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für Astrophysik

Microlensing and Cadence Strategies on Lensed Type Ia Supernovae

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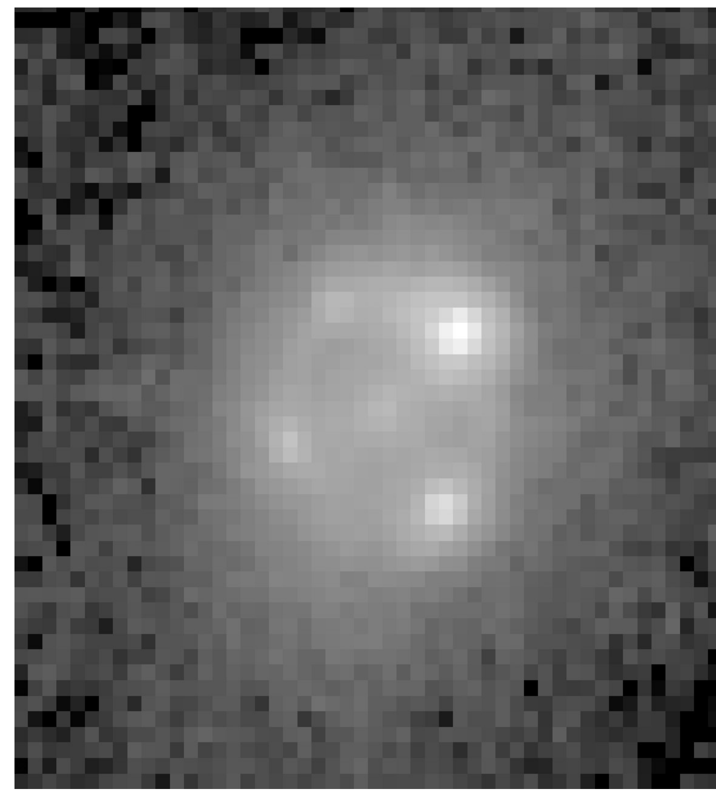
Max Planck Institute for Astrophysics

/ Technical University Munich

Master student working with Sherry Suyu and

Ulrich Nöbauer

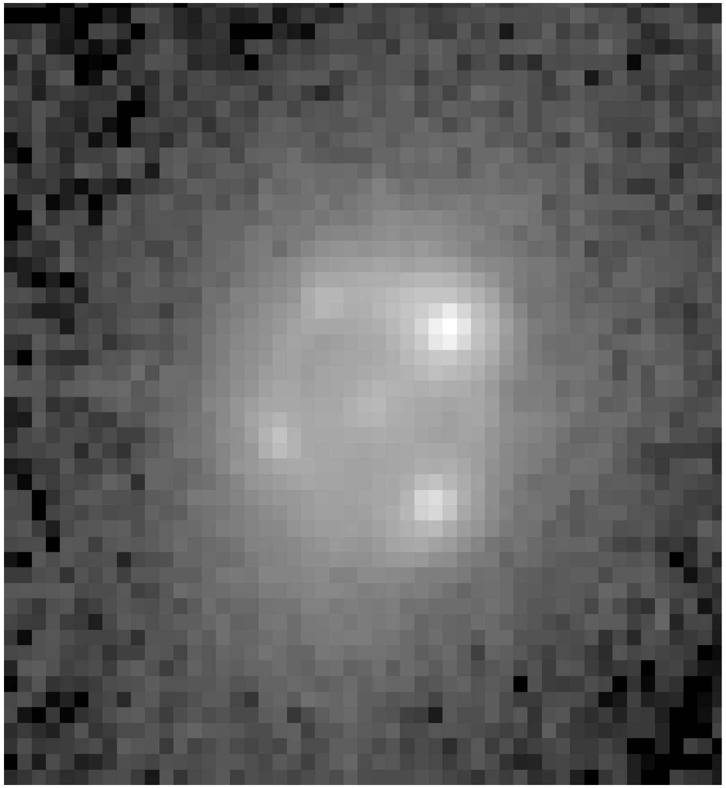
Lyon, June 2018



More, Suyu et al.

Overview

- Strongly Lensed SNe Ia
- Microlensing and Time Delay Measurement
- Cadence and Time Delay Measurement
- Conclusion and Outlook



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Strongly Lensed SN Ia

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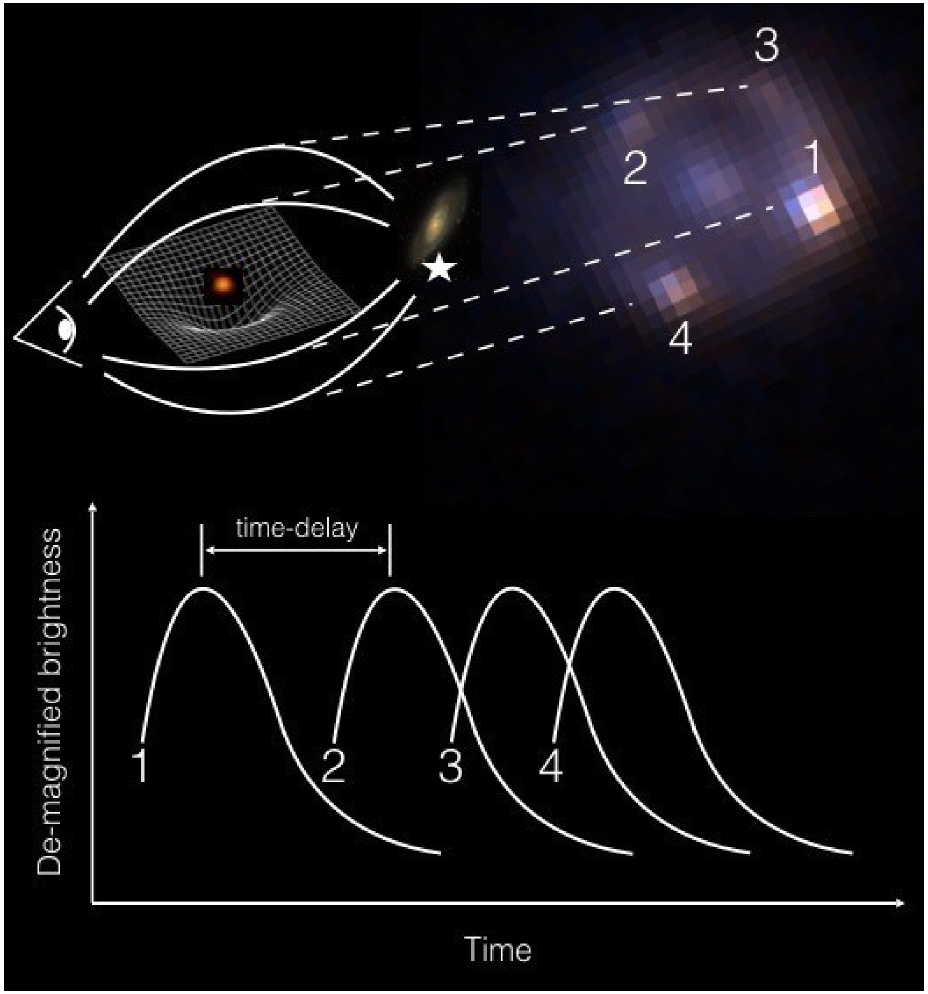
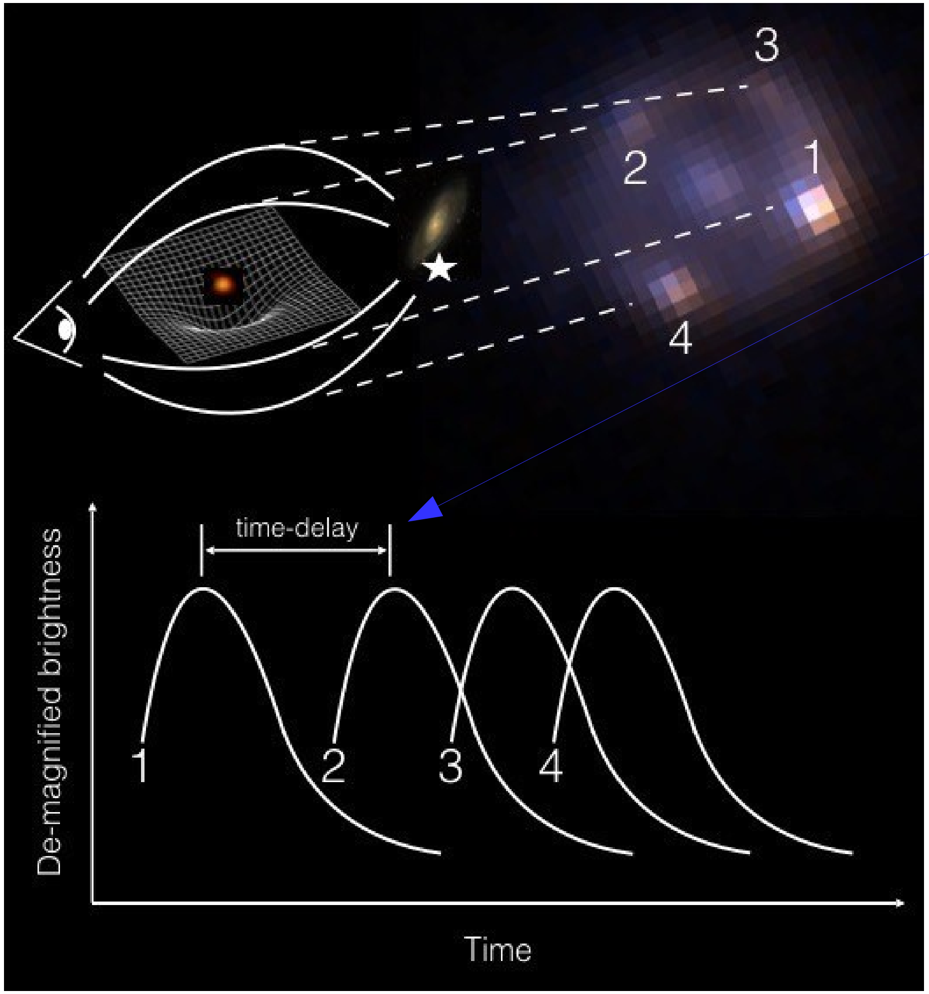


Illustration: Chien-Hsiu Lee/Subaru Telescope

Strongly Lensed SN Ia



Measure Hubble constant

Refsdal 1964

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Time Delay Measurement with LSST

- Expect about 100 SLSNe Ia with LSST (Oguri and Marshall 2010, Goldstein 2017)
  → How many of those for measuring time delays?

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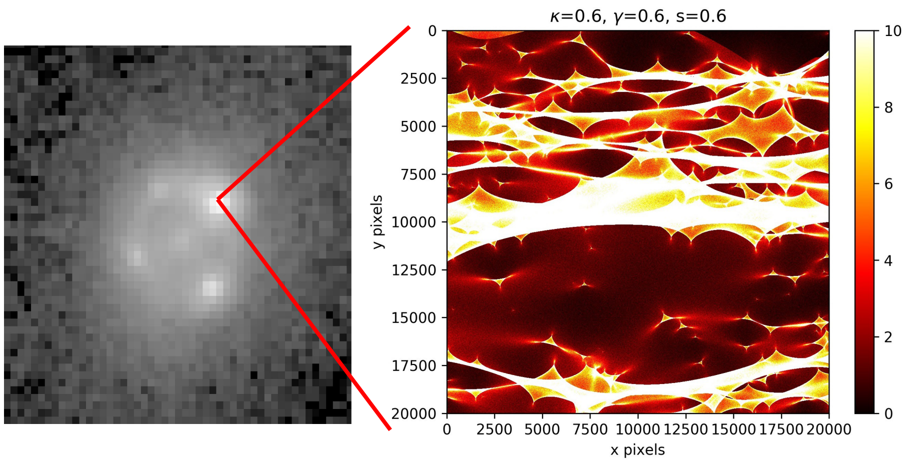
Microlensing by stars



