


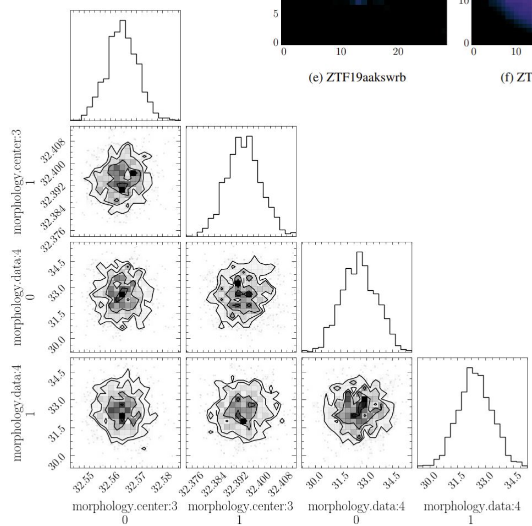
Ward et al. (2025a)

What can a Scarlet2 multi-survey fit provide?

- Multi-survey light curves **without reference images.**
- **MCMC-sampled posteriors** on SEDs, positions and galaxy morphologies.
- **Forced photometry** for transients with a poorly characterized position.
- **Host galaxy optical-IR SEDs and morphology models** with background source and transient contamination removed, anchored on the highest resolution image.
- **Astrometry/PSF corrections** for input imaging.







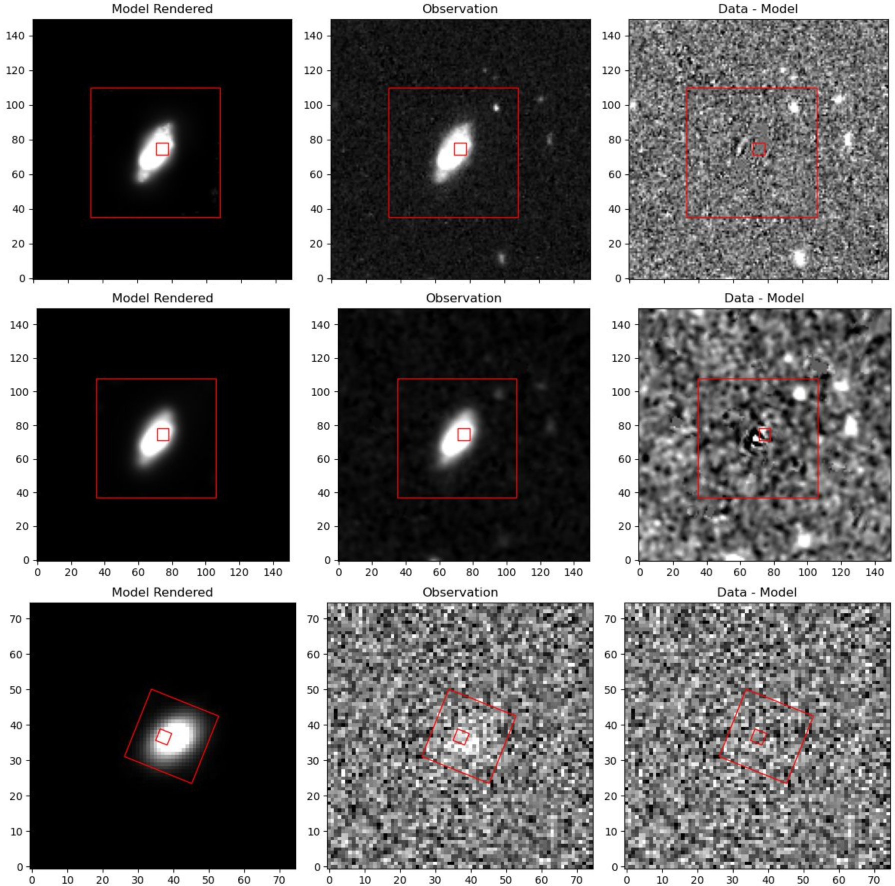
Ward et al. (2025a)

Joint pixel analysis: Euclid Q1 and Rubin DP1

Euclid VIS

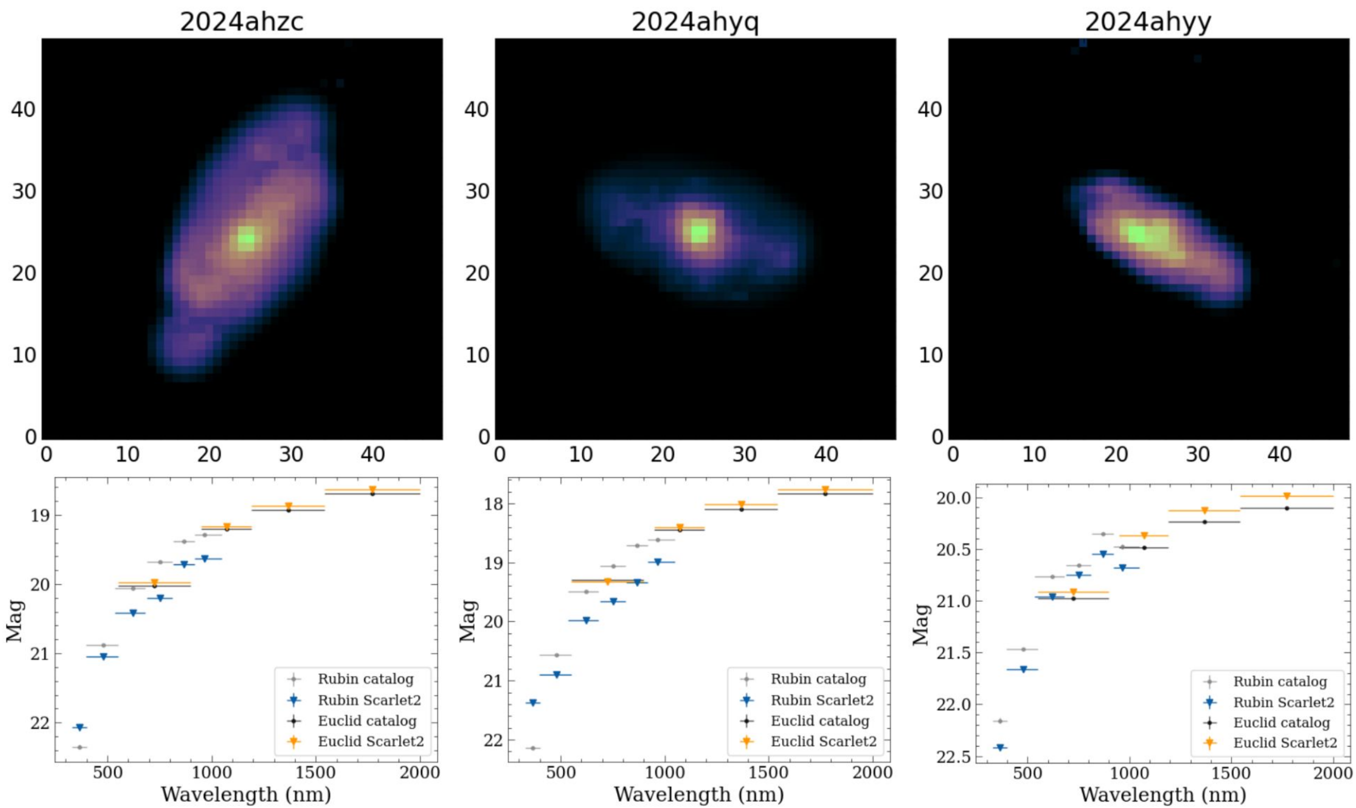
Euclid NIR-H

Rubin g



Ward et al. (in prep)

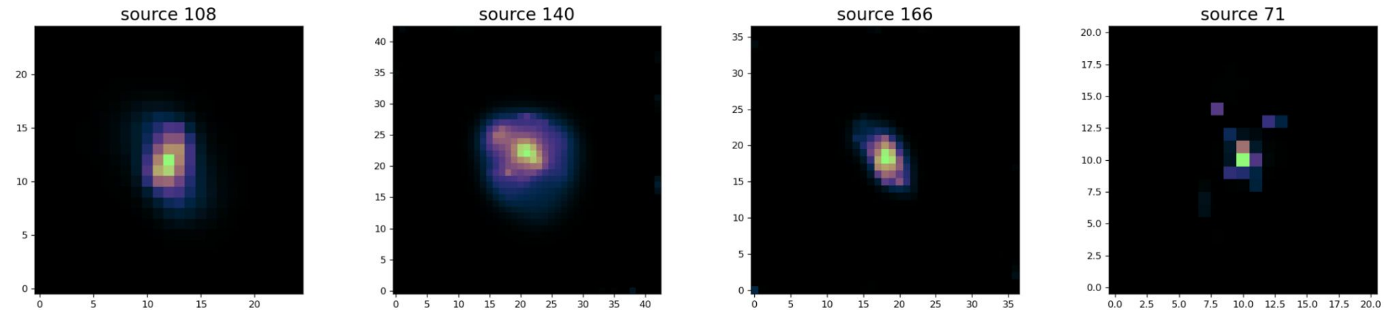
Supernova host galaxies



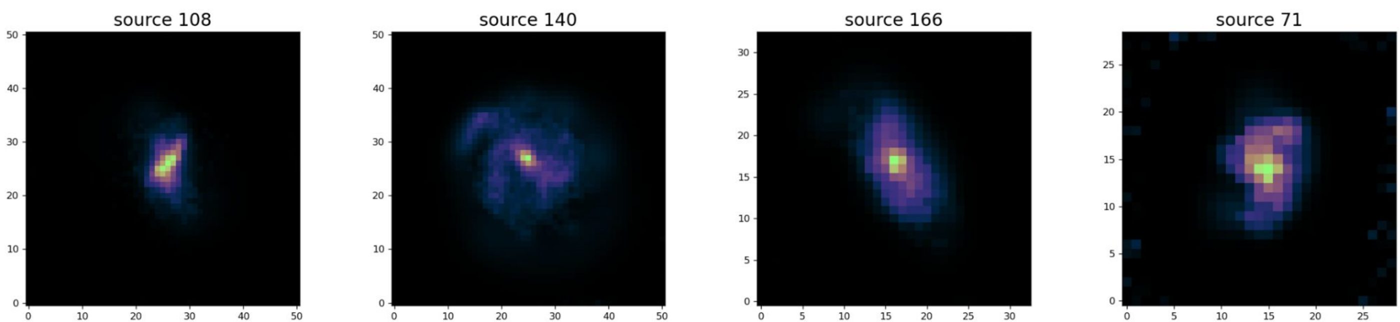
Ward et al. (in prep)

Joint morphology models

Rubin only



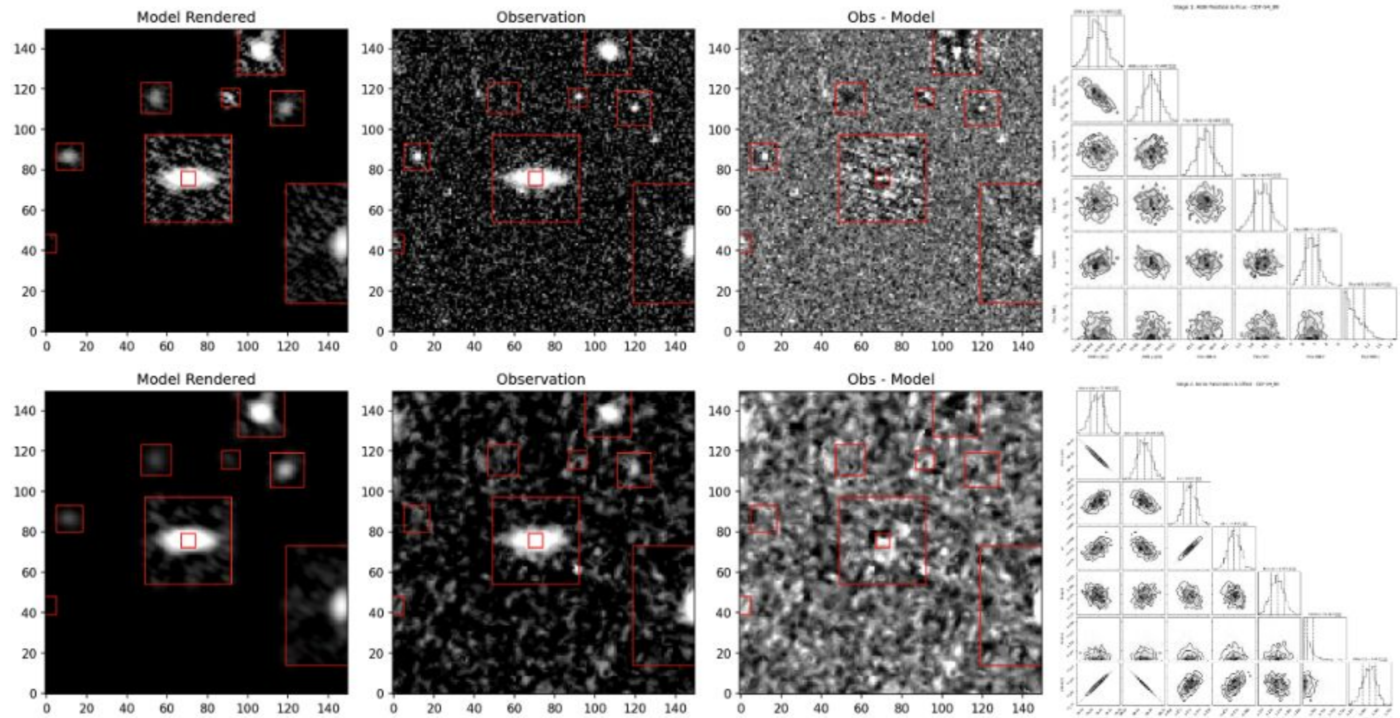
Rubin+Euclid



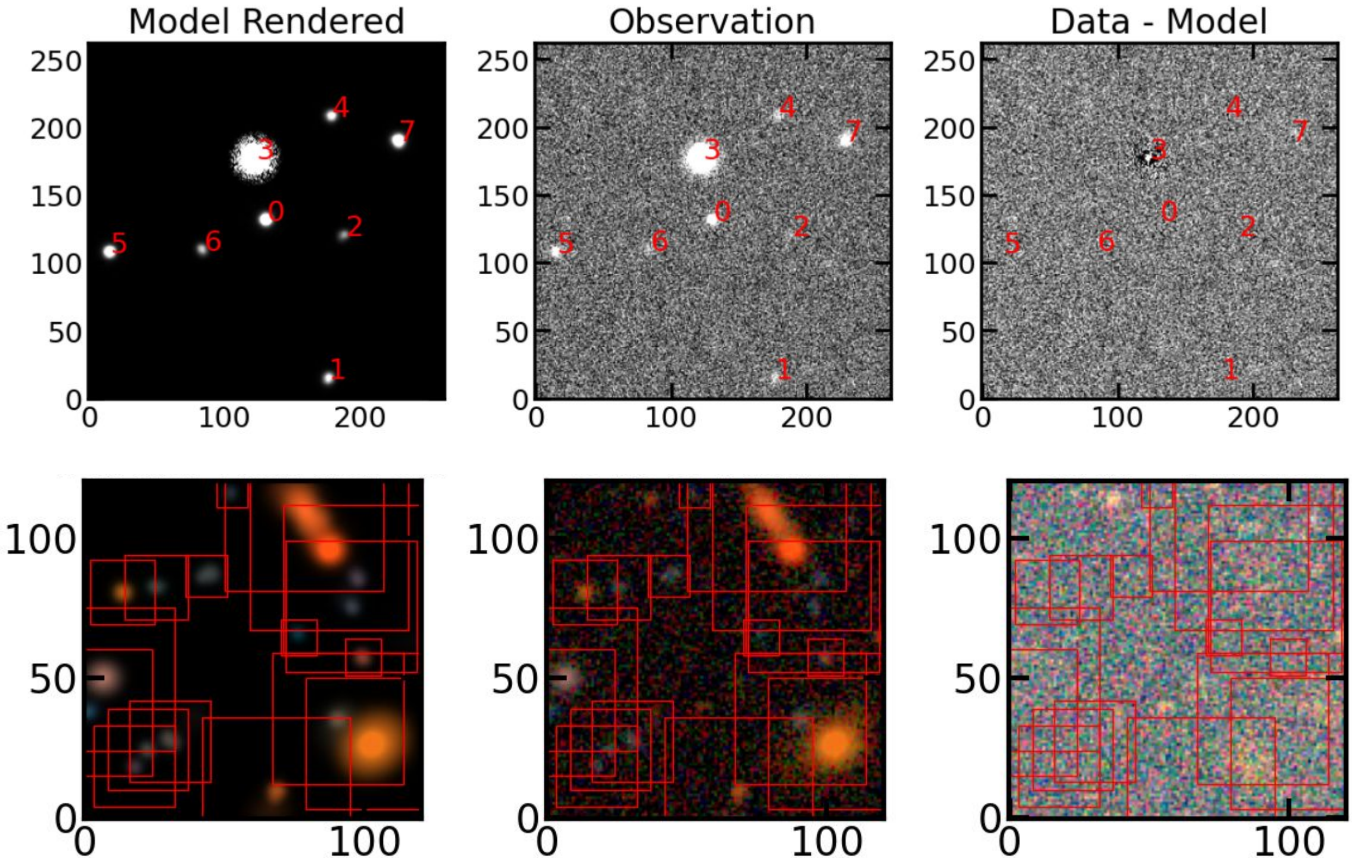
Ward et al. (in prep)

Accounting for correlated noise in coadds/warps

- Detect sources then measure power spectrum of background noise → add to weights during fitting.