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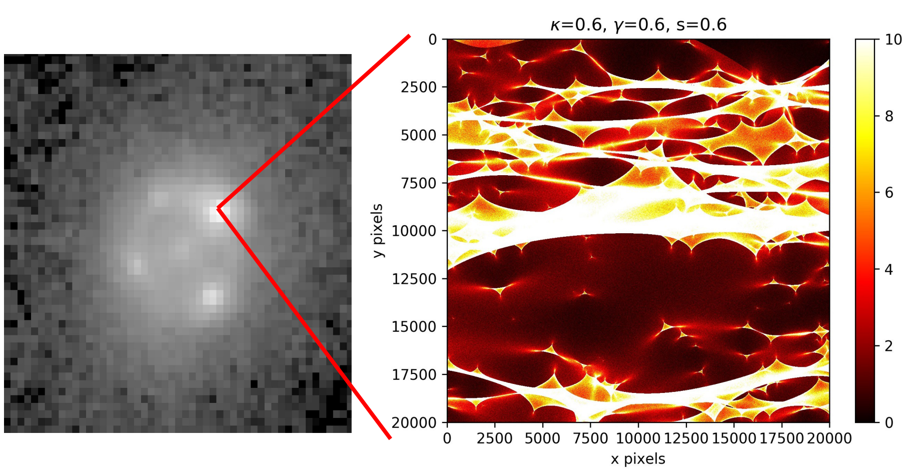
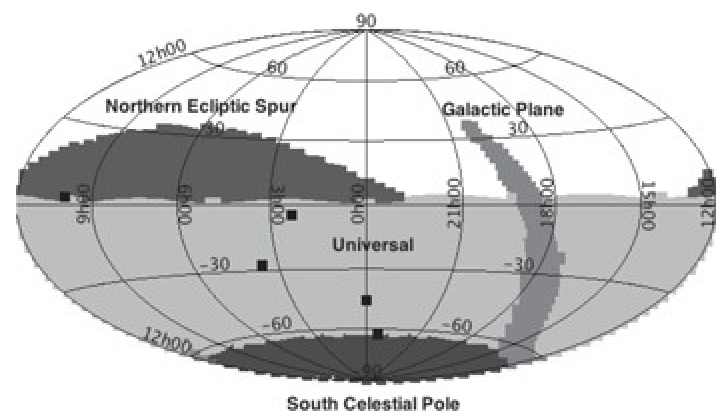
Microlensing by stars

Cadence





Microlensing and Time Delay Measurement

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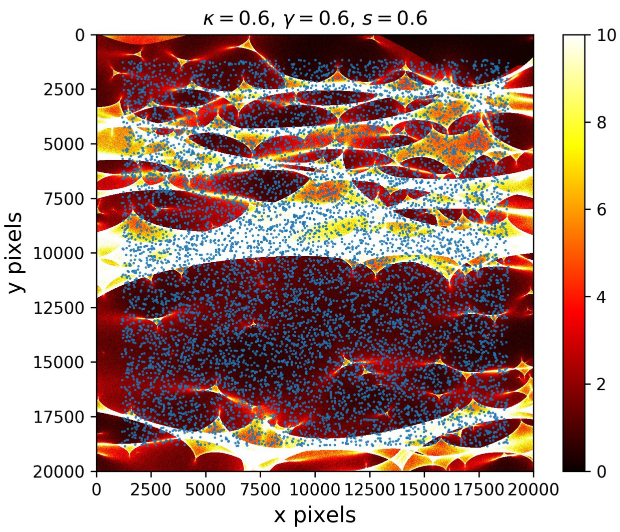

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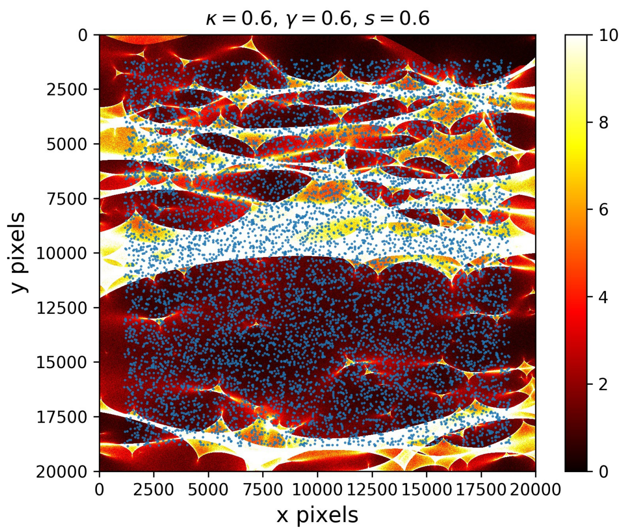

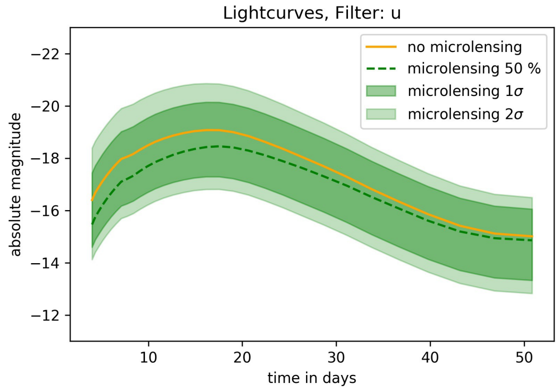

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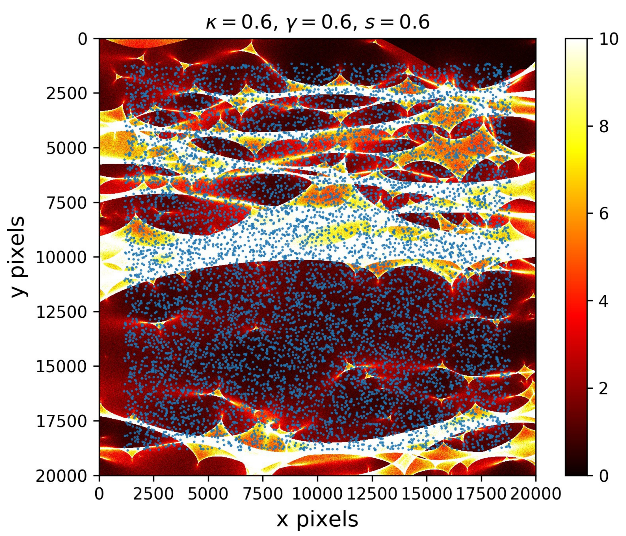

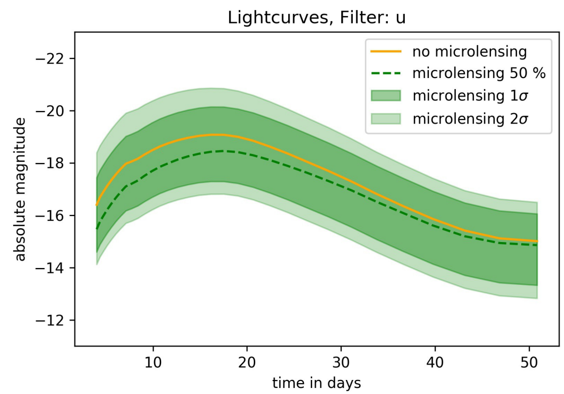

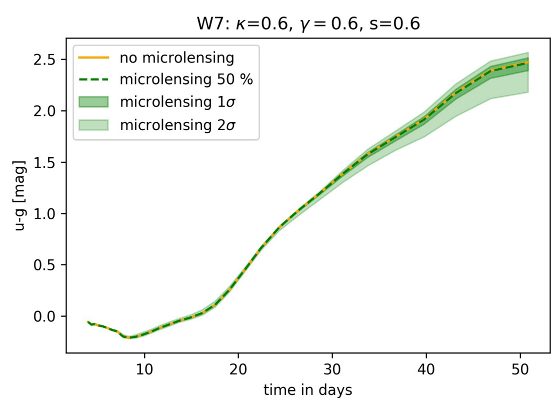

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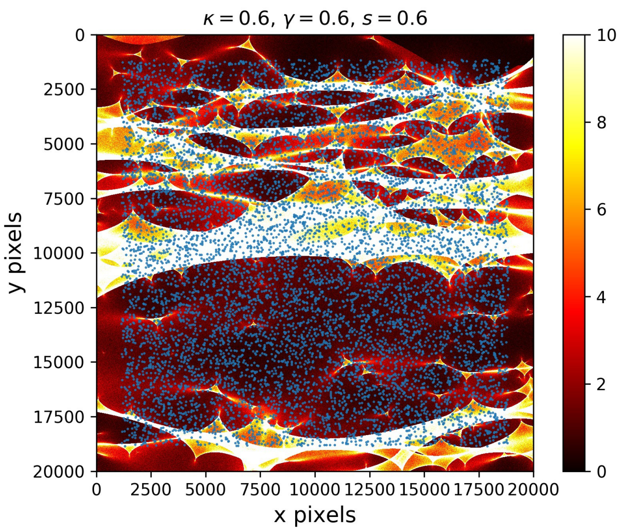
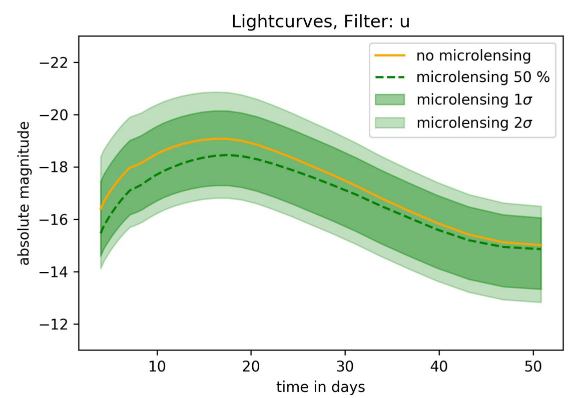
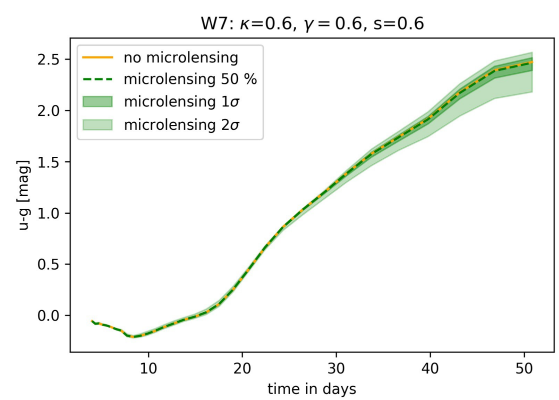


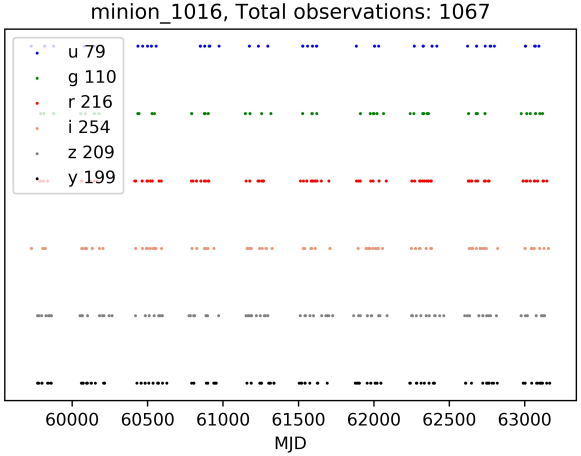




for LSST: 30 minutes revisit in different filters

Cadence and Time Delay Measurement

- One spot in the WFD survey (Ra = 315 deg, Dec = -5 deg)



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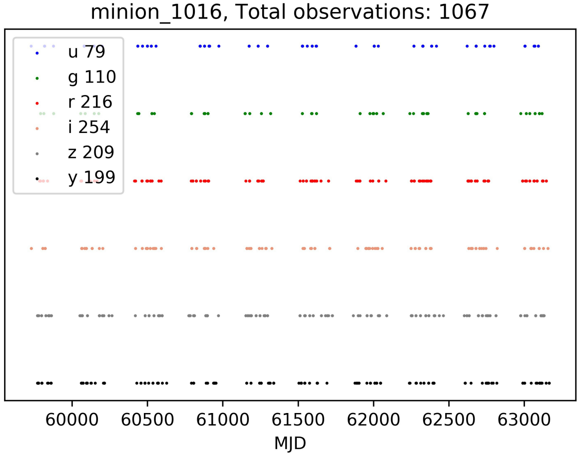

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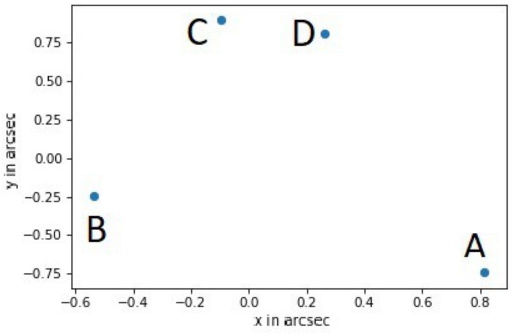

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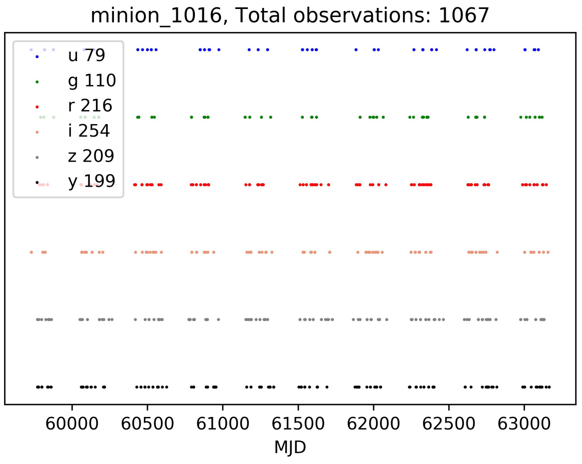