Scarlet2 on the Rubin Science Platform



Building custom code with an interactive questionnaire

```
[1]: from scarlet2.questionnaire import run_questionnaire
     run_questionnaire()
```

Do you have a single image, or multiple images? — Multiple images

Do you wish to model transient or variable sources across multiple epochs? — Yes

Are your images at the same resolution — No

Click to continue — Continue

Click to continue — Continue

Click to continue — Continue

Do you have a position catalog of the sources in the image you wish to model?

No, I don't have positions

Yes, I have positions

Save Answers

```
import scarlet2
import jax.numpy as jnp


channels=[("g",0)]
channels=[("g",1)]

obs = scarlet2.Observation(
    jnp.array(data).astype(float),
    weights=jnp.array(weight).astype(float),
    psf=scarlet2.ArrayPSF(jnp.array(psf).astype(float)),
    wcs=wcs,
    channels=channels,
)

model_frame = scarlet2.Frame.from_observations(
    observations=obs,
    coverage="union",  # or "intersection"
)

norm = scarlet2.plot.AsinhAutomaticNorm(obs)
scarlet2.plot.observation(
     obs, norm=norm, sky_coords=ra_dec, show_psf=True, label_kwargs
={"color": "red"}
)
```

Copy

The observations and PSF models can be plotted as above.

Validation for input observations, initializations, and fits

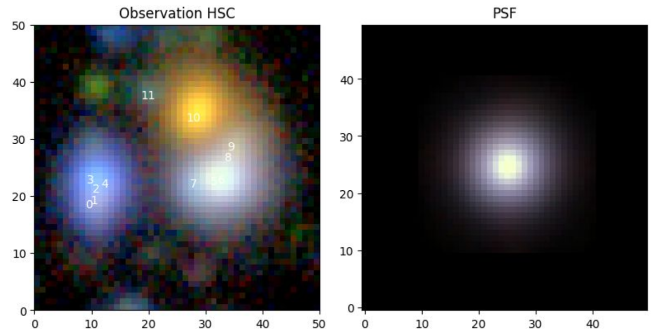
```
obs = Observation(
    data,
    weights,
    psf=ArrayPSF(psf),
    channels=channels,
)
model_frame = Frame.from_observations(obs)
```

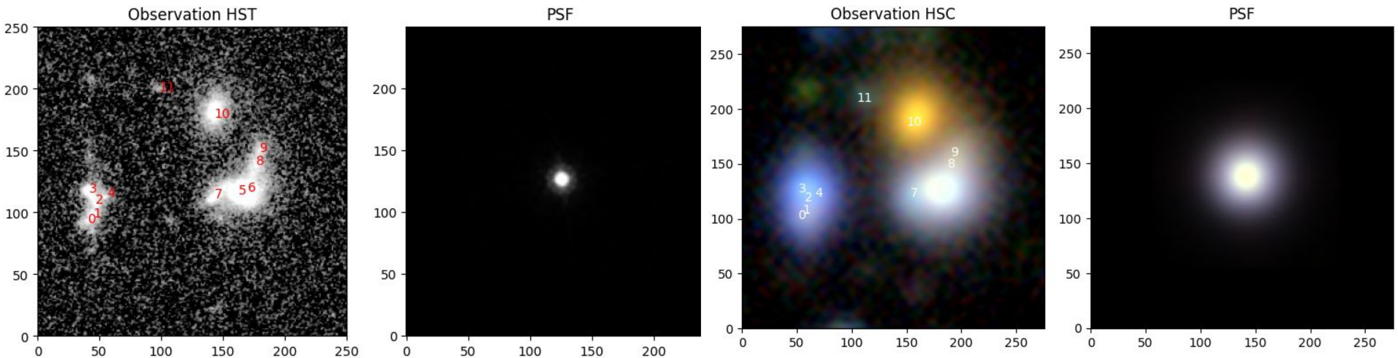
```
Observation validation results:
[000]   INFO   Weights in the observation are non-negative. | Check=ObservationValidator
[001]   INFO   Weights in the observation are finite. | Check=ObservationValidator
[002]   INFO   Data and weights have the same shape. | Check=ObservationValidator
[003]   INFO   Number of channels in the observation matches the data. | Check=ObservationValidato
[004]   INFO   Data in the observation is finite where weights are greater than zero. | Check=Obse
[005]   INFO   PSF is 3-dimensional. | Check=ObservationValidator
[006]   INFO   Number of PSF channels matches the number of data channels. | Check=ObservationVali
[007]  ERROR   PSF centroid is not the same in all channels. | Check=ObservationValidator | Contex
         [ 0.09050751,  0.01180839, -0.03284836,  0.08526038, -0.00099373]],
        dtype=float32)})
```

Performance: fast resampling with jax

The fastest approach for ~1000 images of different rotations, pixel scales, and PSFs:

- Oversample to the WCS of the highest resolution image (or PSF model).
- Measure the power spectrum of the resulting correlated noise in each image and incorporate this into your weights for the loss function.
- A multi-resolution fit across Euclid and Rubin for 1000 cutouts now takes a few seconds on a laptop!

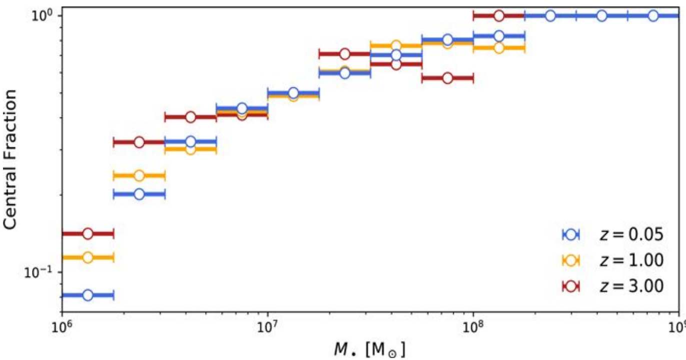




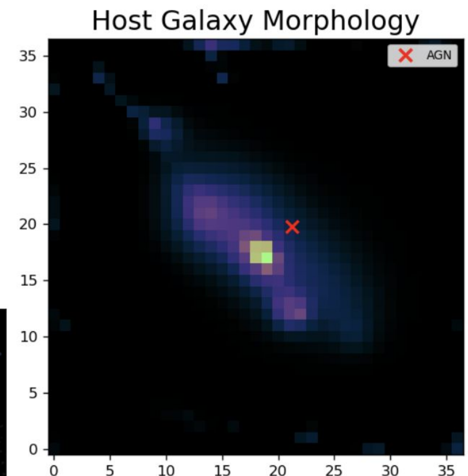
‘Wandering’ massive black holes

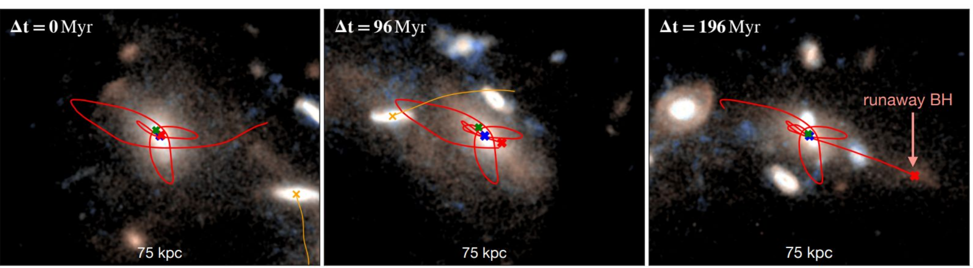
- Simulations suggest that the majority of MBHs in galaxies of mass $<10^{8.5}\,M_\odot$ are spatially offset from their host nuclei.
- This arises due to the cumulative effects of mergers on low mass MBHs in smaller potential wells.

See poster by Kendall Sippy!



Ricarte et al. 2021

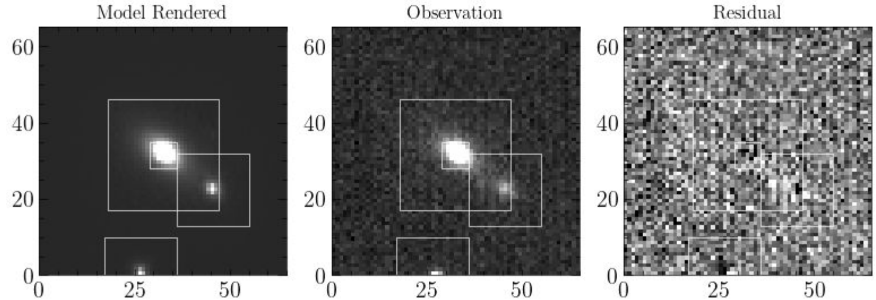


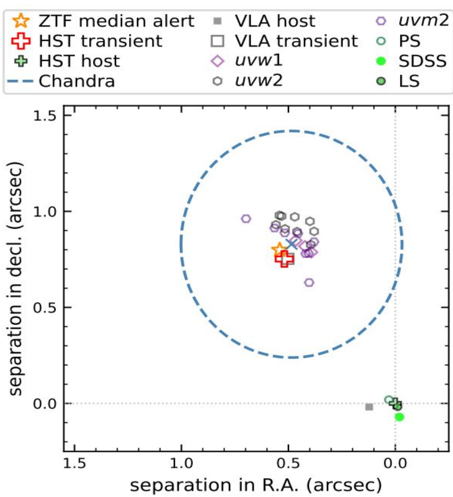


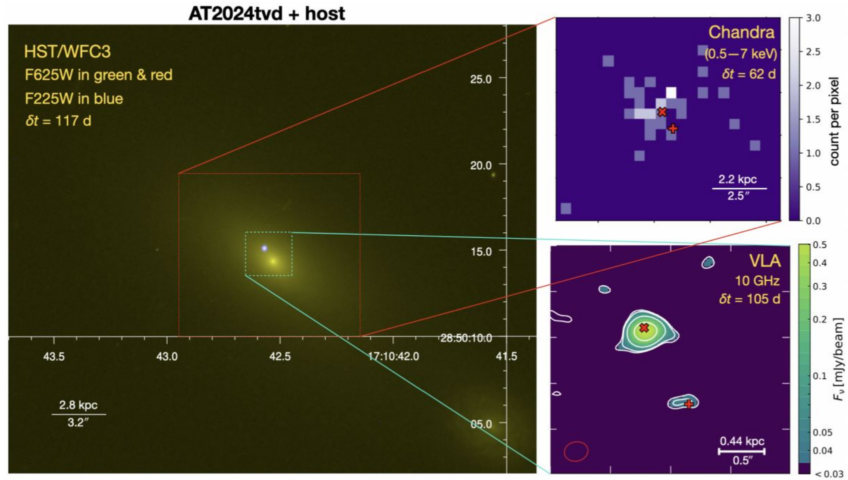
Chen et al. (2023)

First optically detected non-nuclear tidal disruption event

- Scarlet2 confirmed the 1” offset suggested by difference imaging.
- HST/Chandra/VLA follow-up of a ZTF TDE finds a 0.8 kpc offset between a 10^6 solar mass MBH and a galaxy hosting a 10^8 solar mass MBH.



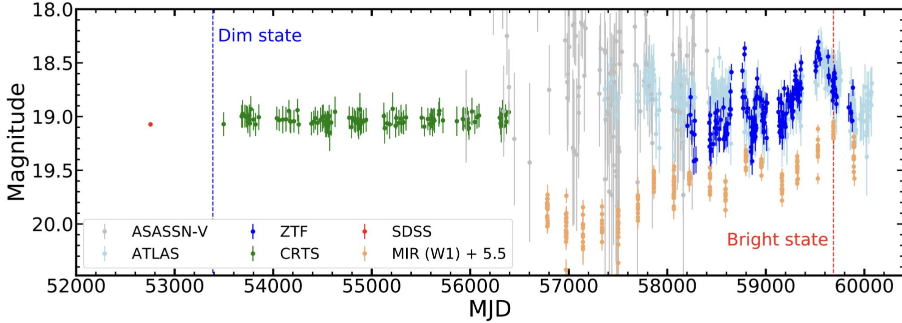




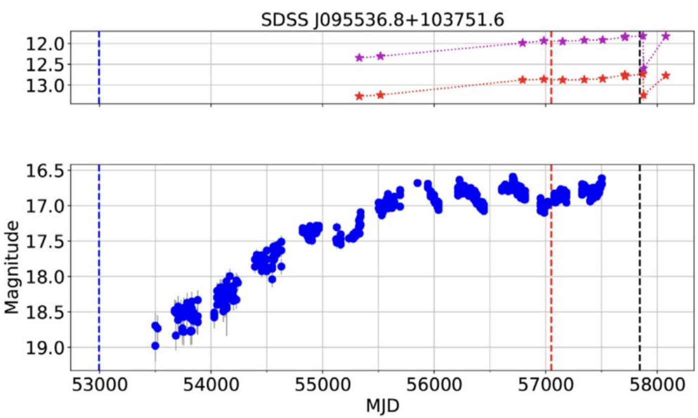
Yao et al. (2025)

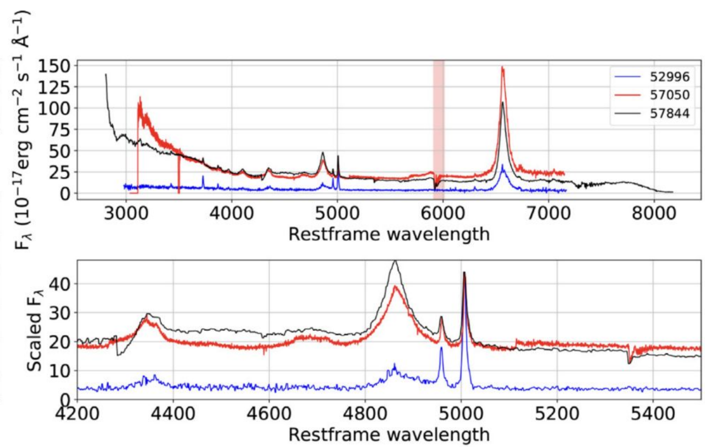
Multi-survey identification of changing-look AGN

- Changing-look AGN require long baselines and high cadence to be identified from time series alone.
- Better light curves allow us to distinguish between predictions from GRMHD simulations.



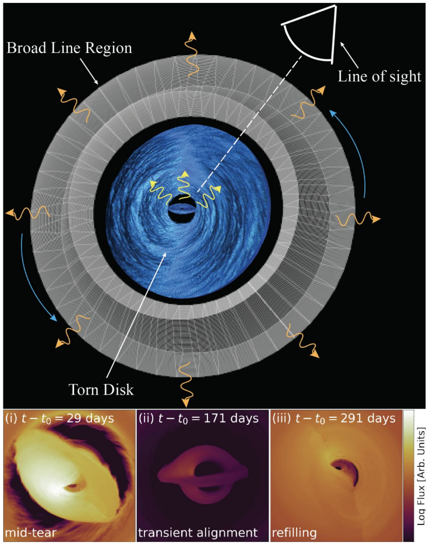
Wang et al. (2024)



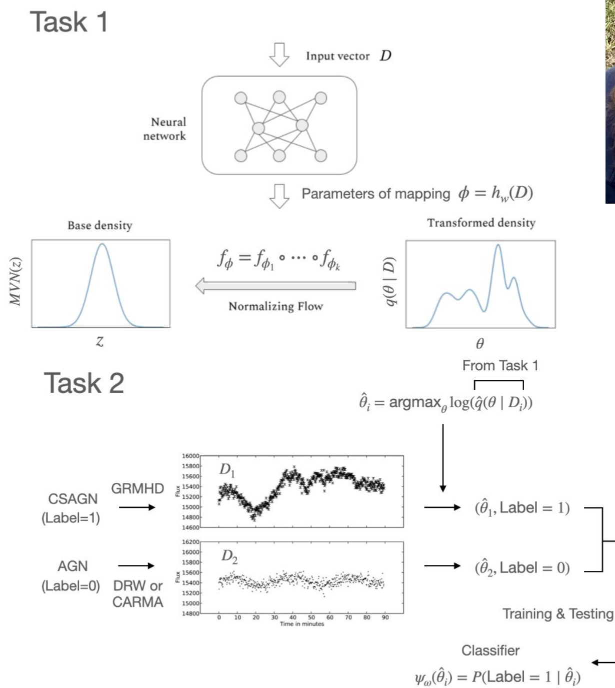


Graham et al. (2020)

An SBI framework for CLAGN

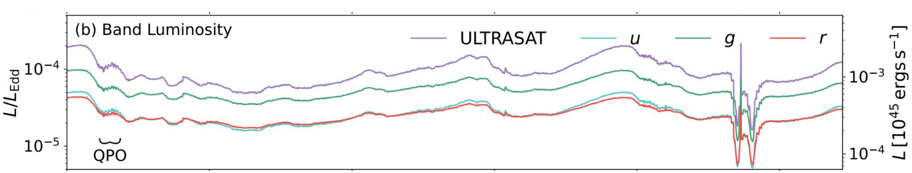


Kaaz, Liska, Ward et al. (2025)

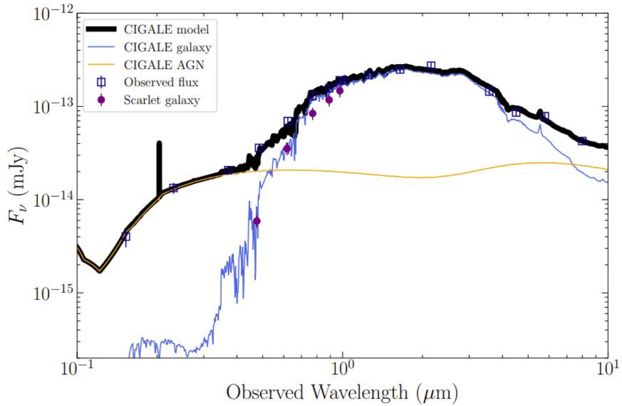


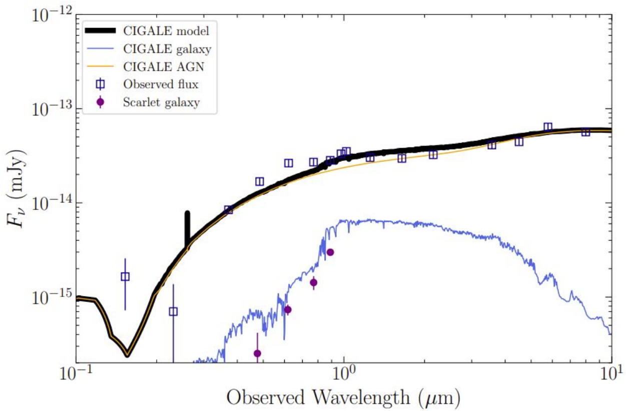
See poster by Miranda Zak!

Zak et al. (in prep)

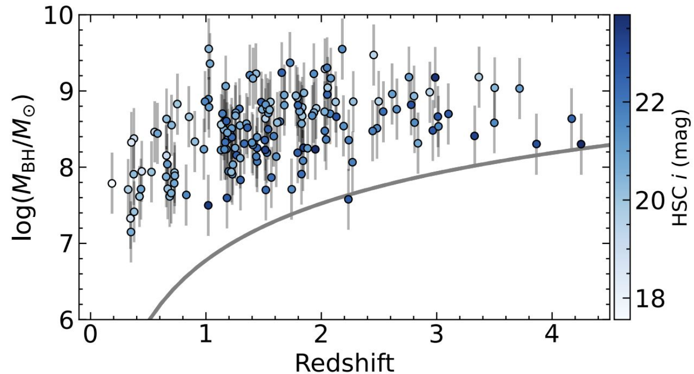


Dwarf galaxy AGN in HSC, DES, and Rubin

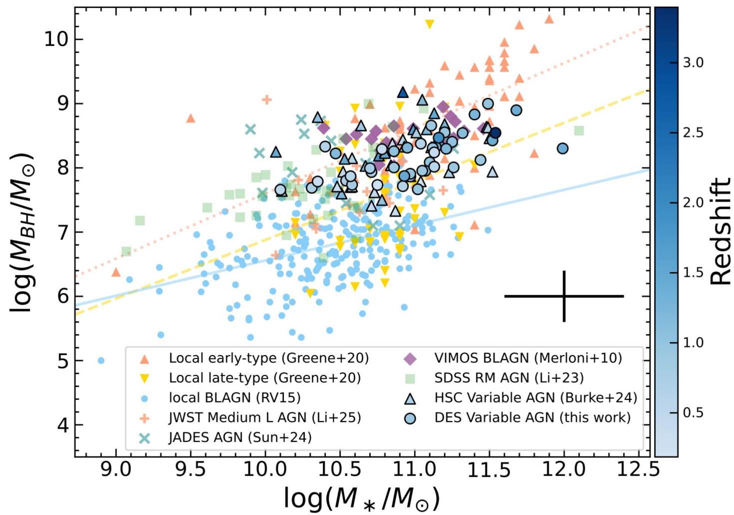




Ward et al. (2025a)



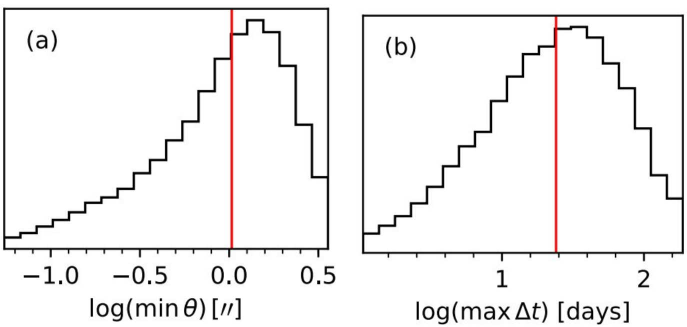
Burke *et al.* (2024)

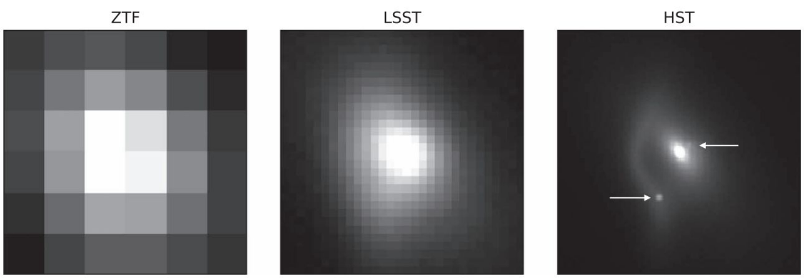


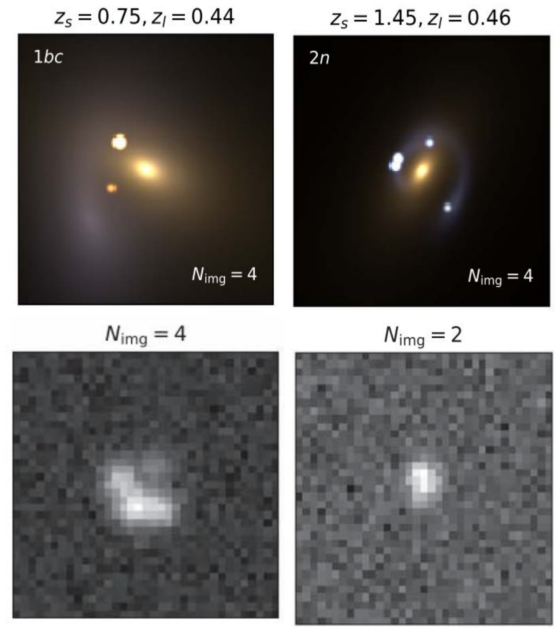
Liu *et al.* (2026)

Time delay cosmography with gravitationally lensed supernovae

- LSST is predicted to find 170 (50) gravitationally lensed SN (SNIa) per year.
- The median separation between doubly imaged gLSNe in LSST will be 0.6”.



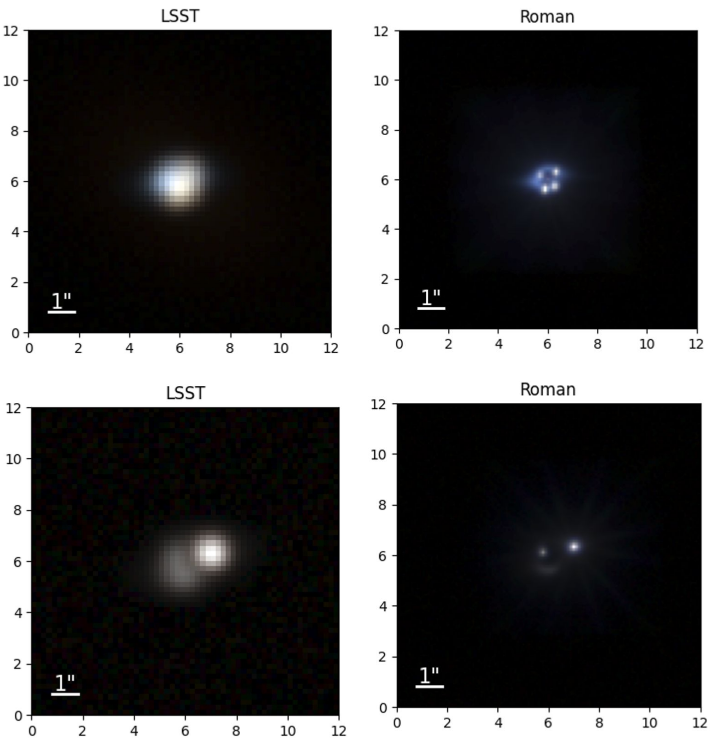




Goldstein et al. 2019

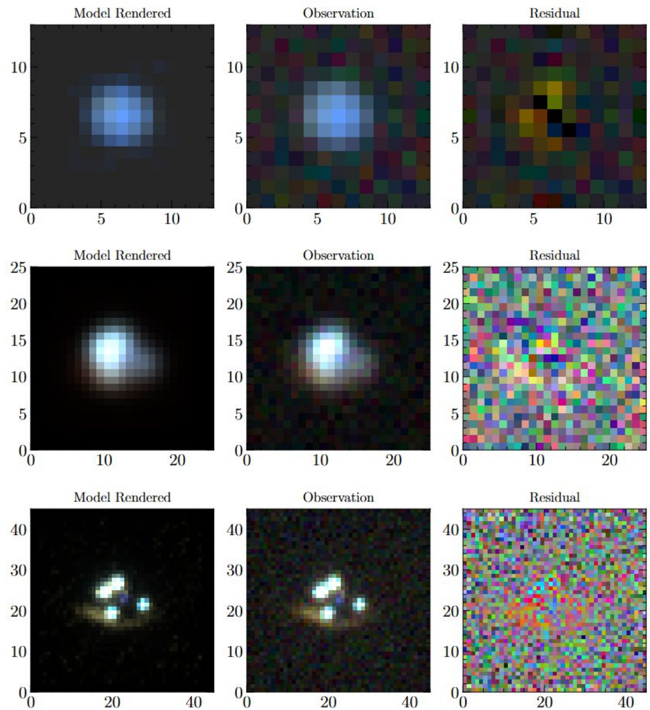
Deblending gLSNe at multiple resolutions

Pixel-level simulations of the Rubin gLSNe population



Krishnaraj & Ward (in prep)

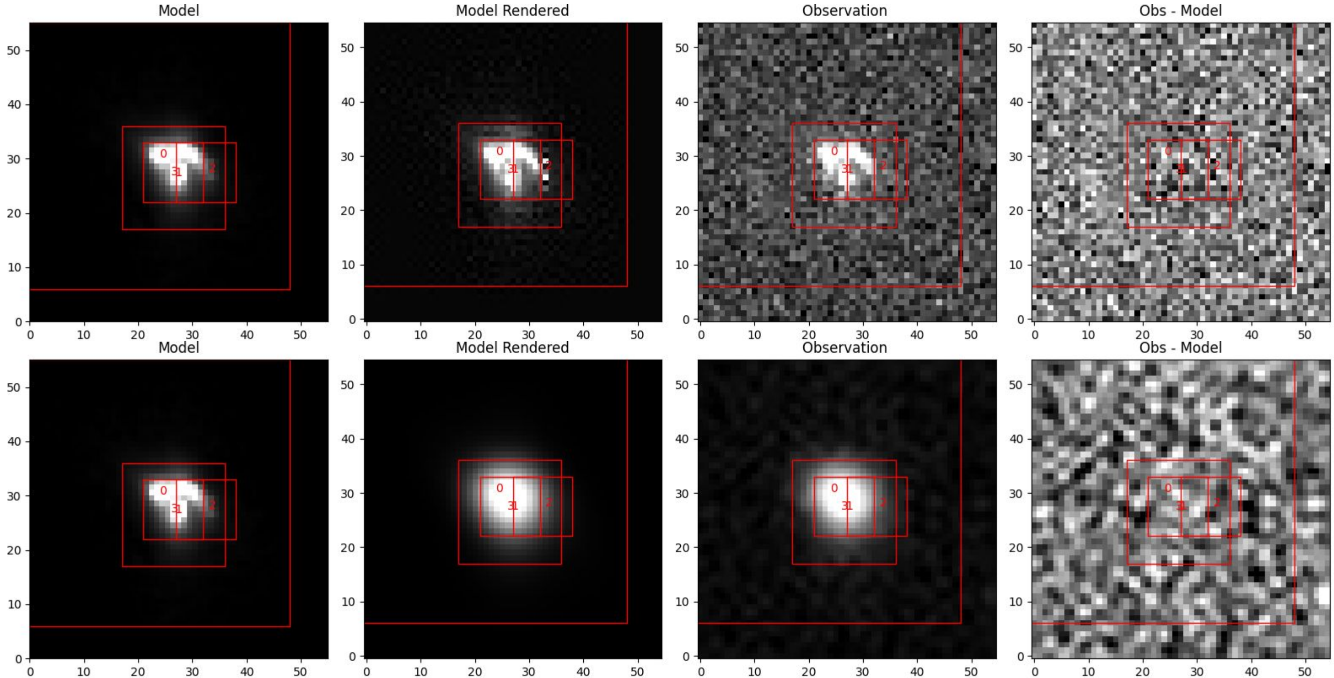
Scarlet2 extraction of lens model and light curves