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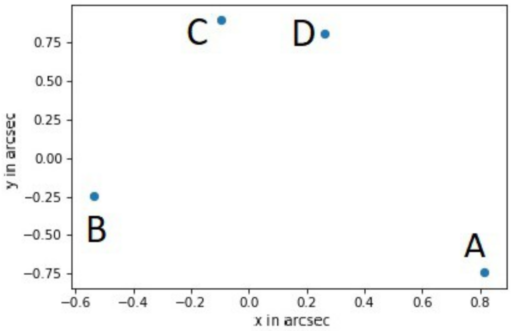

SIE ↓

μ, τ

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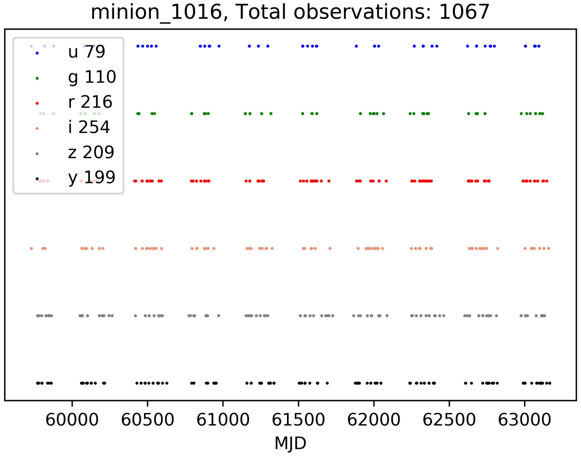

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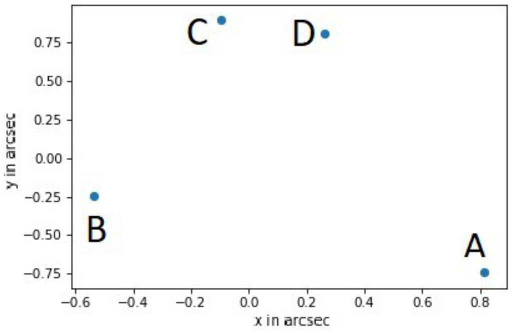

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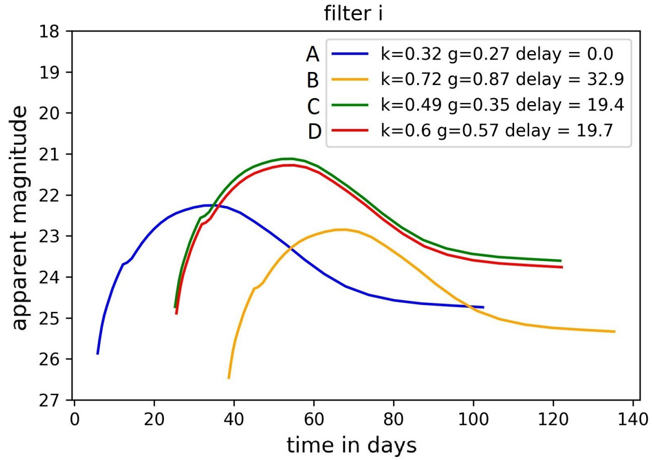
W7



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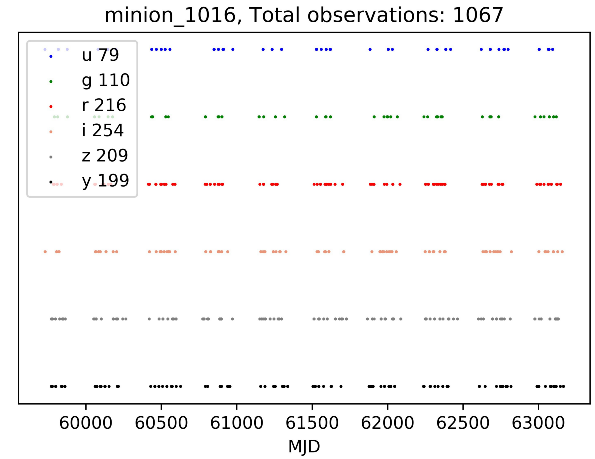

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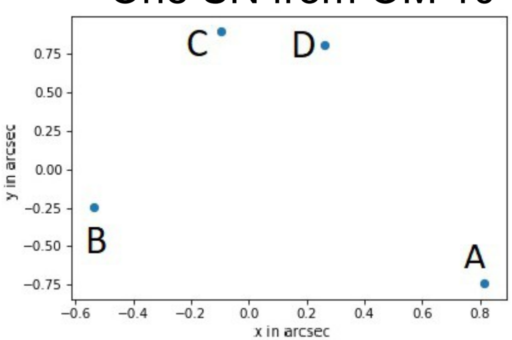

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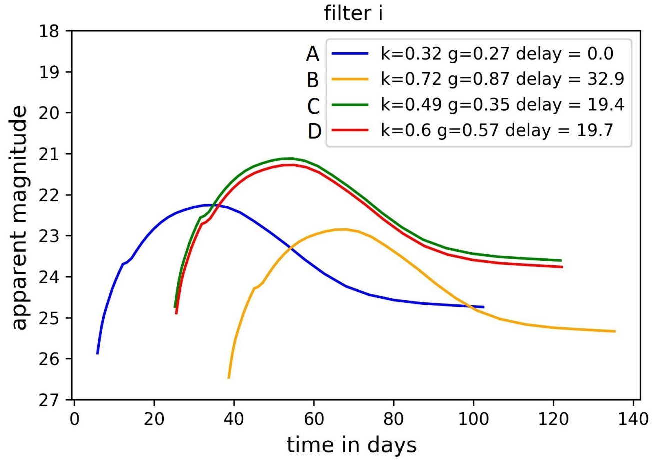
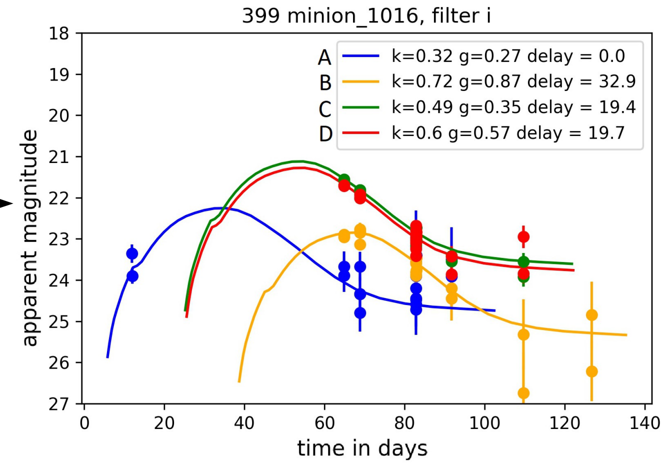
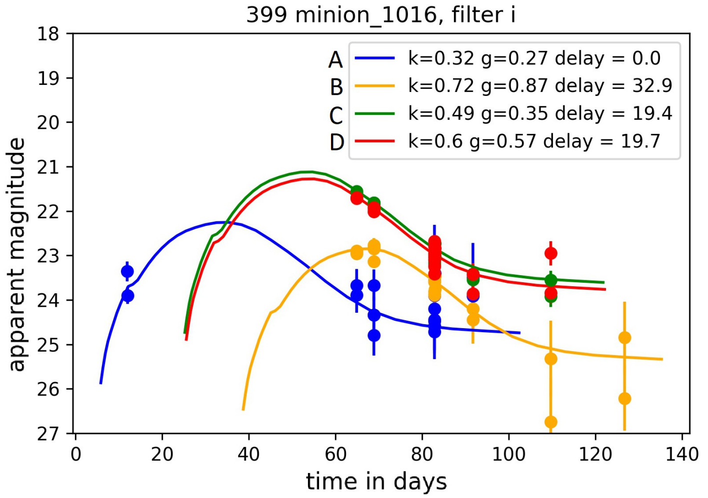




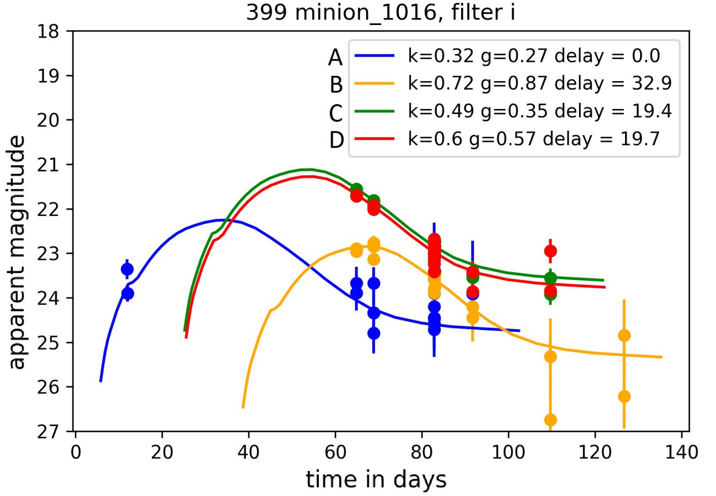
Cadence and Time Delay Measurement

Feed simulated light curves into PyCS
(Tewes et al. 2013, Bonvin et al. 2016)
→ Use free-knot spline optimizer



Cadence and Time Delay Measurement

SN explosion randomly at beginning of season (100 x)



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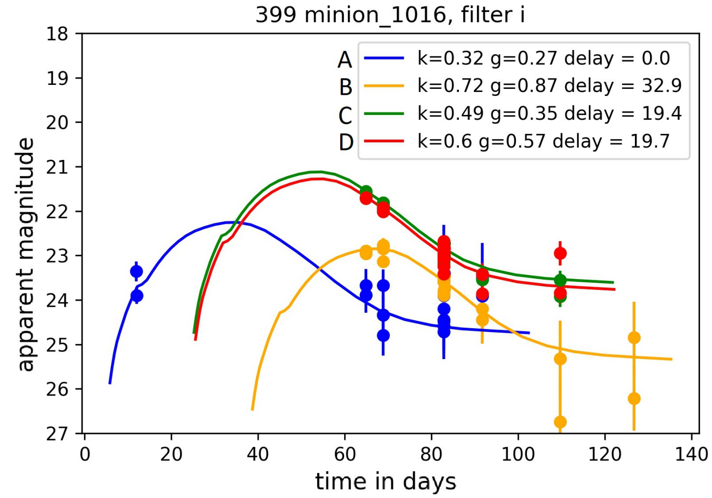

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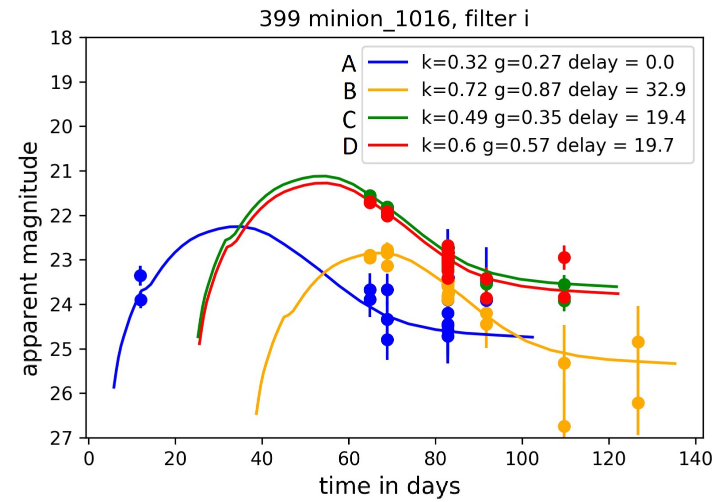
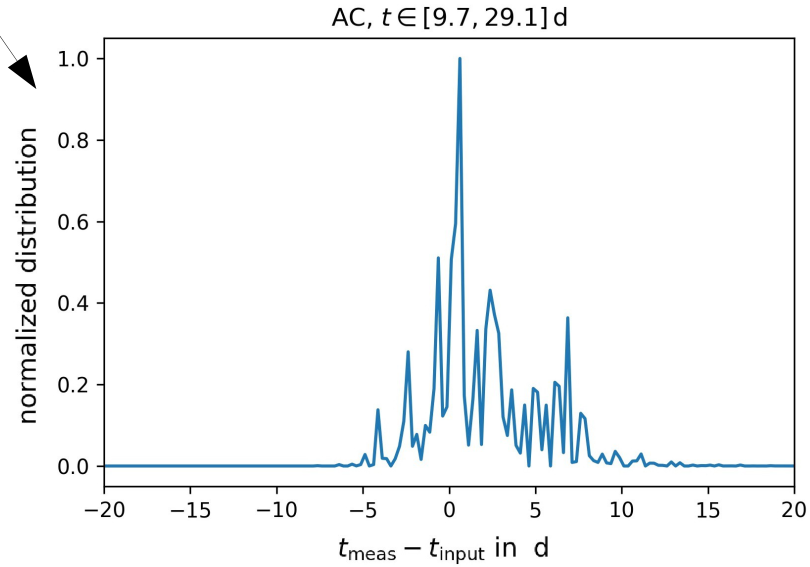