Miller et al (2025)

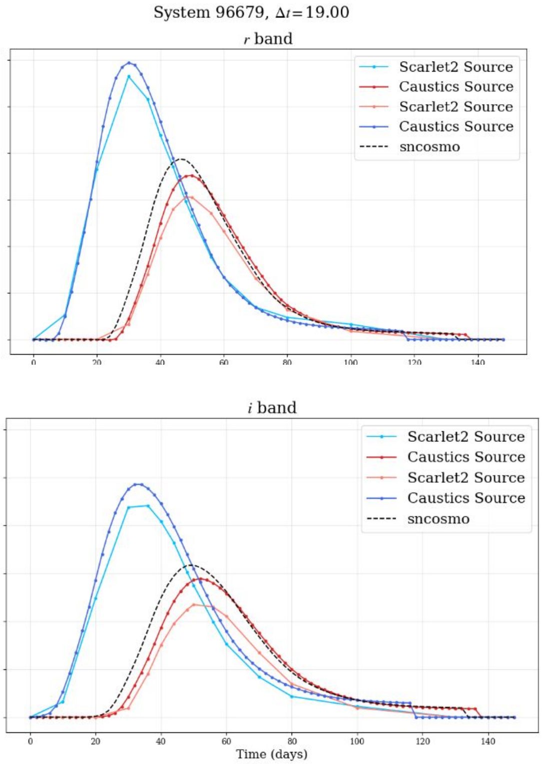
A time delay cosmography pipeline for Rubin, Euclid, and Roman

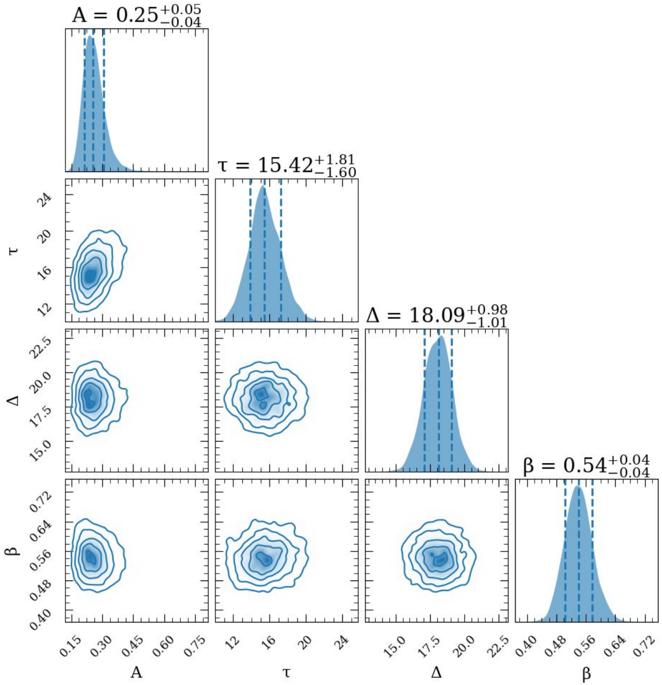
Veena Krishnaraj



Krishnaraj & Ward (in prep)

A time delay cosmography pipeline for Rubin, Euclid, and Roman

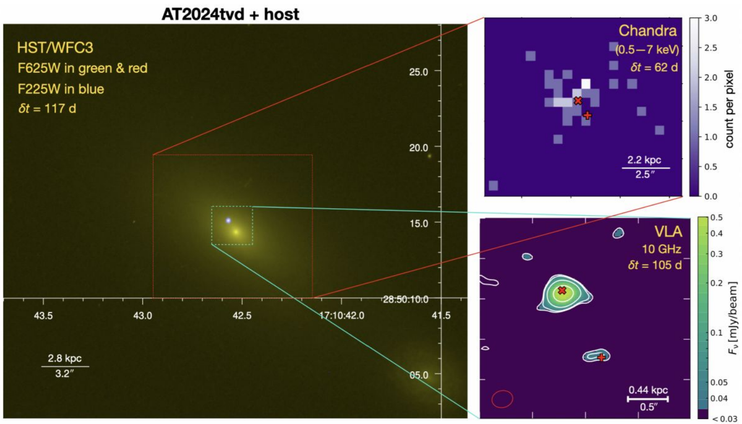


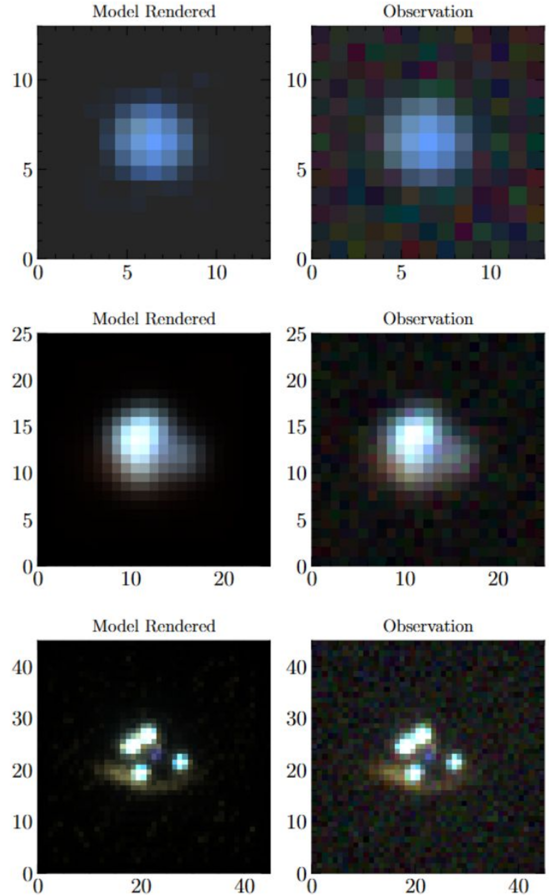


Krishnaraj & Ward (in prep)

Summary

- Multi-resolution analysis of Rubin, LS4, *Euclid* and *Roman* data will leverage the strengths of the surveys to **characterize transients and their host galaxies**.
- Scarlet2 provides a **GPU-accelerated framework for joint pixel forward modeling**, with neural network priors.
- We are using Scarlet2 to study **tidal disruption events from wandering black holes, strongly lensed supernovae,** and **variable AGN.**





Preparations for Roman

- **What have we learned from existing alert streams and Rubin alerts?**

Ability to access imaging (not just cutouts) is sometimes essential to verify alert info, especially for rare objects e.g. non-nuclear TDEs.

- **Are we ready for alerts from Roman and beyond?**

We can learn from the ZTF→ LSST transition, and will need to expect similar challenges for Roman.

- **How do we optimize transient discovery with multi-wavelength and multi-messenger alert streams?**

Scalable and automated methods for light curve analysis and accurate host associations, and access all available complementary survey data e.g. DESI.

- **How do we effectively utilize machine learning for time-domain science?**

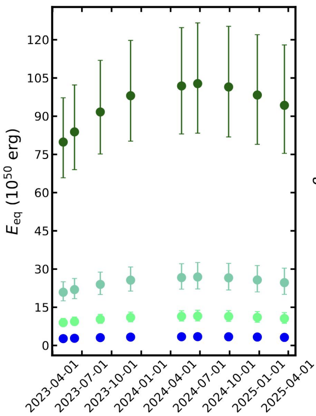
Integrate into broadly used broker infrastructure to ensure wider community tests the code and provides feedback - especially ML-based anomaly detection.

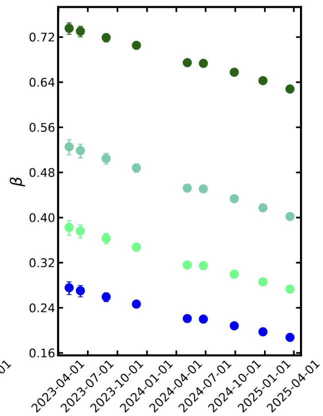
- **What physics of stellar explosions/eruptions/variability can be revealed with rapid, multi-wavelength/messenger observations?**

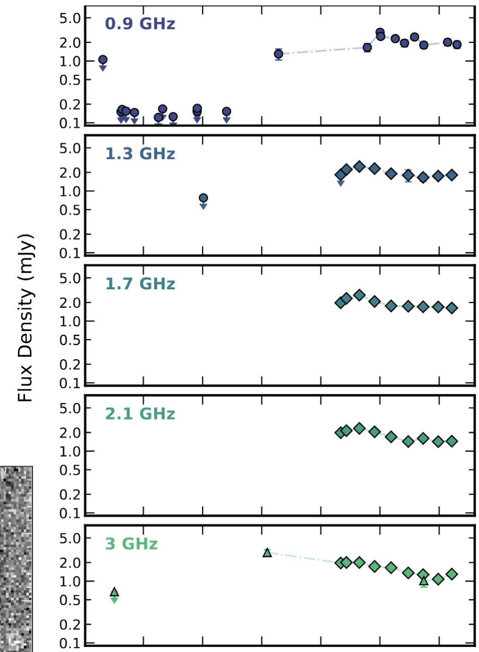
Accretion disk physics instabilities in changing-look AGN, partial tidal disruption events, SNIa progenitors.

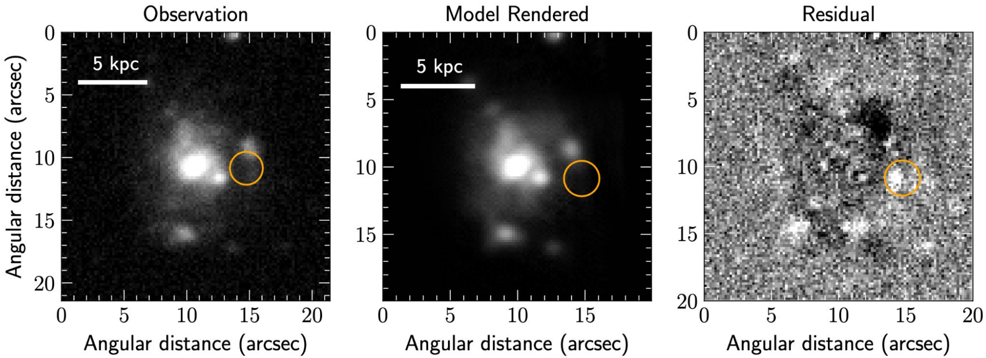
Backup slides

Probing the environment of an IMBH TDE candidate identified via a delayed radio jet





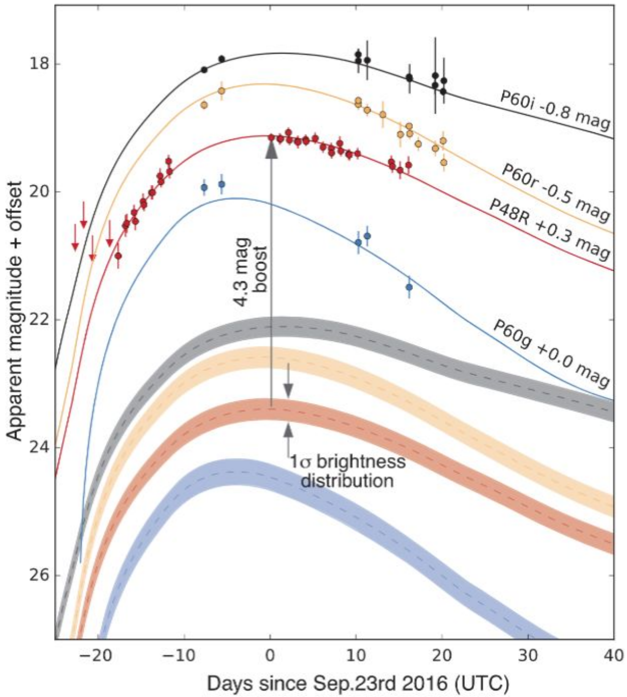


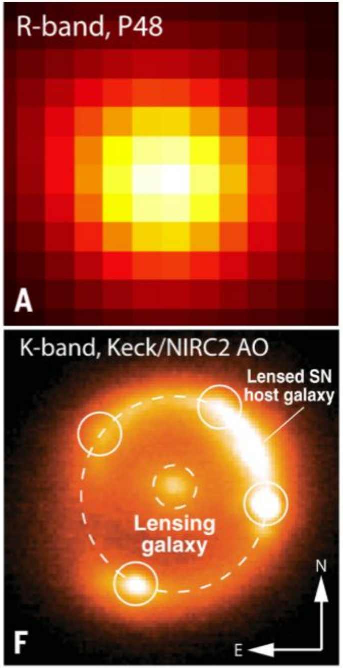


Gulanti et al. (2026)

Gravitationally lensed supernovae

- Time delays from strongly lensed SNe enable measurement of H_0 at intermediate redshifts.
- One in 10^4 galaxies are strongly lensed, and ~10 strongly lensed SNe have been found so far, most of which were lensed by clusters.

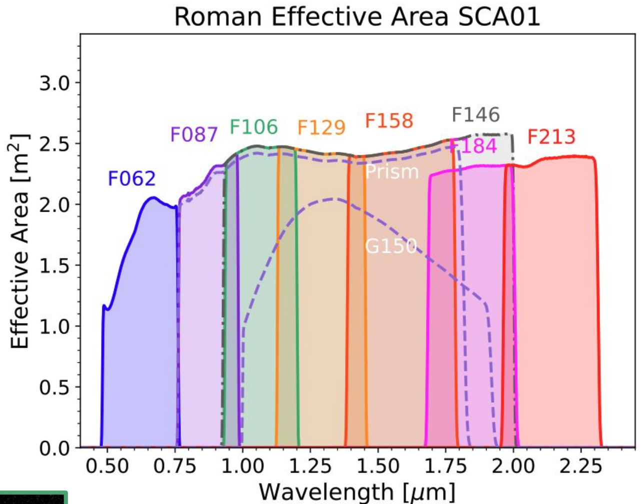


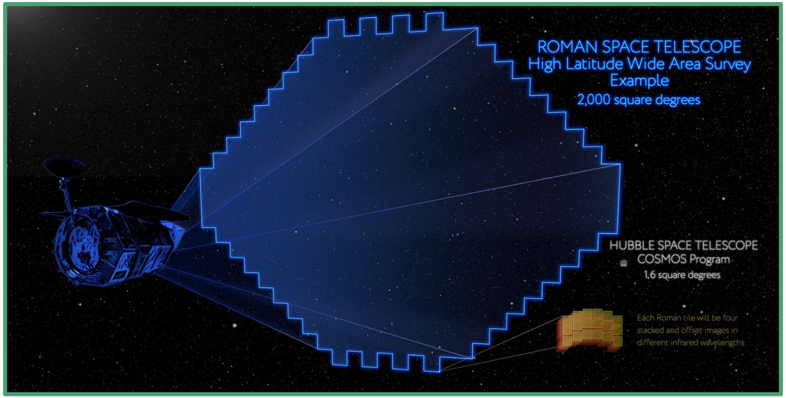


Goobar et al. 2017

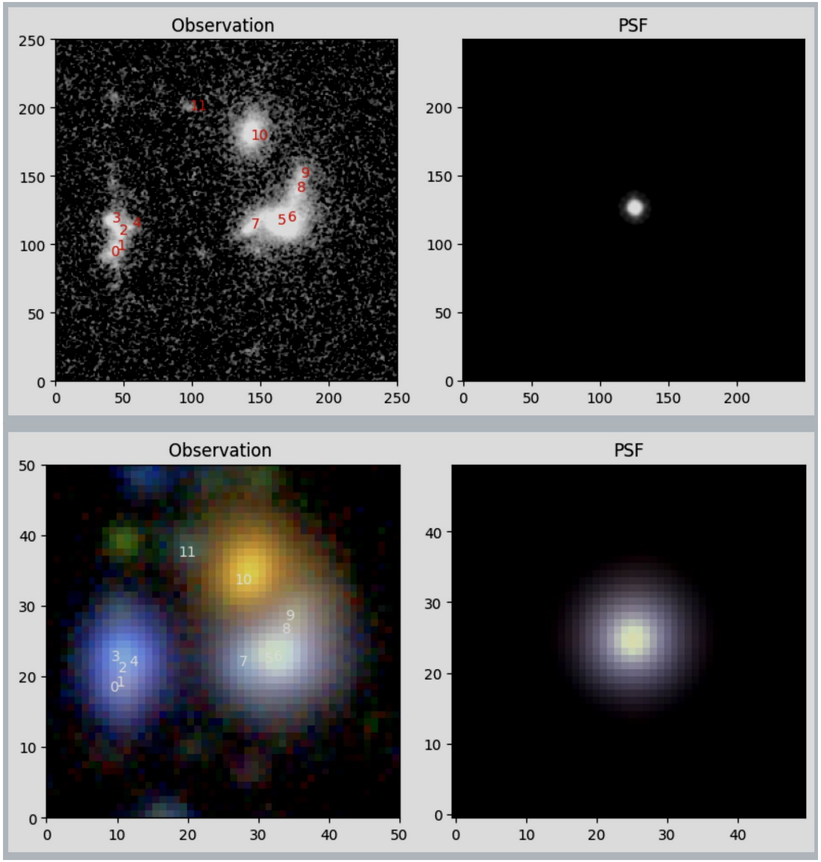
The *Roman Space Telescope* (2027-2032)

- Launching mid-2027.
- Near-infrared imaging and spectroscopy: 0.48–2.3 μm.
- High Latitude Wide Area Survey: 2000 deg^2, depth J ~ 26.7
- High Latitude Time-Domain Survey: 5 day cadence of 5 deg^2 over 2 years, depths of J ~ 27-29.





Validating input observations

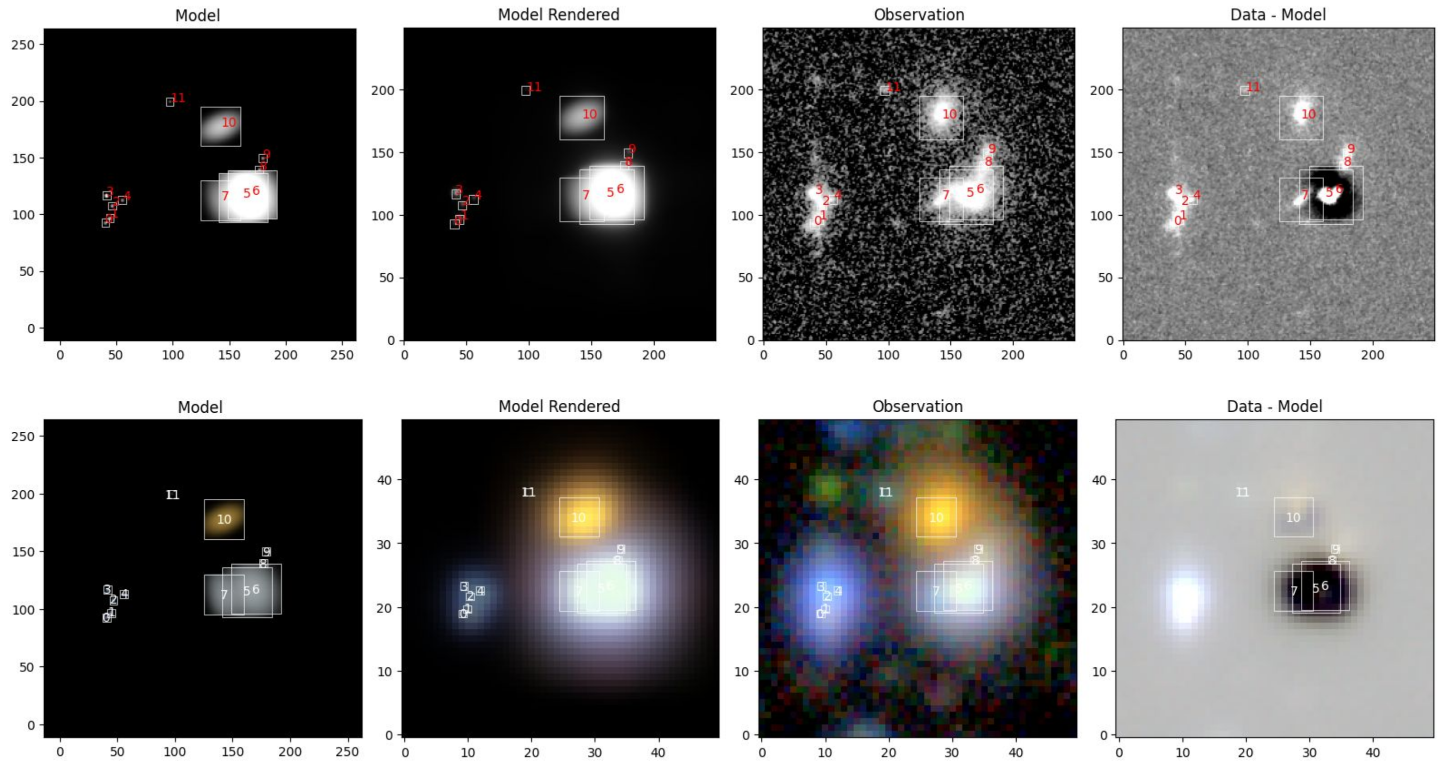


Validating input observations

```
obs = Observation(
    data,
    weights,
    psf=ArrayPSF(psf),
    channels=channels,
)
model_frame = Frame.from_observations(obs)
```

```
Observation validation results:
[000]   INFO   Weights in the observation are non-negative. | Check=ObservationValidator
[001]   INFO   Weights in the observation are finite. | Check=ObservationValidator
[002]   INFO   Data and weights have the same shape. | Check=ObservationValidator
[003]   INFO   Number of channels in the observation matches the data. | Check=ObservationValidato
[004]   INFO   Data in the observation is finite where weights are greater than zero. | Check=Obse
[005]   INFO   PSF is 3-dimensional. | Check=ObservationValidator
[006]   INFO   Number of PSF channels matches the number of data channels. | Check=ObservationVali
[007]  ERROR   PSF centroid is not the same in all channels. | Check=ObservationValidator | Contex
         [ 0.09050751,  0.01180839, -0.03284836,  0.08526038, -0.00099373]],
        dtype=float32)})
```

Validating fit initializations



Validating fit initializations

```
Source validation results:
[000]   INFO   Source model has positive contributions. | Check=SourceValidator
Source validation results:
[000]   INFO   Source model has positive contributions. | Check=SourceValidator
Source validation results:
[000]   INFO   Source model has positive contributions. | Check=SourceValidator
Source validation results:
[000]   INFO   Source model has positive contributions. | Check=SourceValidator
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[000]   INFO   Source model has positive contributions. | Check=SourceValidator
Source validation results:
[000]   INFO   Source model has positive contributions. | Check=SourceValidator
Source validation results:
[000]   INFO   Source model has positive contributions. | Check=SourceValidator
```
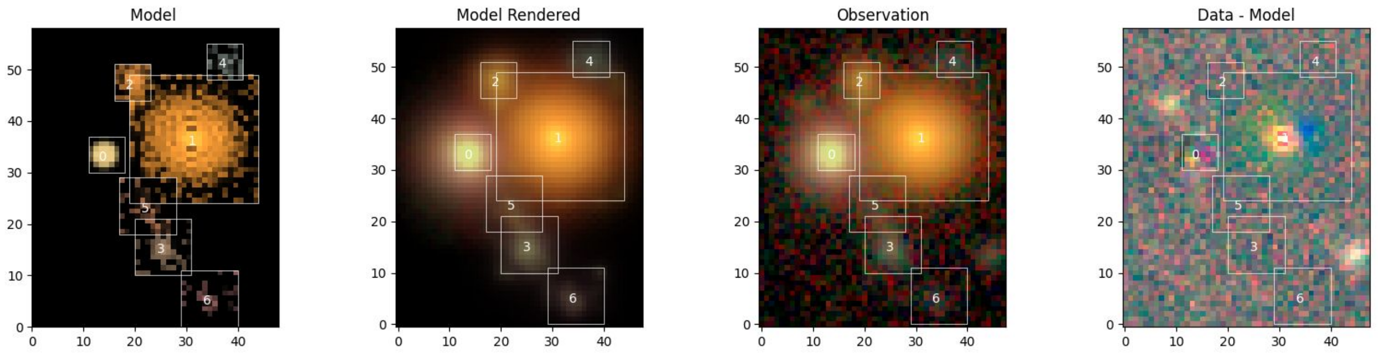
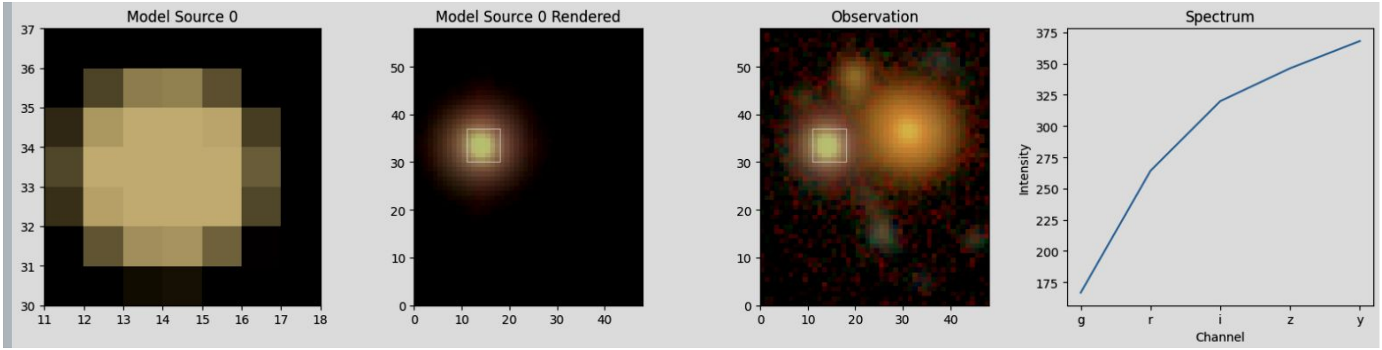

Validating fit quality



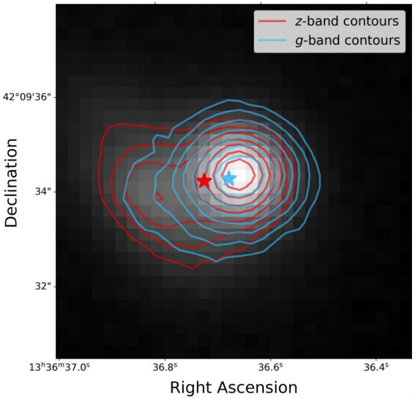


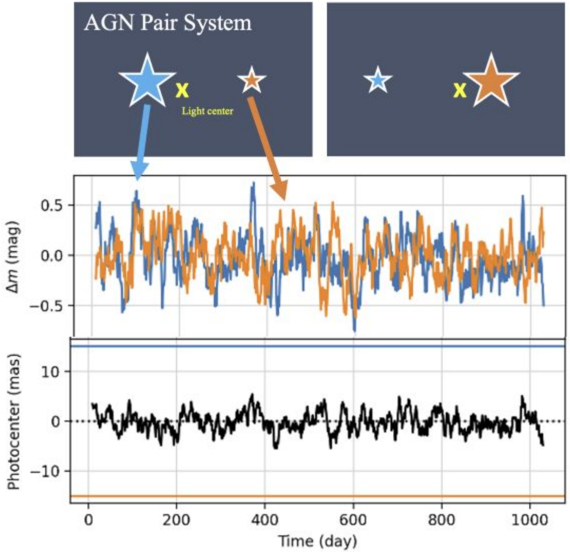
Validating fit quality

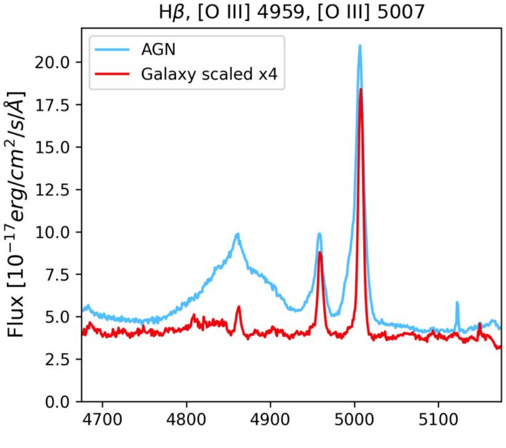
```
Fit validation results:
[000]  INFO   The model fit is good. | Check=FitValidator
[001]  WARN   The chi-square in the box for source 0 is acceptable, but not optimal. | Che
[002]  INFO   The chi-square in the border for source 0 is good. | Check=FitValidator | Co
[003]  WARN   The chi-square in the box for source 1 is acceptable, but not optimal. | Che
[004]  INFO   The chi-square in the border for source 1 is good. | Check=FitValidator | Co
[005]  INFO   The chi-square in the box for source 2 is good. | Check=FitValidator | Conte
[006]  INFO   The chi-square in the border for source 2 is good. | Check=FitValidator | Co
[007]  INFO   The chi-square in the box for source 3 is good. | Check=FitValidator | Conte
[008]  INFO   The chi-square in the border for source 3 is good. | Check=FitValidator | Co
[009]  INFO   The chi-square in the box for source 4 is good. | Check=FitValidator | Conte
[010]  INFO   The chi-square in the border for source 4 is good. | Check=FitValidator | Co
[011]  INFO   The chi-square in the box for source 5 is good. | Check=FitValidator | Conte
[012]  INFO   The chi-square in the border for source 5 is good. | Check=FitValidator | Co
[013]  INFO   The chi-square in the box for source 6 is good. | Check=FitValidator | Conte
[014]  INFO   The chi-square in the border for source 6 is good. | Check=FitValidator | Co
```

Detecting spatially offset AGN: astrometric jitter

- PanSTARRS time domain imaging used to search for offset AGN via 'astrometric jitter'.
- 5 new offset AGN found, with Keck spectroscopy confirming a new dual AGN at 6.7 kpc separations.