6 x 100 distributions



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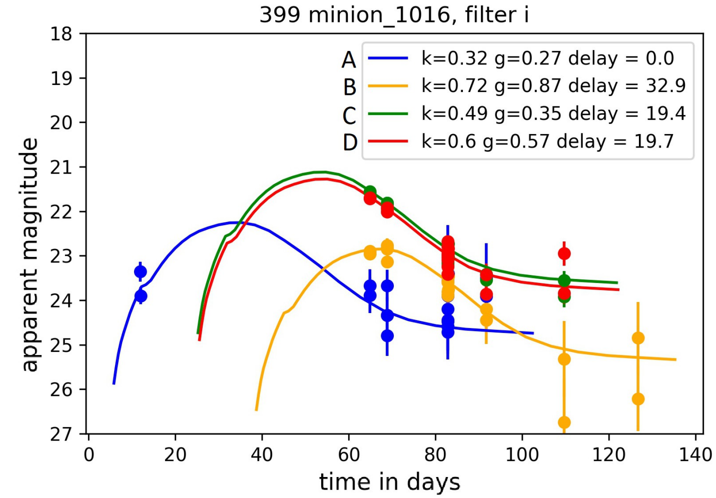

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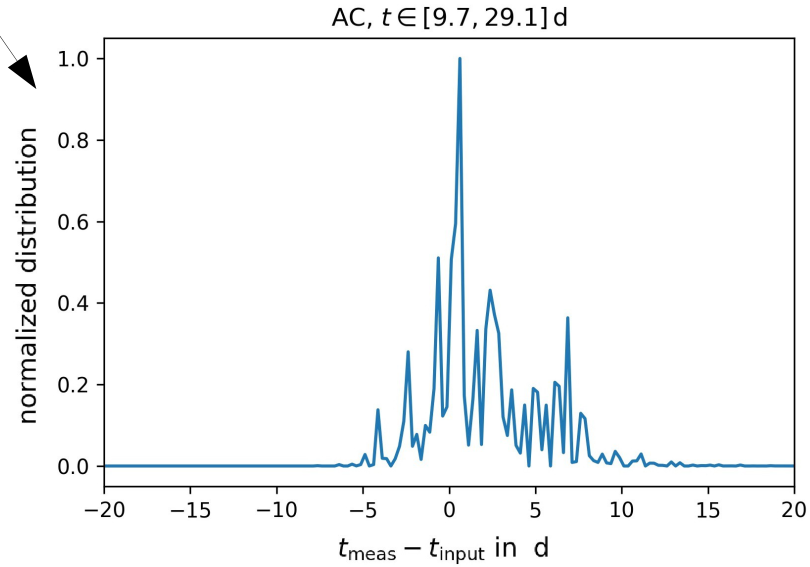

mean

6 distributions

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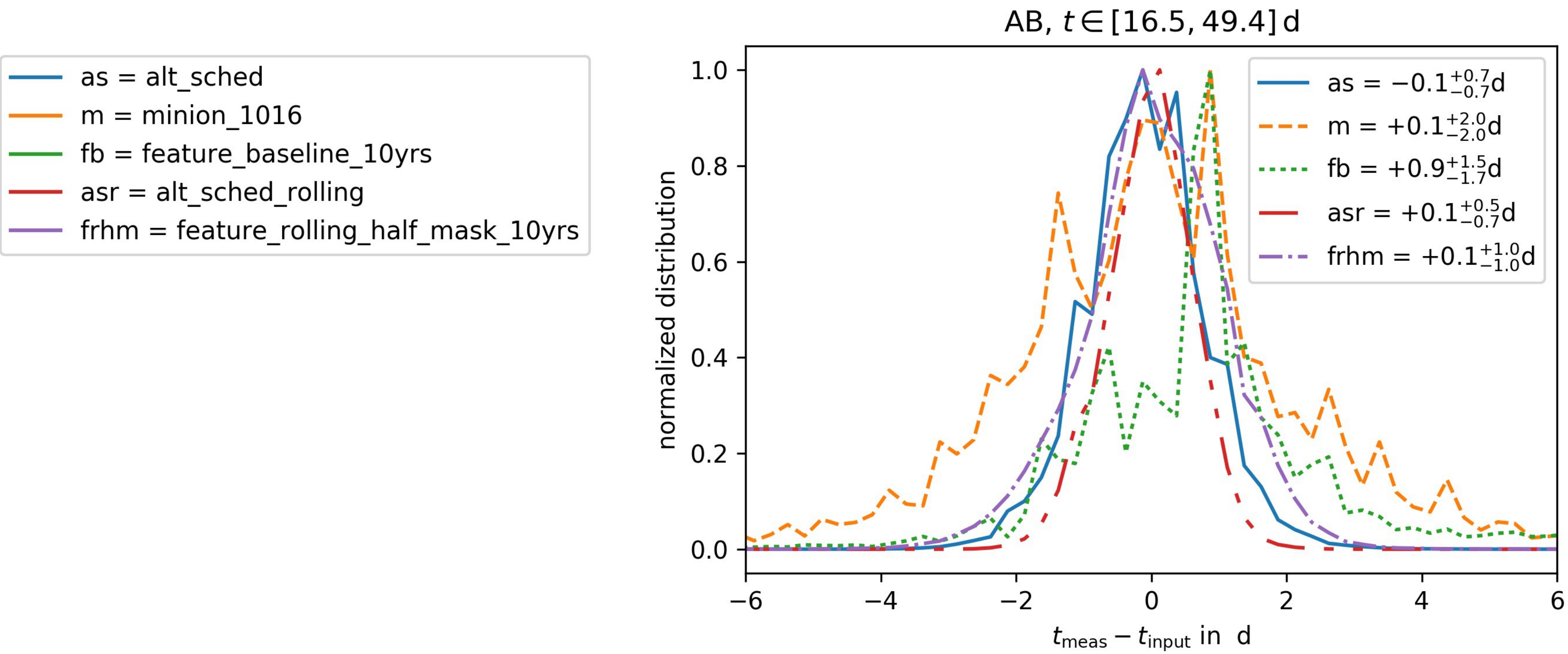
Cadence and Time Delay Measurement

- Results for one spot in the sky and one SN from OM 10 catalog:



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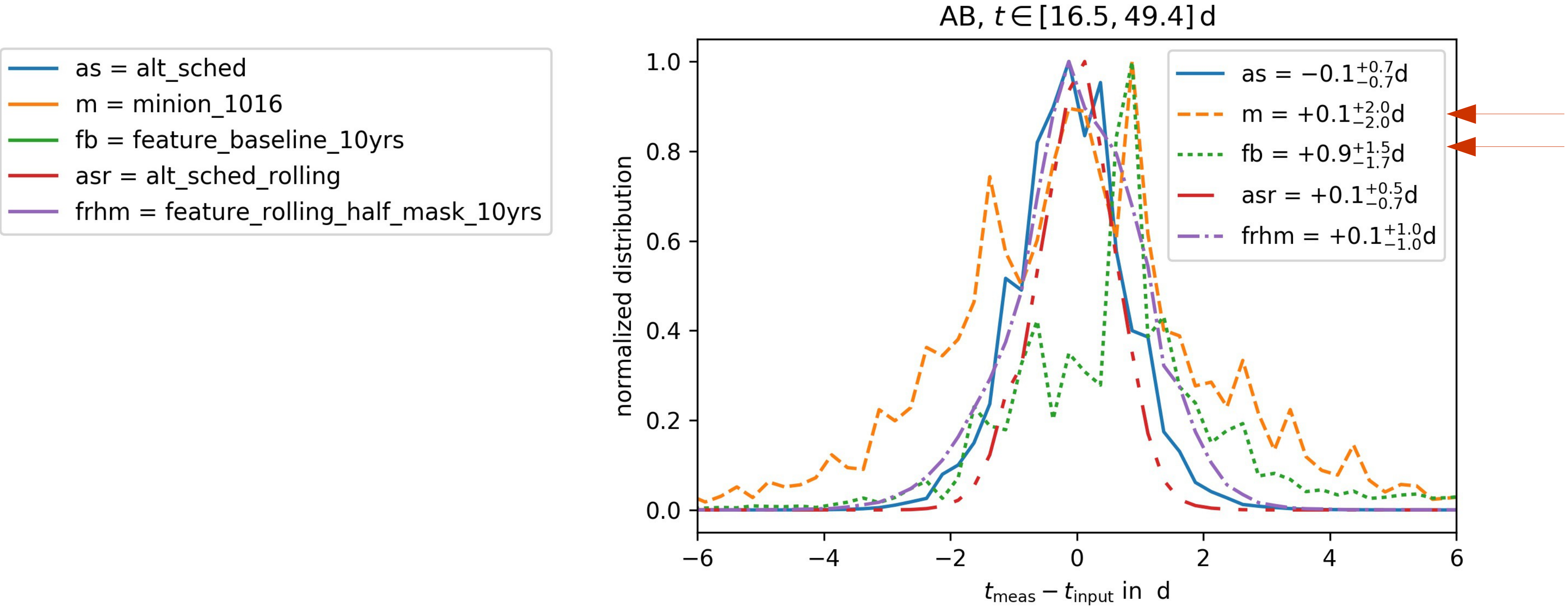

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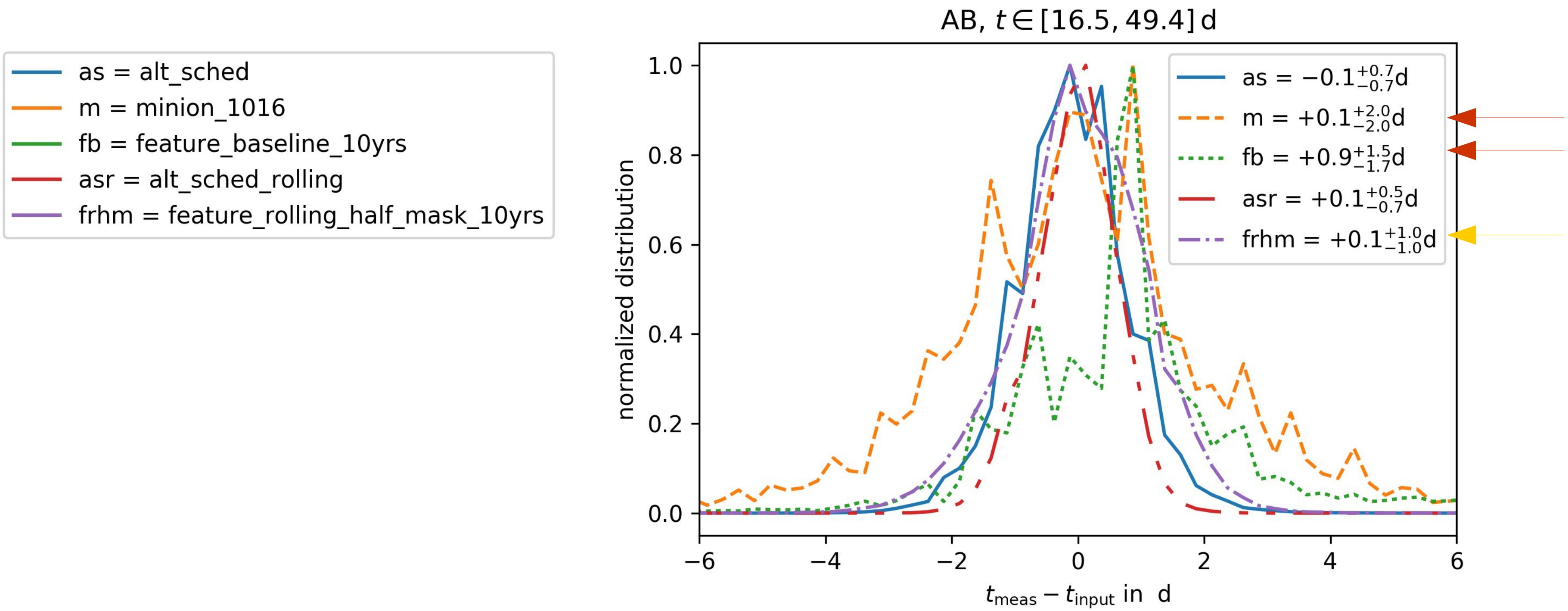

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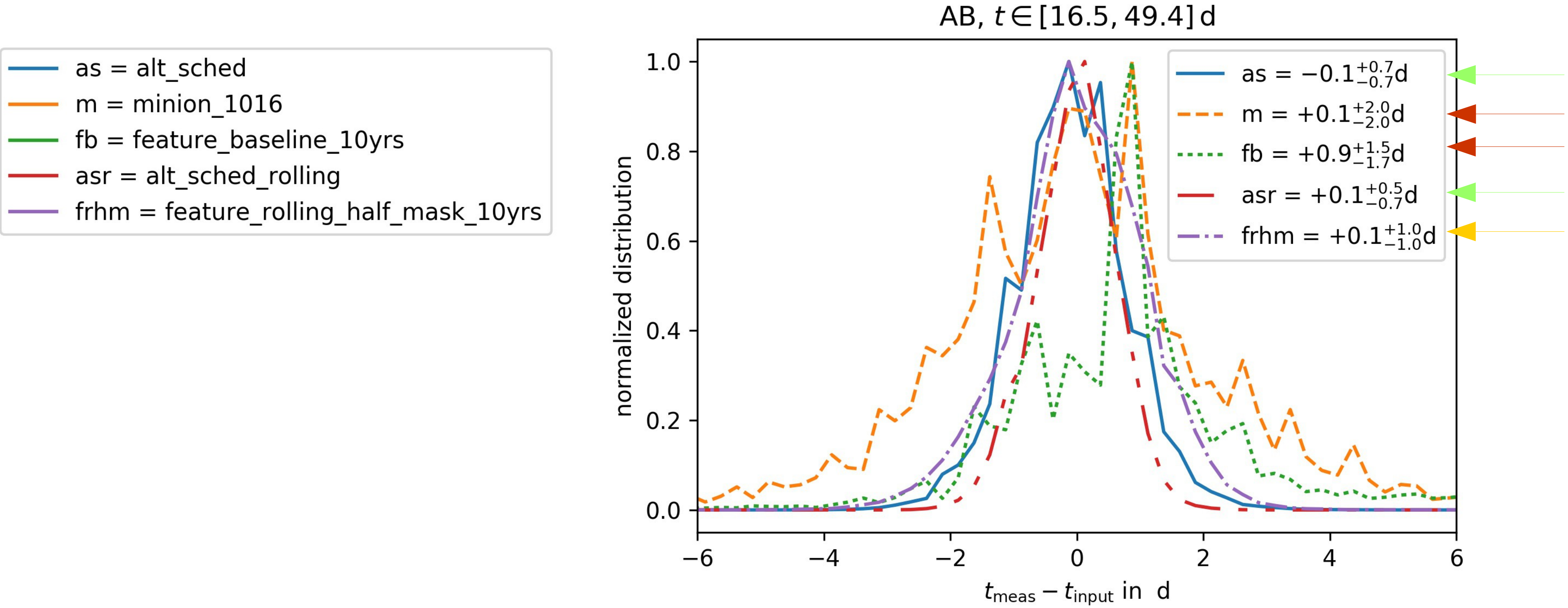

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Conclusion & Outlook

- 30 minute revisit in different filters
- First cadence investigation of SLSNe Ia:
  - favours alt_sched and alt_sched_rolling
  - → Investigate more spots on sky and more SLSNe Ia from OM 10
  - → Place SNe Ia more realistic in observation season
  - → Investigate fraction of SLSNe Ia which would be useful for time delay measurments
  - → Include microlensing in cadence investigation
  - → Use SN template fitting instead of splines

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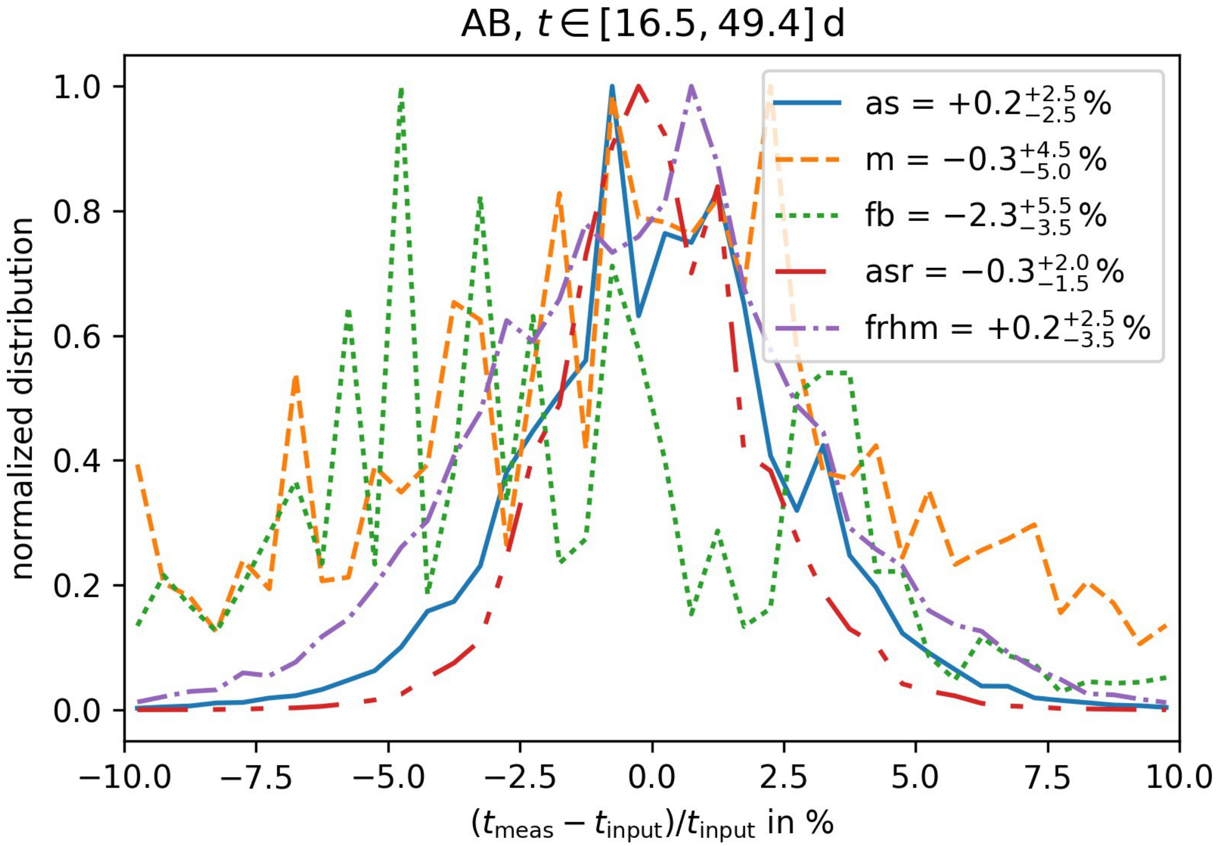
Backup



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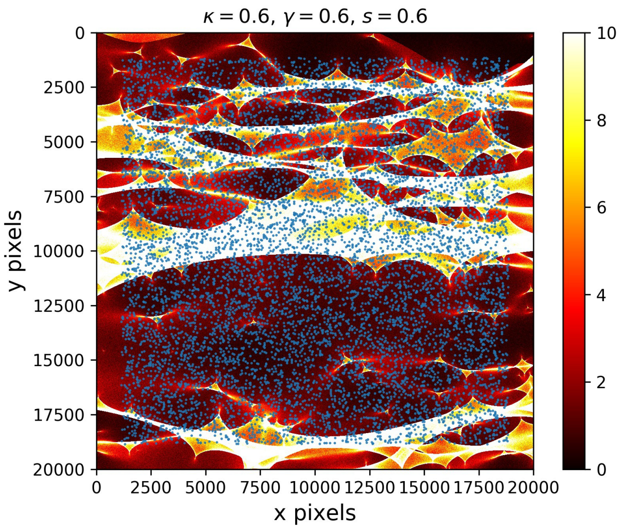
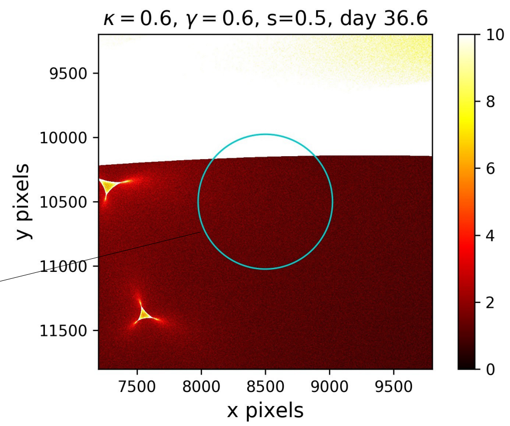


$$F_\lambda = \frac{1}{D_\mathrm{A}^2} \int_0^{2\pi} \mathrm{d}\phi \int_0^{p_\mathrm{S}} \mathrm{d}p\, p\, \mu\, I_{\lambda,\mathrm{o}}$$



Cadence and Time Delay Measurement

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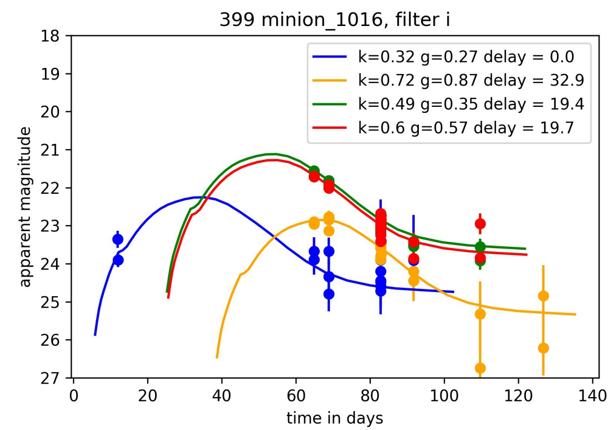
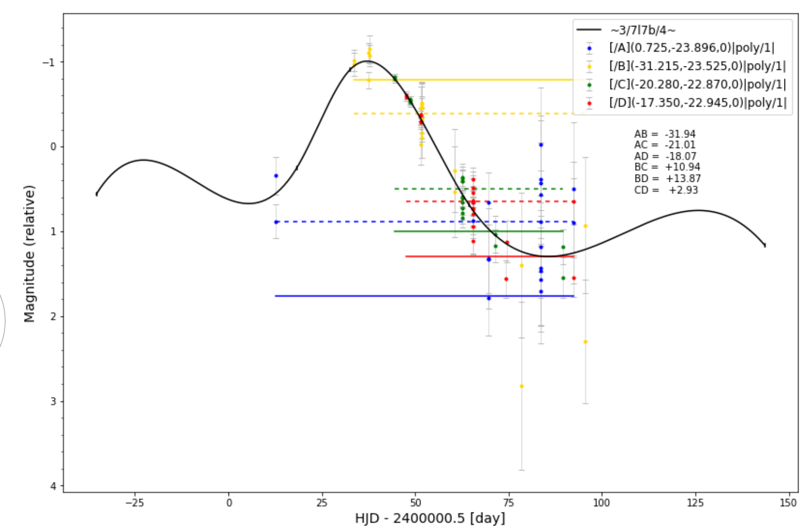
Piecwise combination of polynomial functions of degree 3

Constant extrinsic spline to model macrolensing





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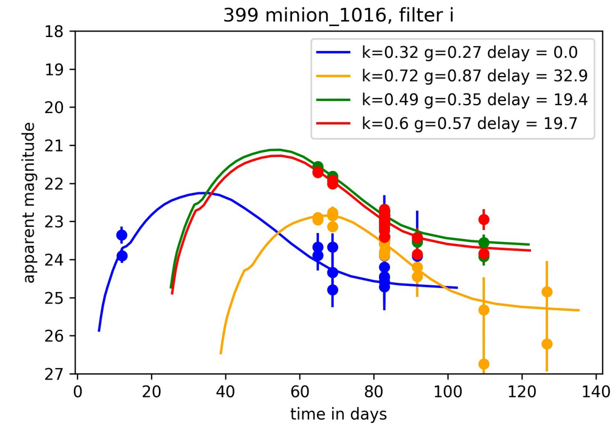

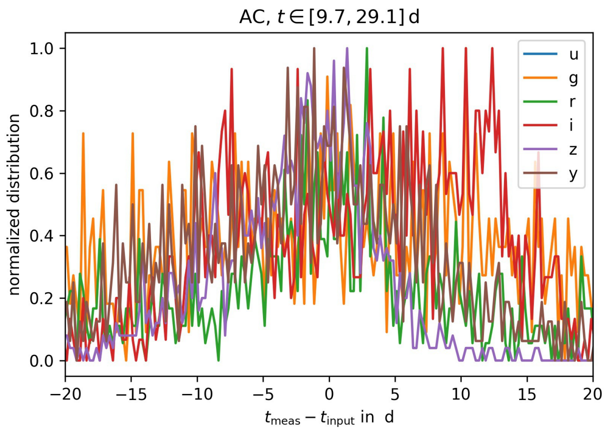

6 x 100 x 6 distributions

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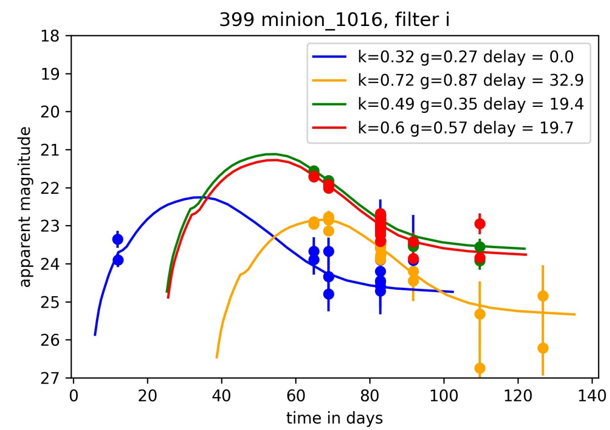