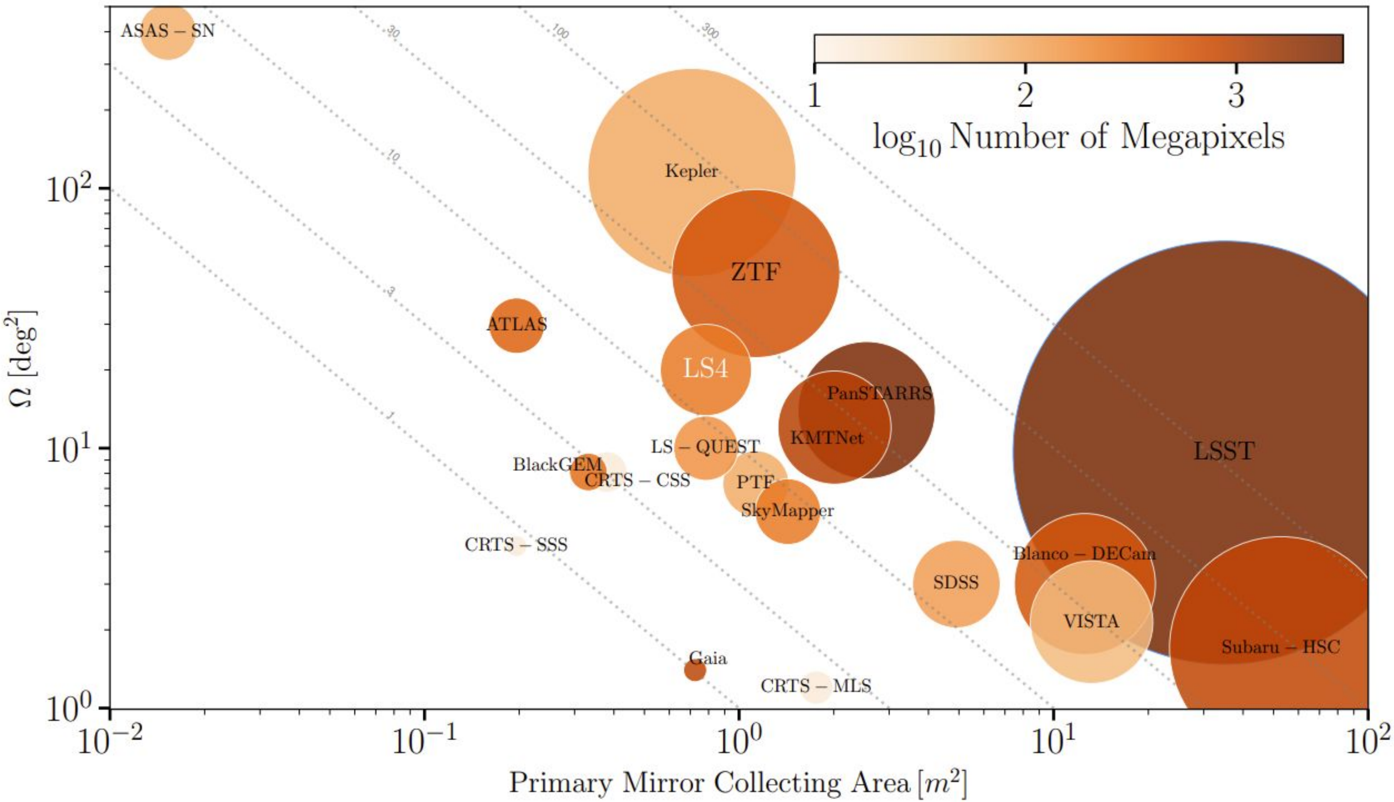




Schwartzman et al. (2024)

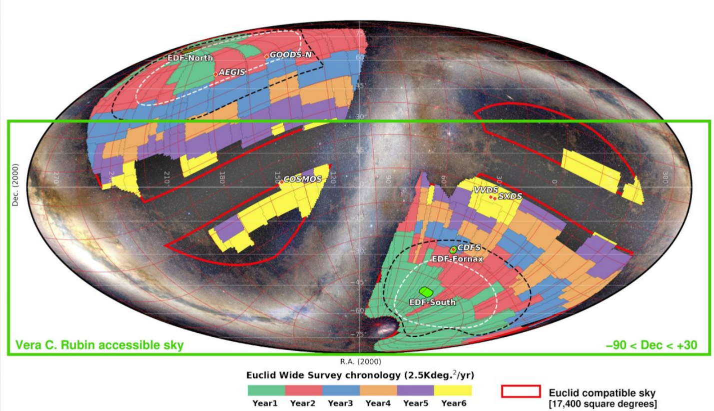
Uppal, Ward et al. (2024)

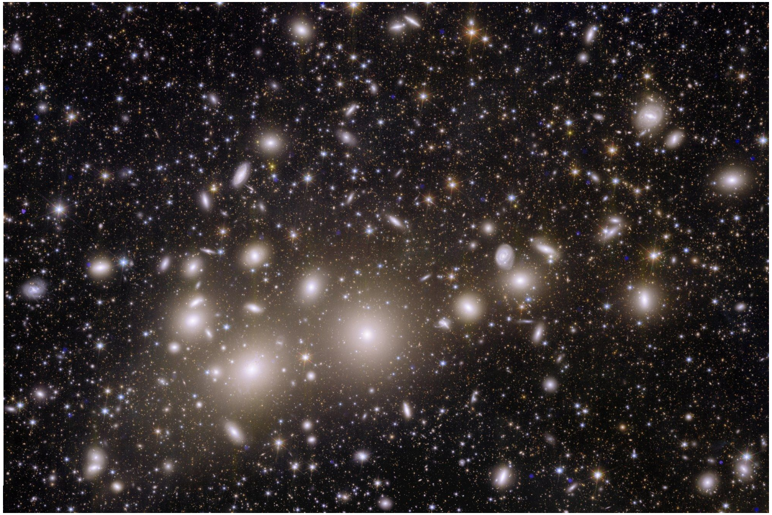
The time-domain survey landscape

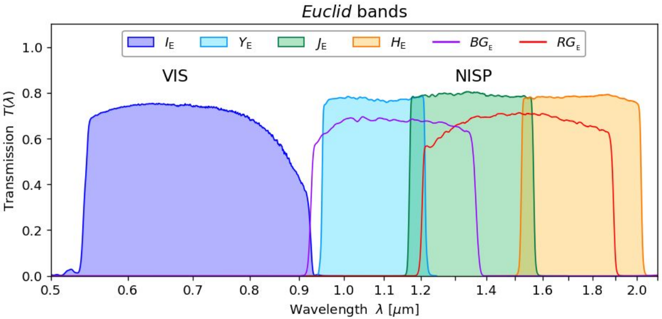


Euclid (2025-2030)

- Wide survey covering 15,000 deg^2 and deep survey of 50 deg^2.
- VIS instrument with 0.18” resolution.
- NISP covers ~950 and 2020nm in 3 bands at 0.3” resolution.
- Depths of ~24.3 in wide survey

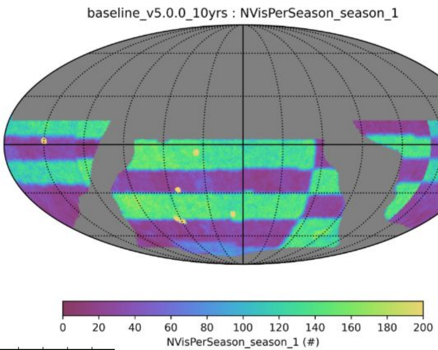


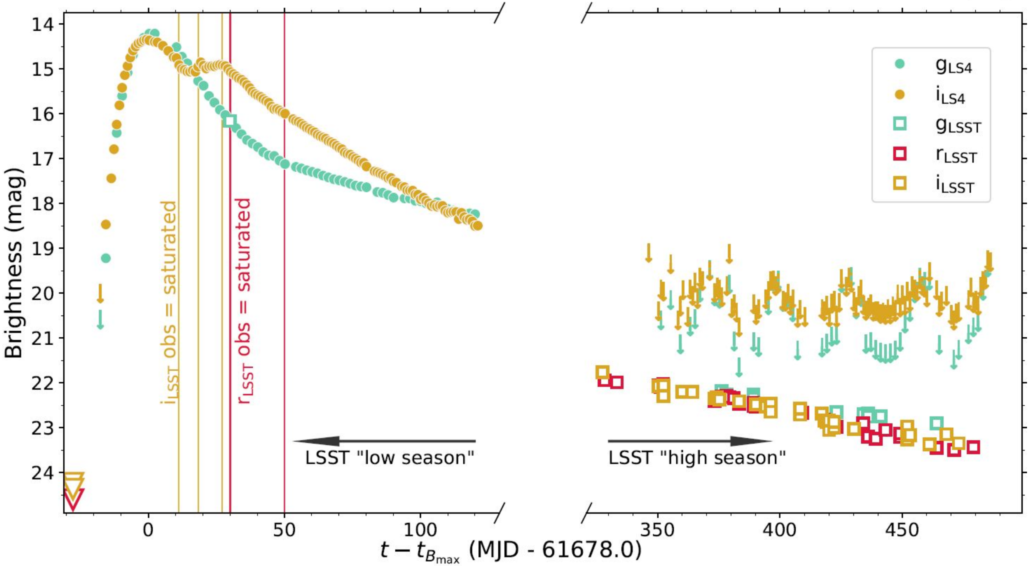




The La Silla Schmidt Southern Survey (LS4)

- Single exposure depths of ~21 mag in g, i and z.
- 1.0” pixel scale.
- Shadows Rubin to observe transients evolve across 10 orders of magnitude in flux, filling in the gap where Rubin saturates.





Joint analysis for **cosmology**

- **Large scale structure** analysis with Rubin *requires* **accurate photometric redshifts** .
- **Dark matter** studies with microlensing *rely on* **accurate galaxy morphologies**

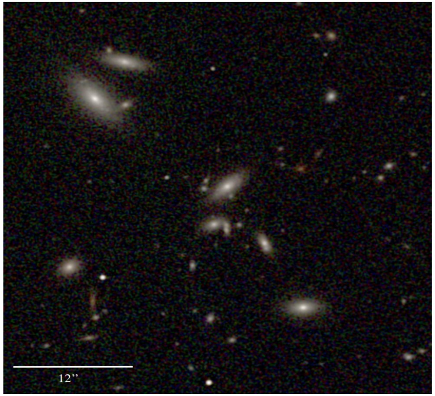
Rubin Observatory/NSF/AURA/J. Pinto

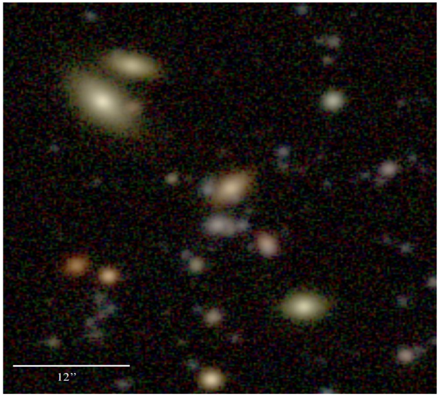
The Euclid-Rubin Derived Data Products (DDPs)

Cross-Cutting (CC)

DDP-1-CC	B	P1+U1+YR	T1	Multi-band Rubin+Euclid photometry list-driven catalogs
DDP-2-CC	B	P1+U2+DR	T2	Multi-band Rubin+Euclid forced photometry catalog from joint-pixel processing
DDP-3-CC	B	P2+U2+DR	T3	Multi-band Rubin+Euclid deblended photometry catalog from joint-pixel processing

- General Proposed Trends as DDP-1 -> DDP-2 ->: DDP-3
  - Increase in accuracy and decrease in impact of contamination/confusion
  - Increase in complexity and need for resources (FTEs, computing)
  - Increase in delivery time to community
  - Potential decrease in proprietary restrictions

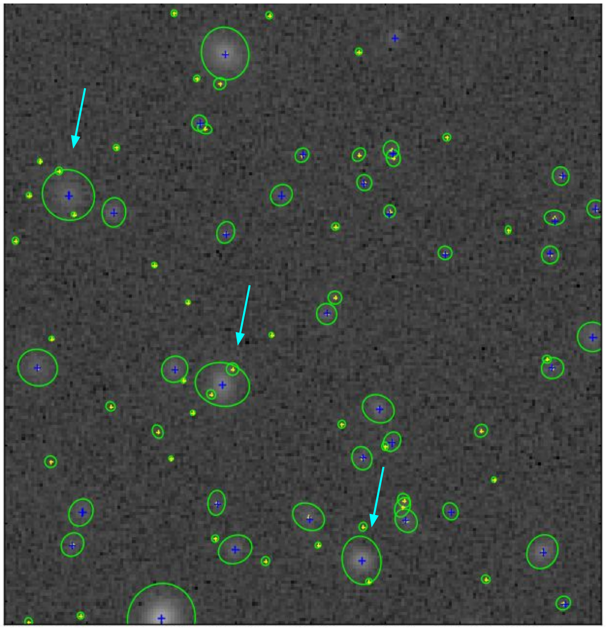


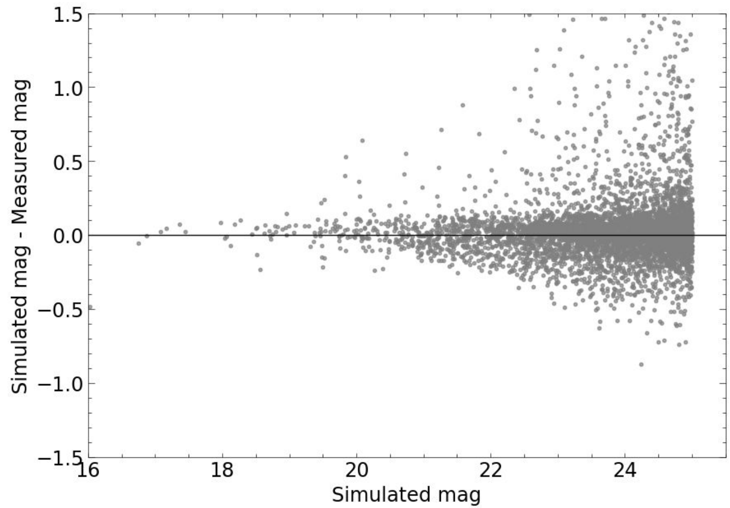


OpenUniverse simulations (2025)

Rubin photometry with the *Euclid* catalog

Using *Euclid* positions and shapes





Position detected by Euclid

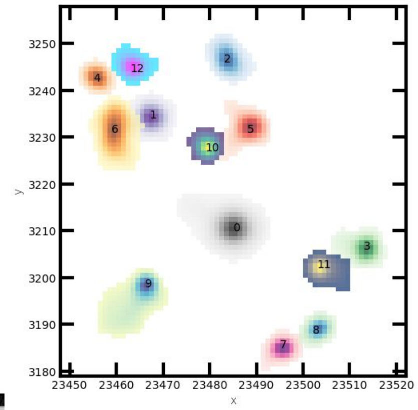
Position detected by Rubin and Euclid

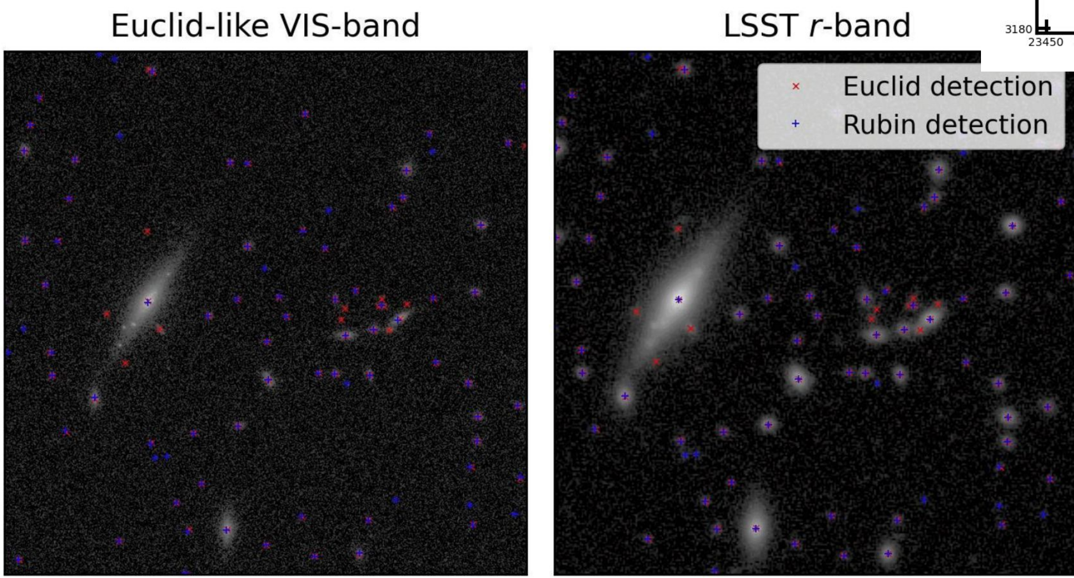
Rubin PSF aperture shape (left)

Euclid - derived aperture shape (right)

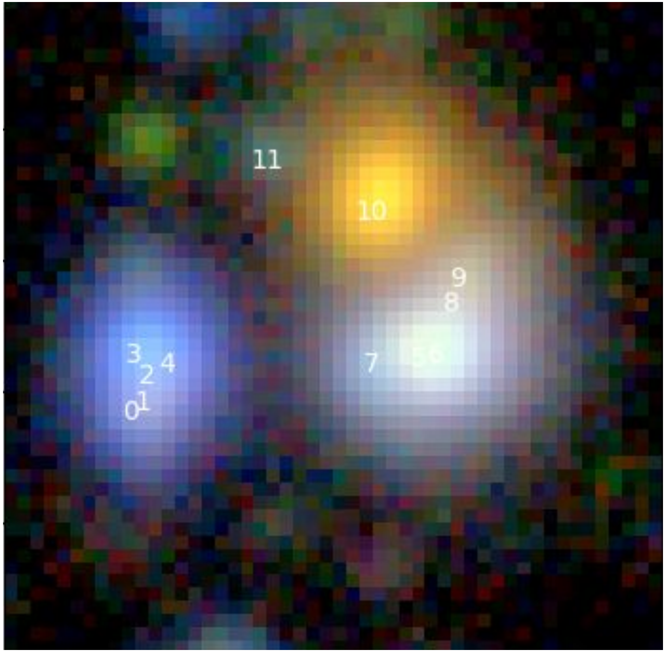
DDP2: deblending with combined source catalogs

- **Rubin is deeper than** ***Euclid***, but ***Euclid*** **is higher resolution**, so some sources will only be detected by Rubin and some will only be detected by *Euclid.*
- We can **merge the detection catalogs** and rerun the LSST deblender.