Magnification map
(GERLUMPH, Vernardos et al. 2015)

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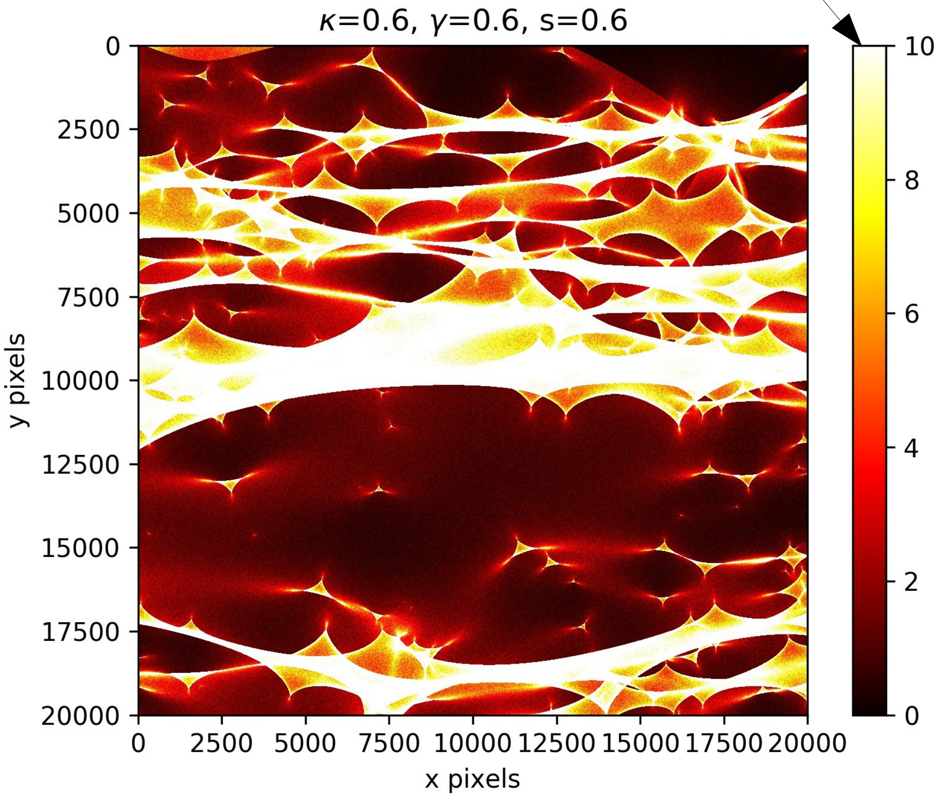
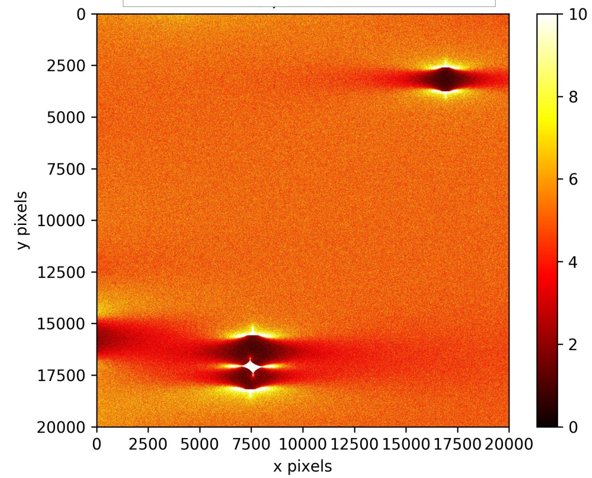
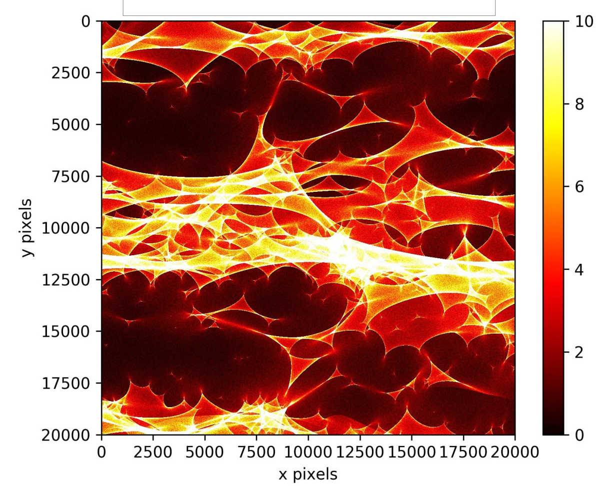
Magnification



s=0.99



s=0.01



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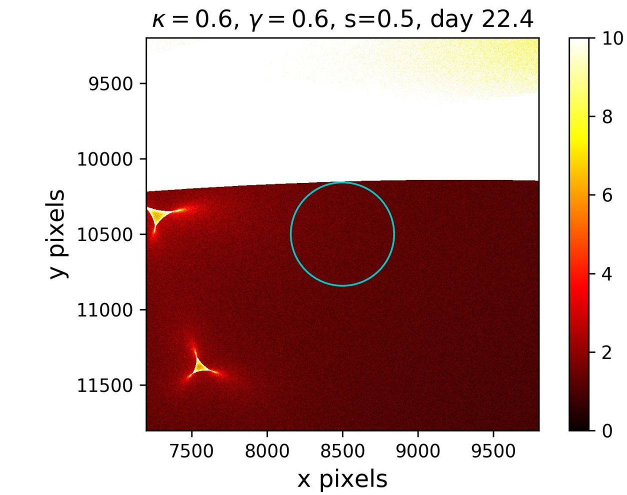
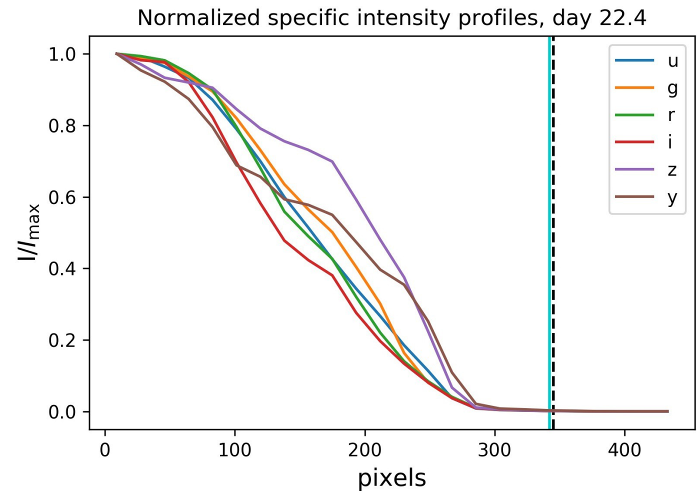
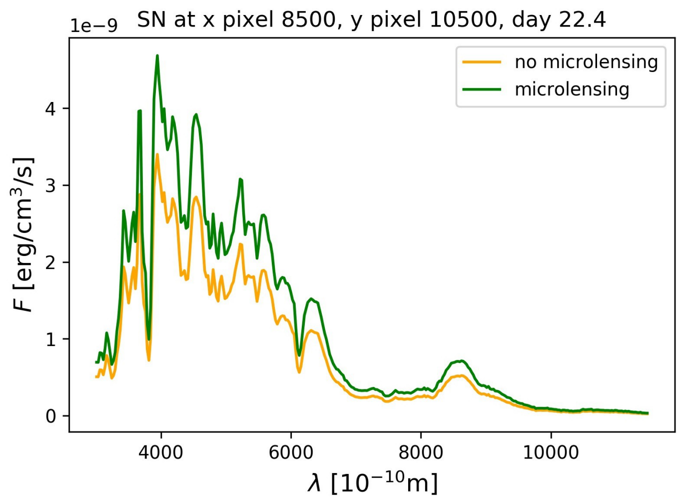
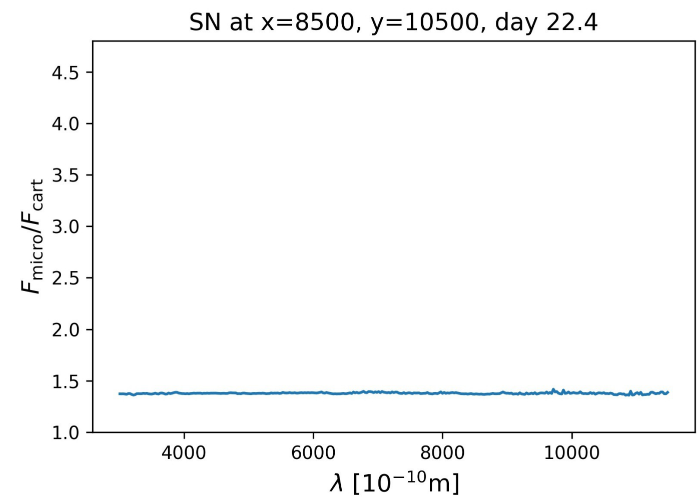
Microlensing Effect on Spectra









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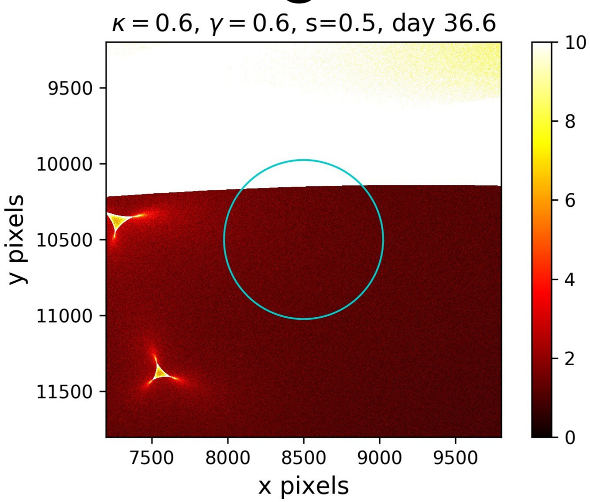

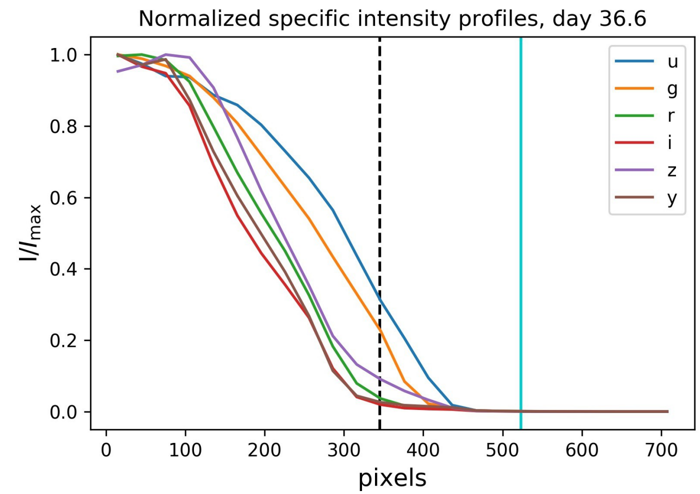

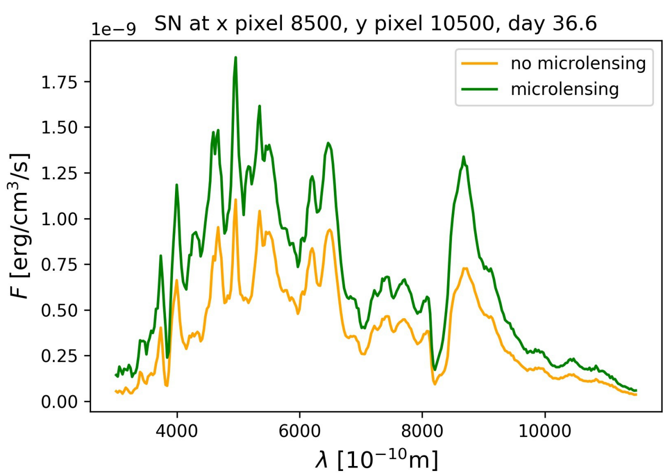

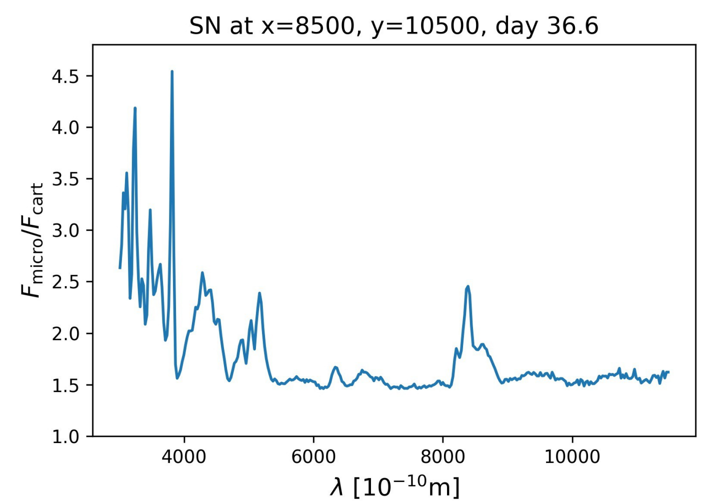

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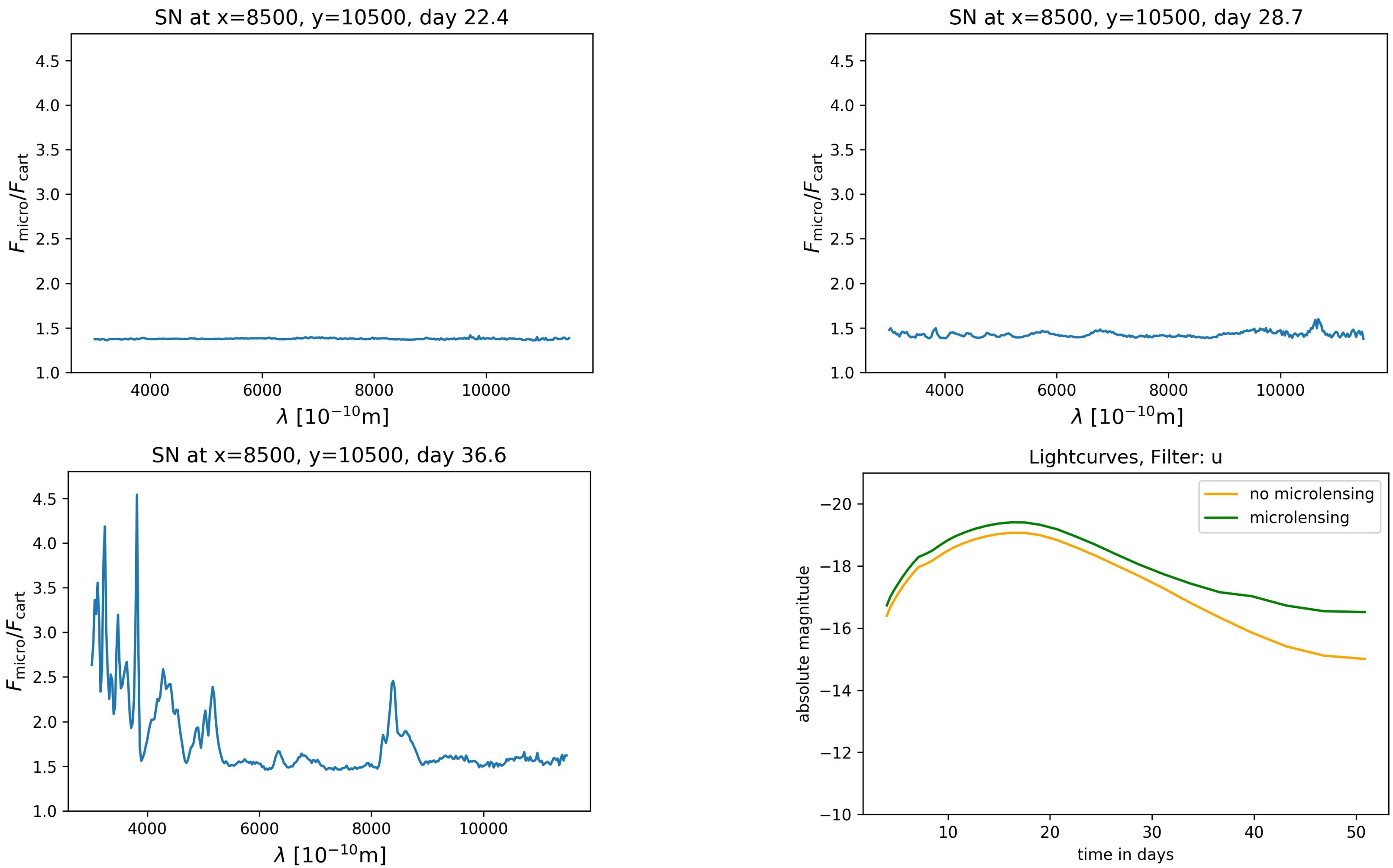
Microlensing Effect on Light Curve



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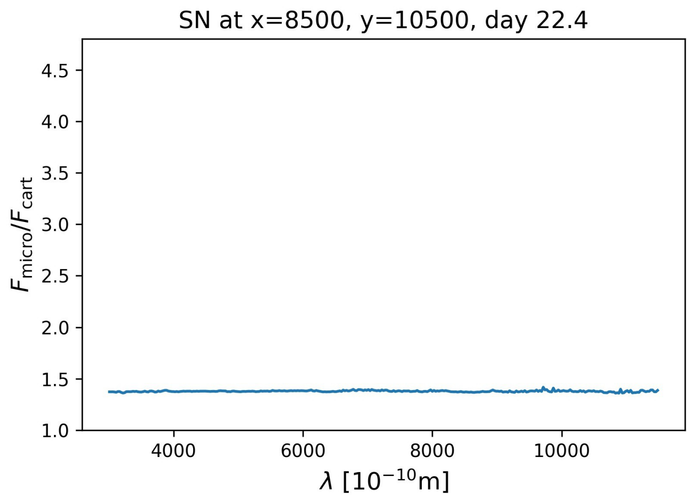
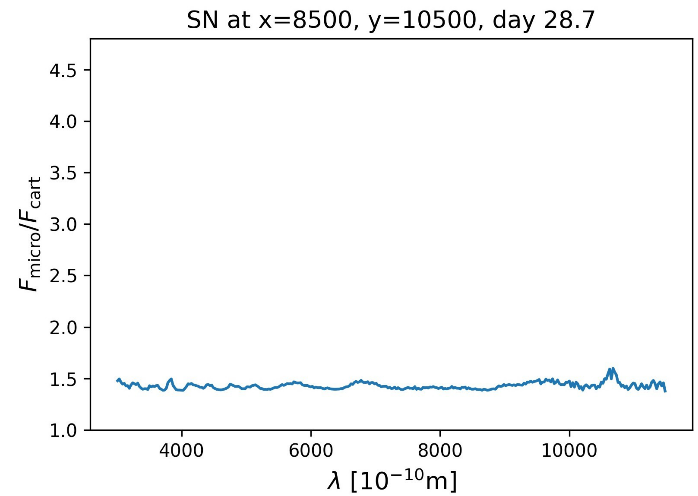
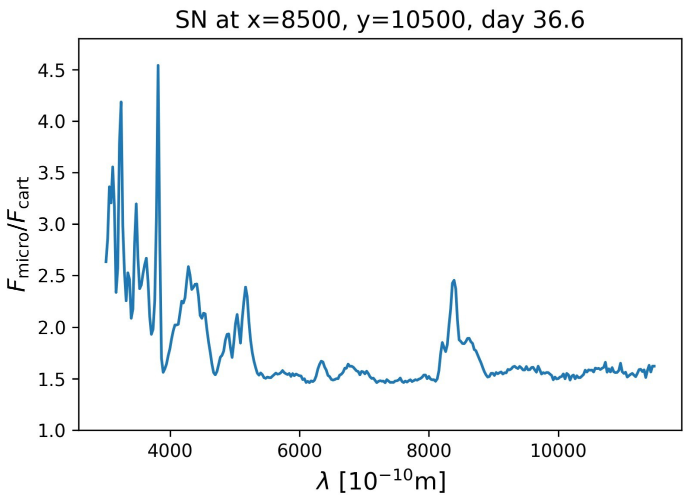
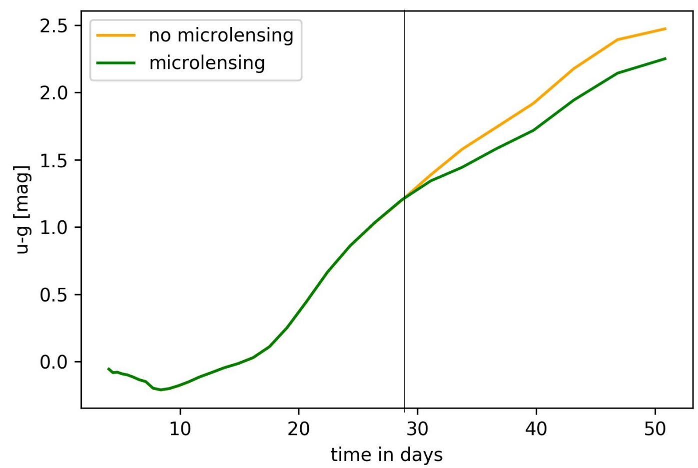
Microlensing Effect on Color Curve