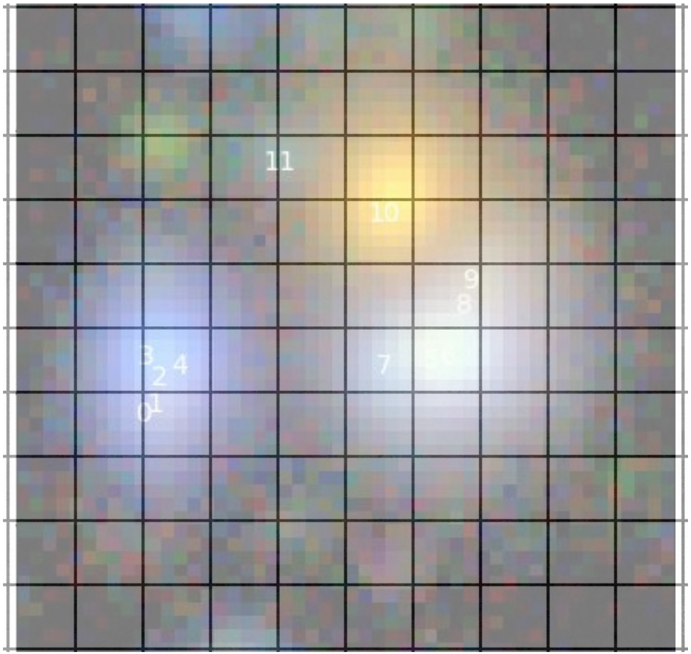




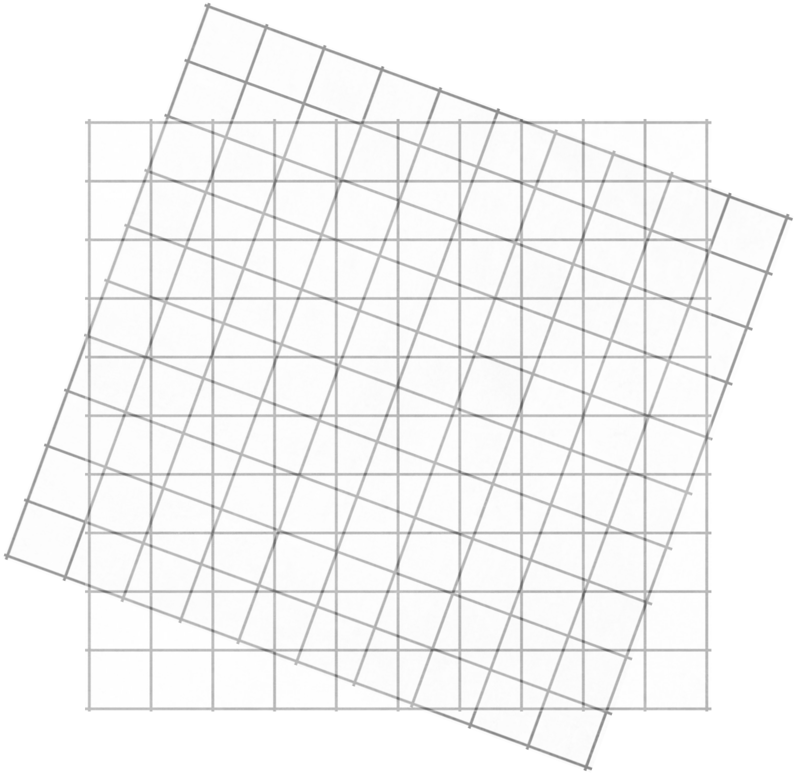
Joint pixel processing: Why is this not trivial?



Joint pixel processing: Why is this not trivial?



Joint pixel processing: Why is this not trivial?



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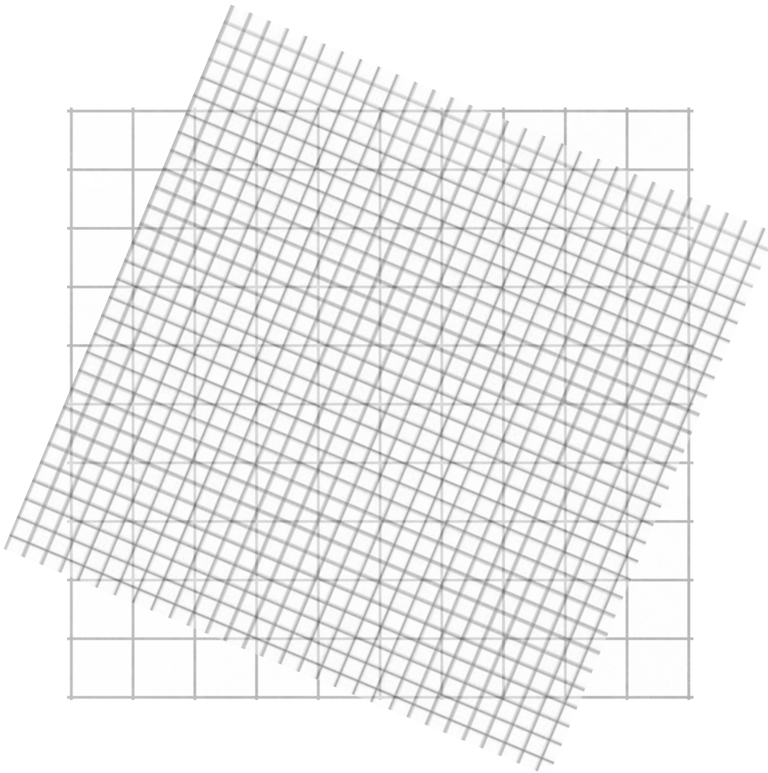
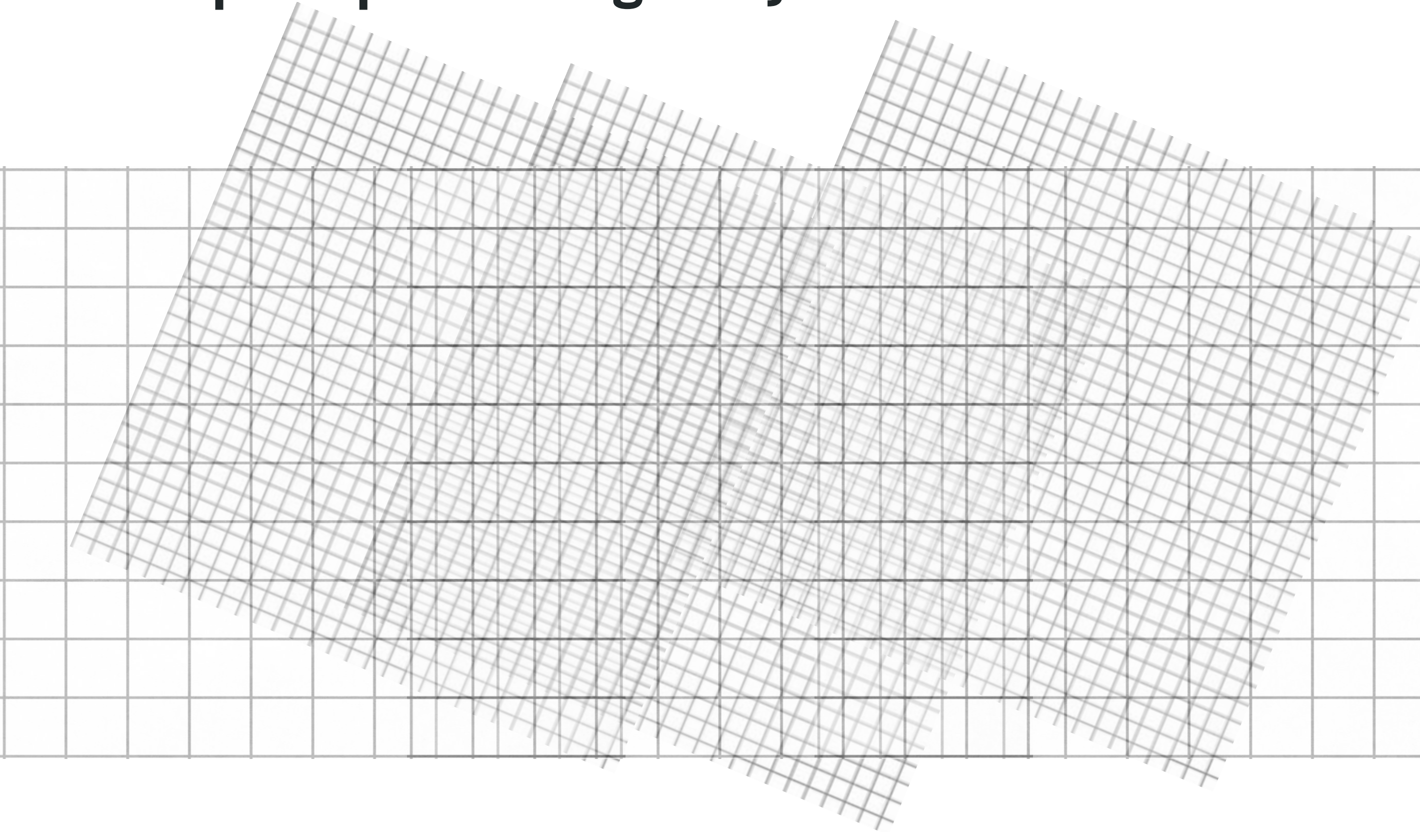
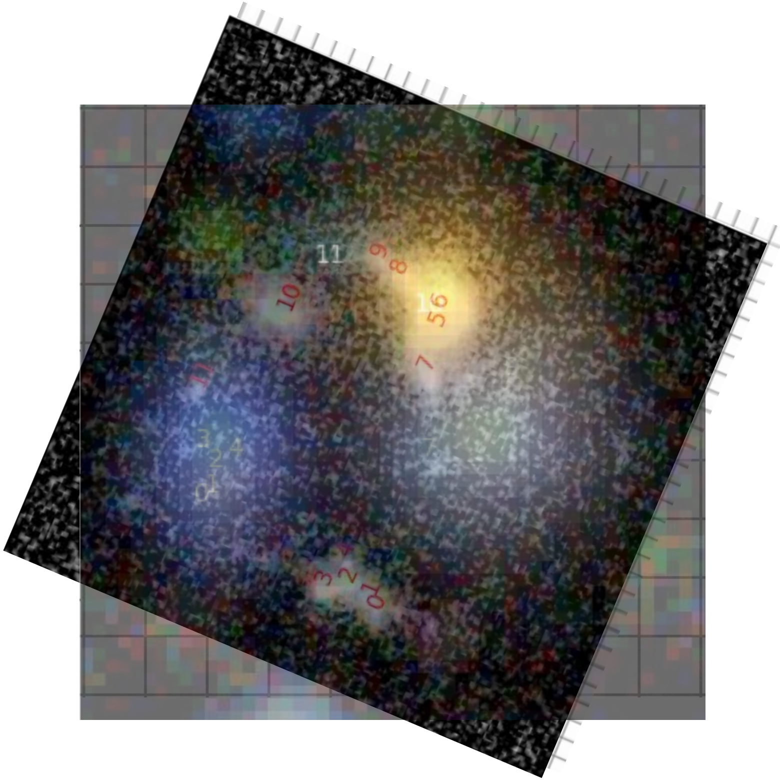
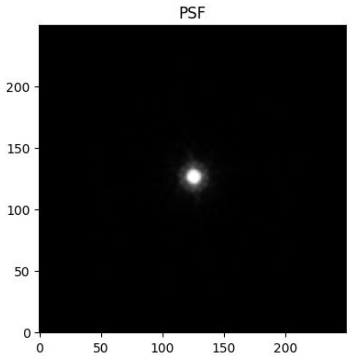


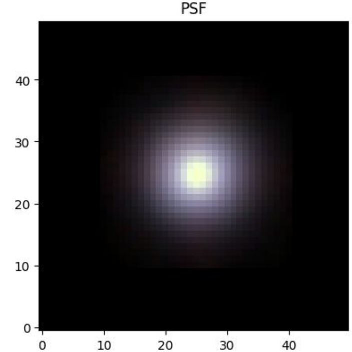
Joint pixel processing: Why is this not trivial?



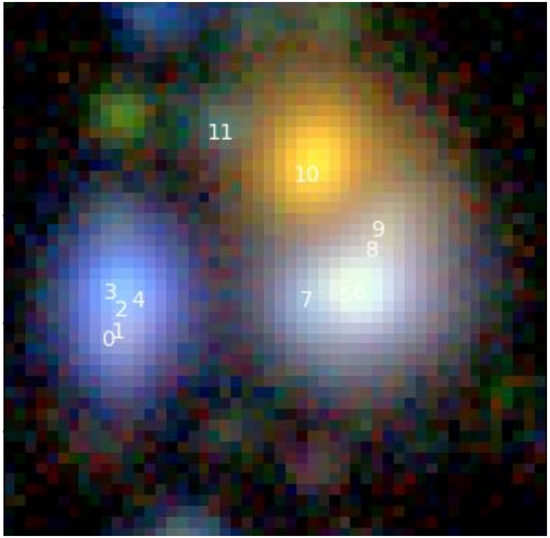
Joint pixel processing: Why is this not trivial?

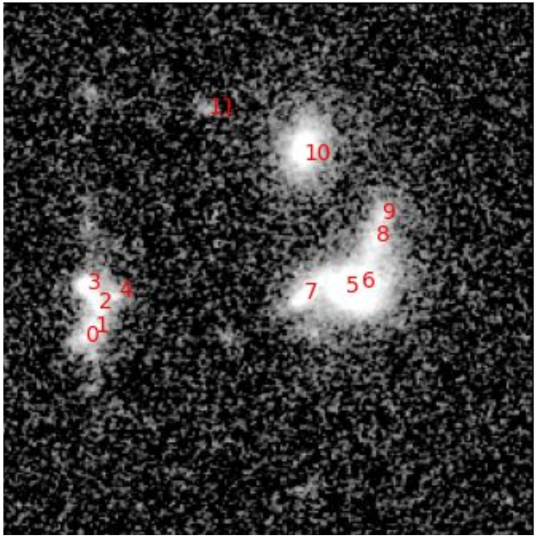




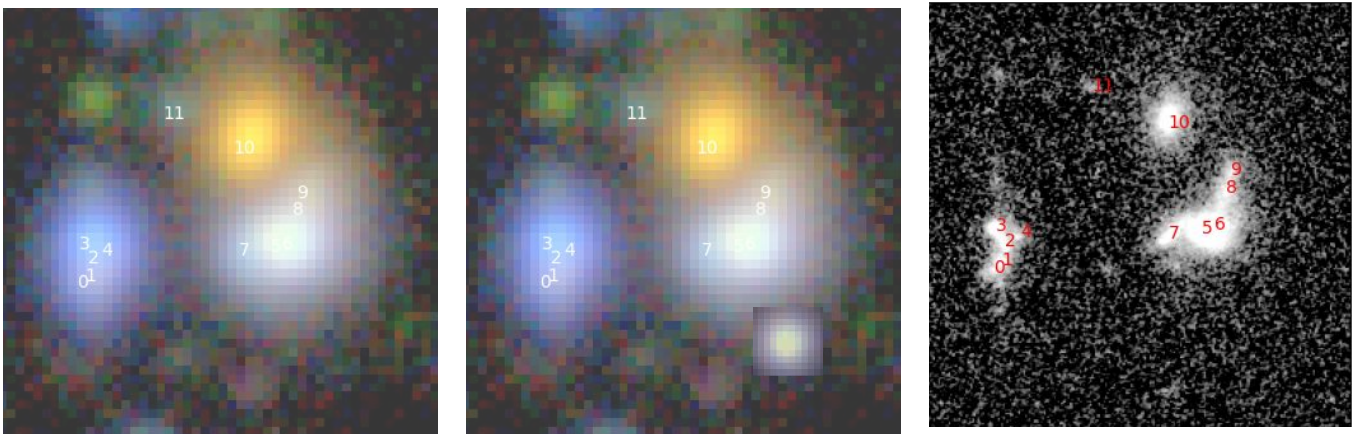


Joint pixel processing: Why is this not trivial?





Joint pixel processing: Why is this not trivial?



The Tractor: The first multi-resolution deblender run at scale

the Tractor

astronomical source detection, separation, and photometry
now with an inferential basis!

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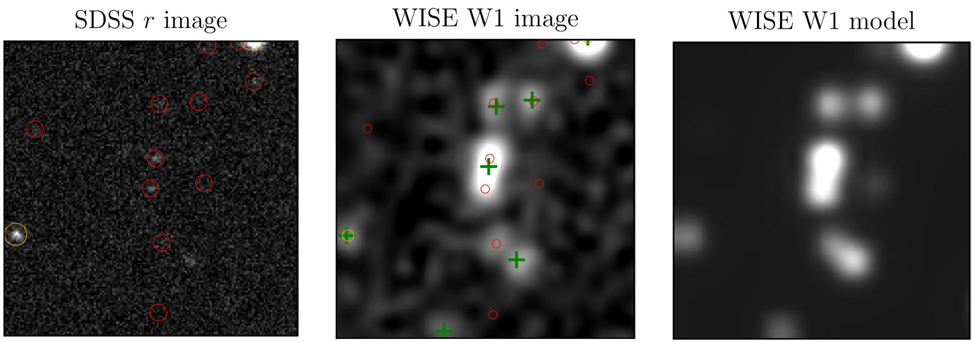
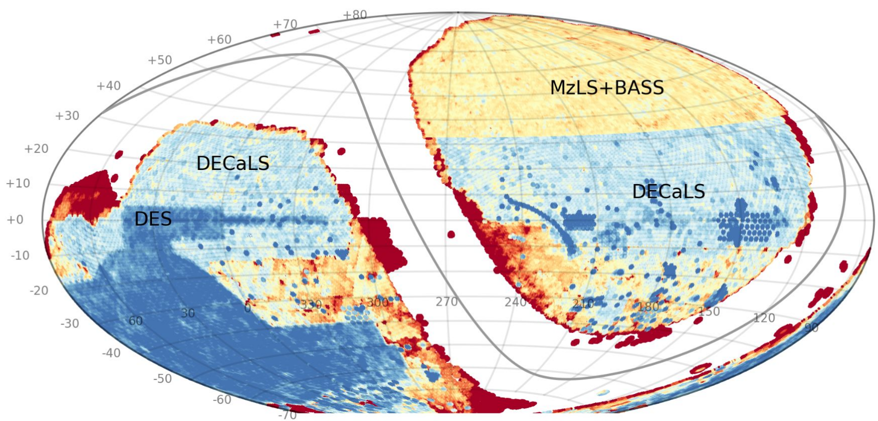
"It took one hell of a long time, but I felt so probabilistically righteous."
— J. J. User

The DESI imaging surveys

- Tractor modeled the DECaLS, BASS, MzLS and WISE surveys to create galaxy photometry catalogs for DESI target selection.



Lang, Hogg and Schlegel (2016)



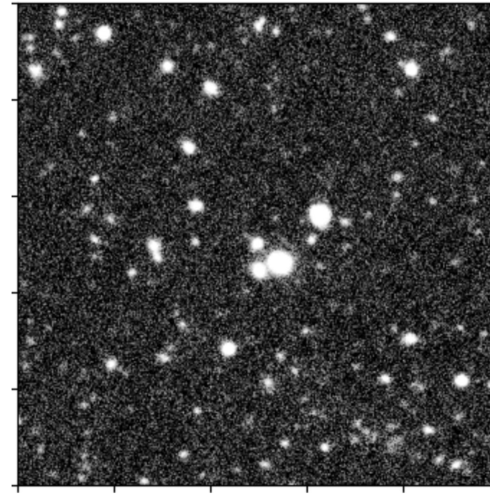
Plans for *Euclid*/Rubin joint analysis

Near term:

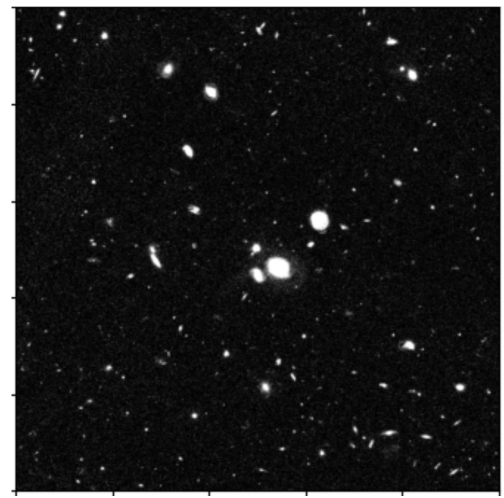
- Example jupyter notebooks for the Rubin Science Platform.
- Science papers demonstrating applications to supernovae and variable AGN host galaxies.

Longer-term:

- Coadd-based joint galaxy catalogs.
- Single-exposure based transient/variable catalogs.



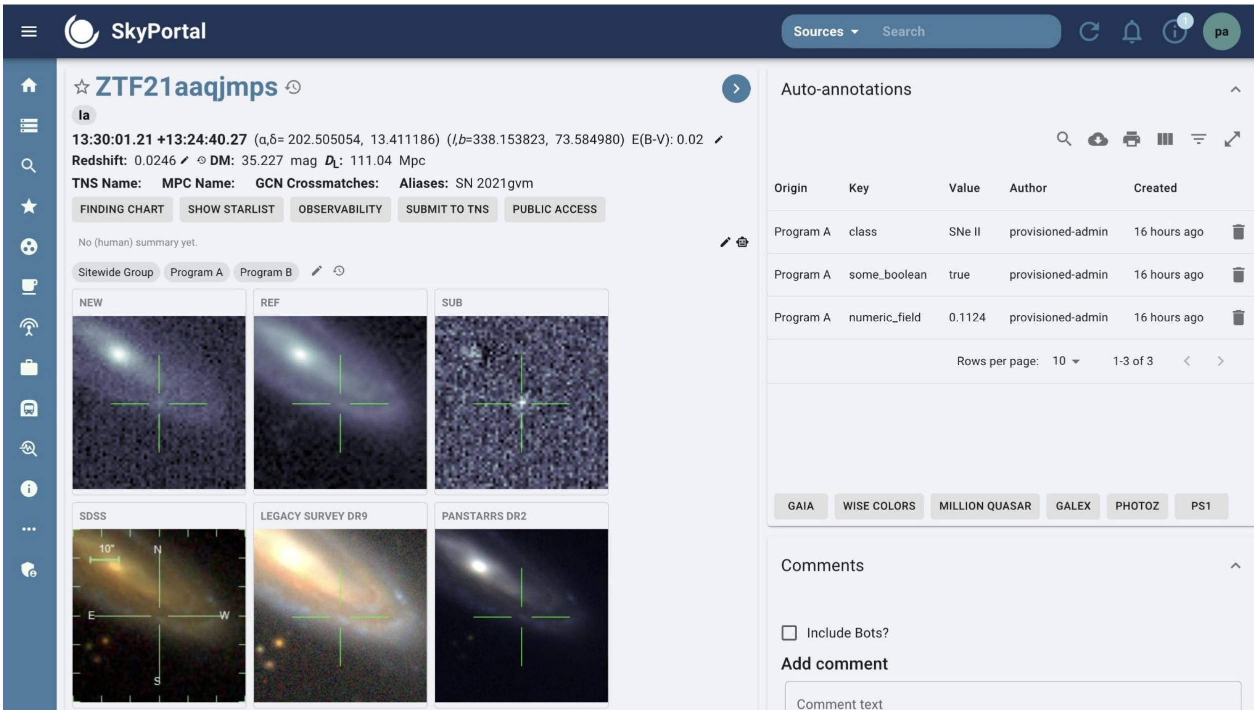
Rubin z-band



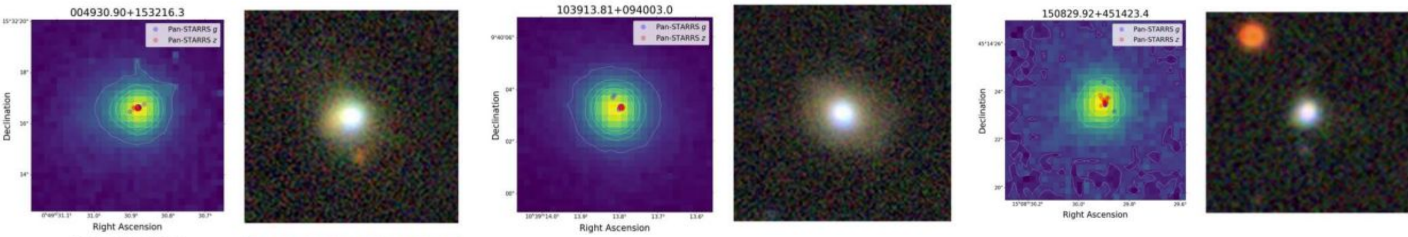
Euclid VIS

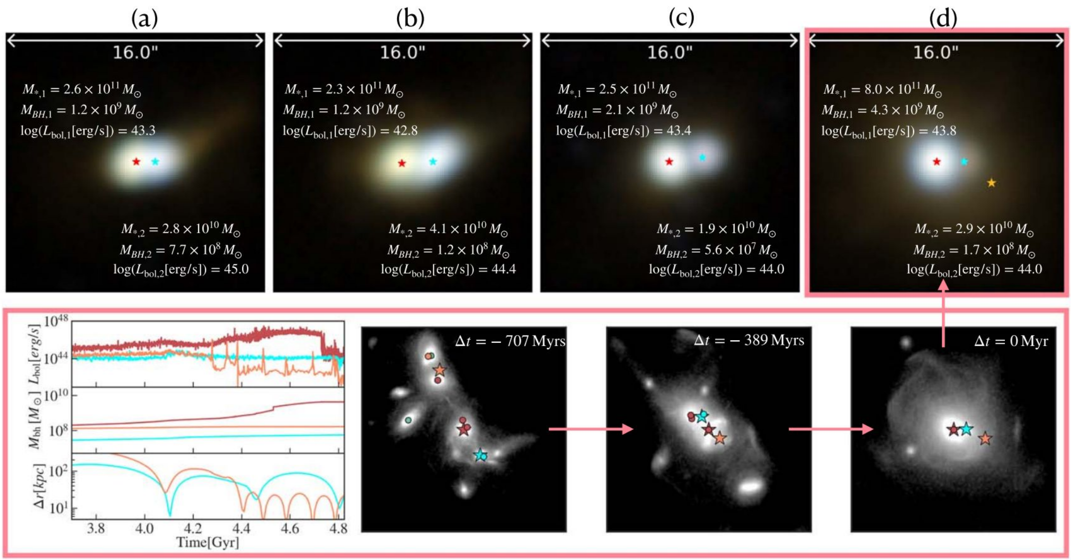
Plans for the LS4 time-domain survey

- Joint LS4/Rubin/Euclid transient light curves, host galaxy models, and spatial offsets when requested on **SkyPortal** .



Wandering AGN candidates from PanSTARRS





Uppal, Ward et al. (2024)

Wandering AGN in Rubin/Euclid

- We predict **200-1000 non-nuclear AGN** detectable as **variable to Rubin** and with **resolvable host-galaxy offsets in Euclid** .

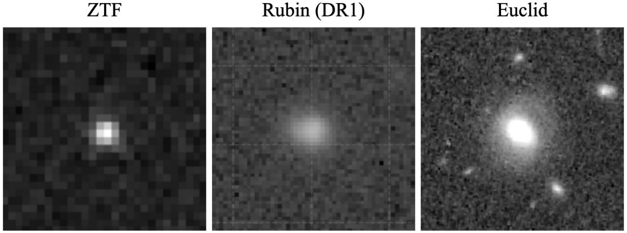
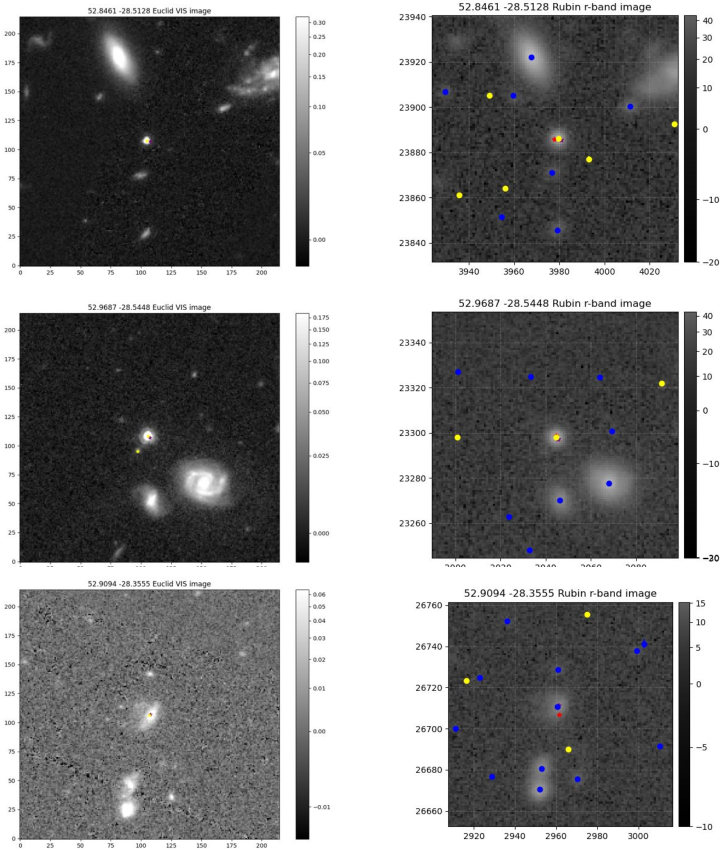


Figure 1: Comparison of ZTF, Rubin, and Euclid images of the variable-AGN-hosting galaxy ZTF20acmafsg



Sippy, Ward et al. (in prep)