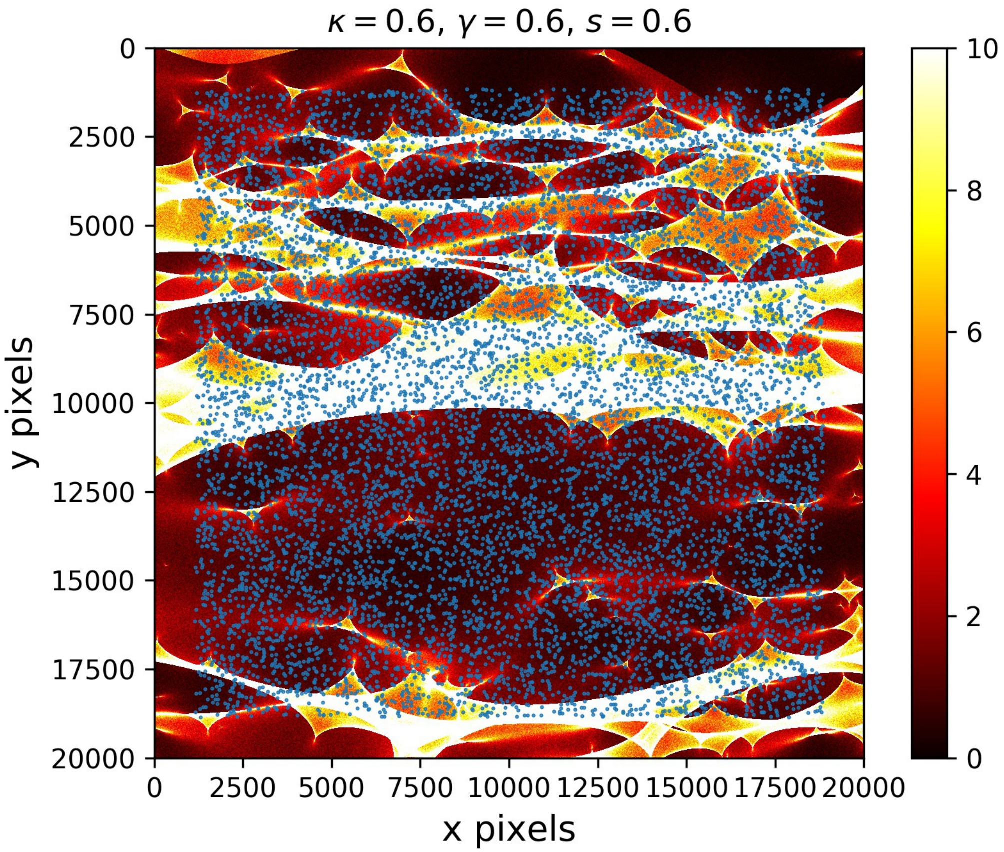




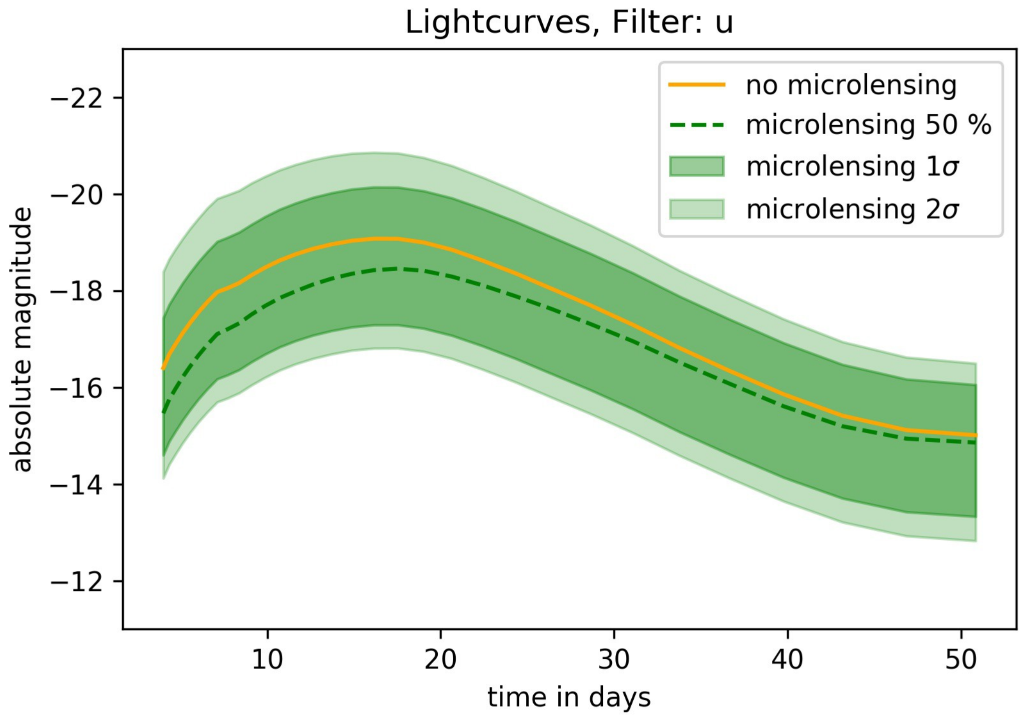




10000 randomly distributed SNe



Randomly distributed SNe – W7 ARTIS



Huge spread → bad for measuring time delays

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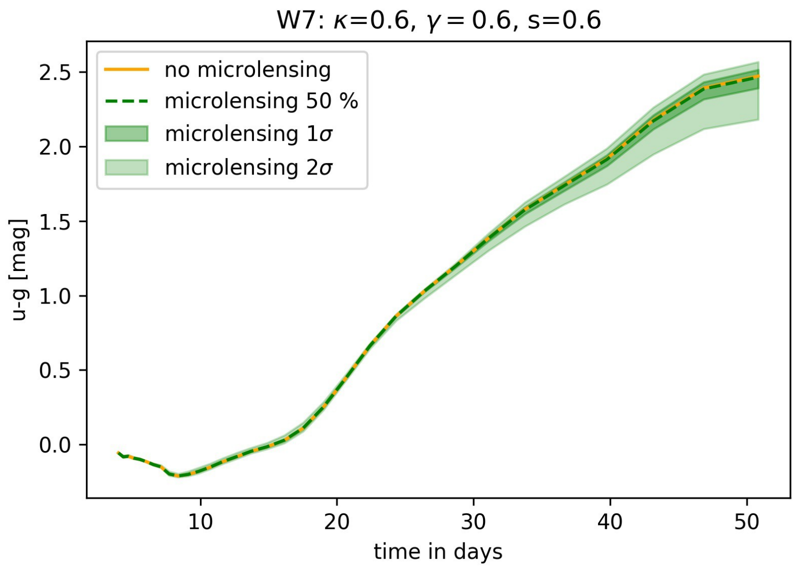
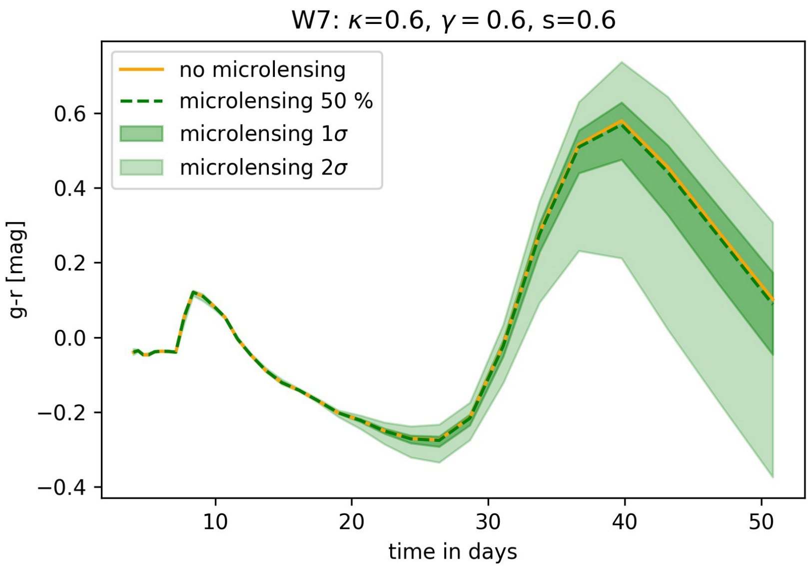
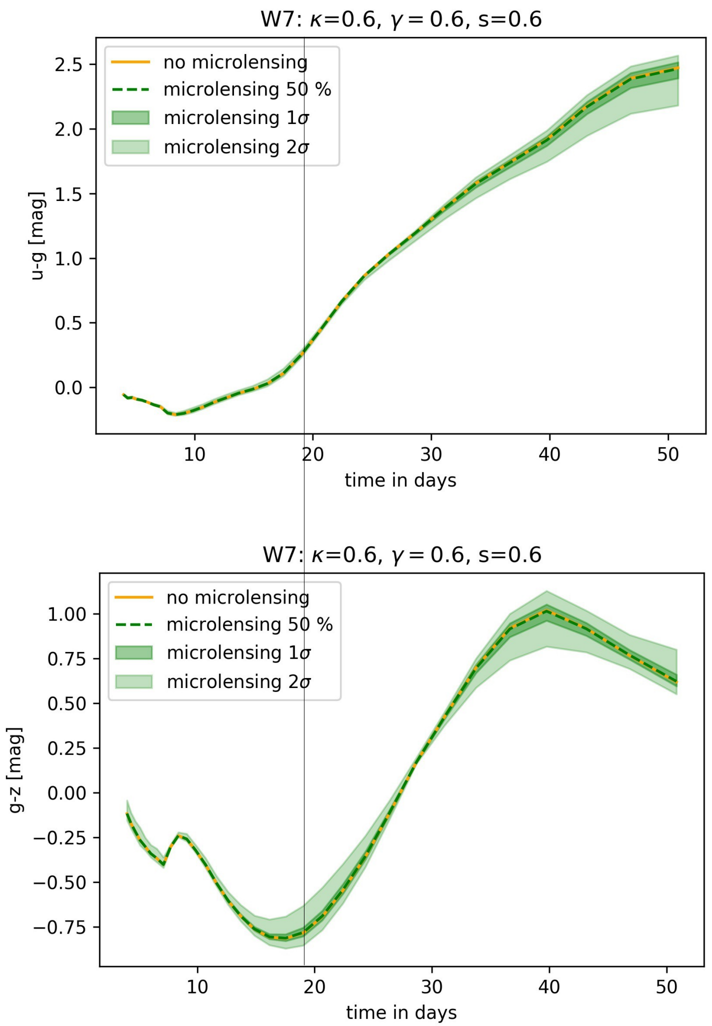
W7 ARTIS - Randomly distributed SNe

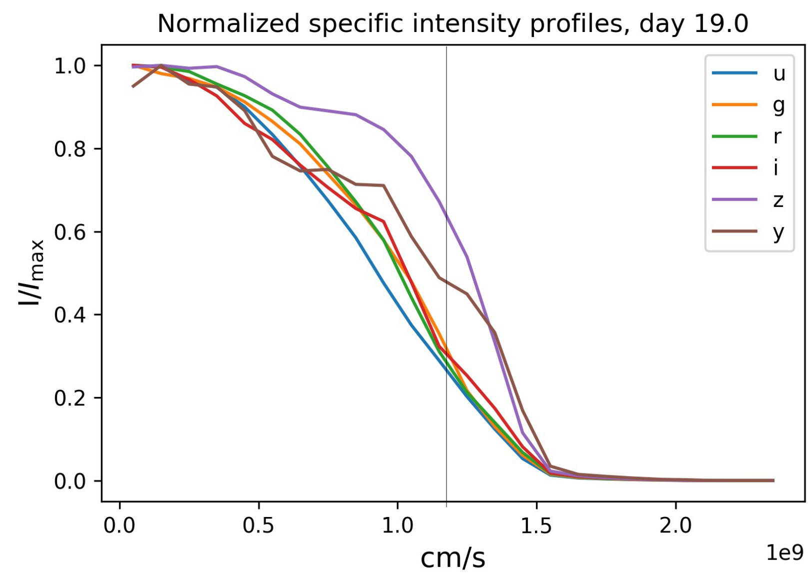




Small spread for early times → excellent for measuring time delays

W7 ARTIS - Randomly distributed SNe





→ Rest frame color curves containing combinations of u,g,r show achromatic behaviour → time delays

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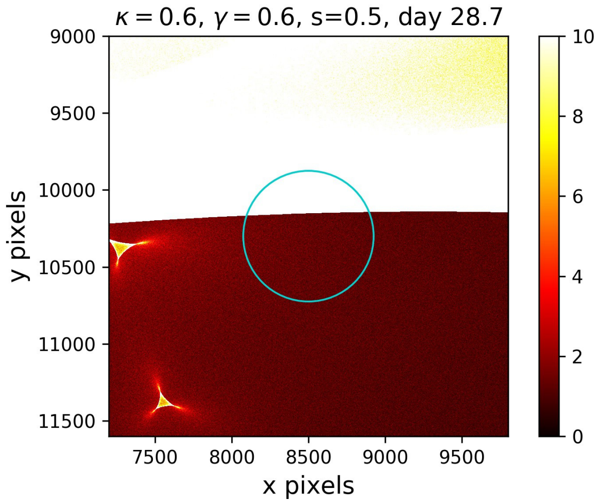
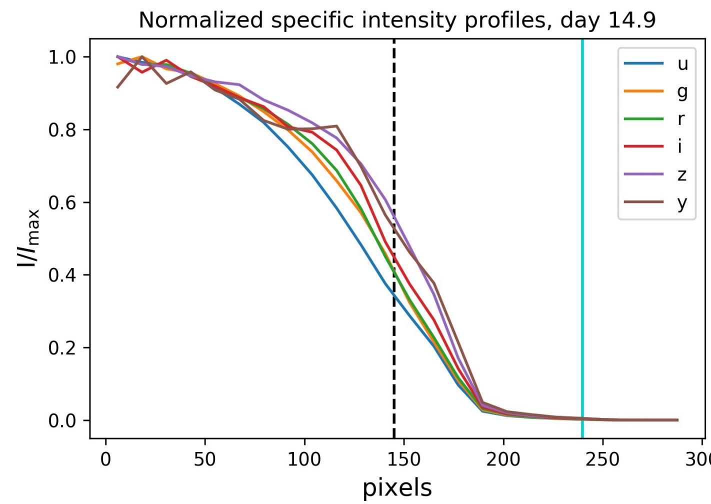
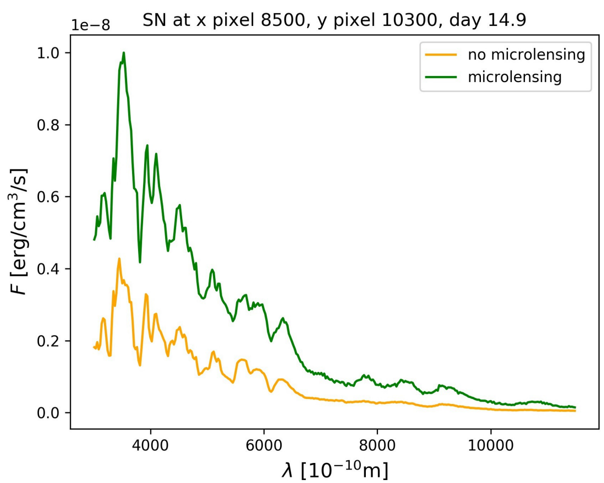
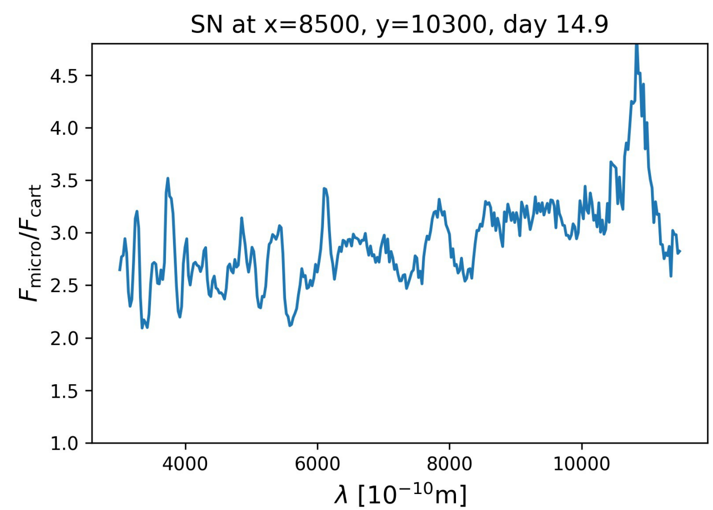
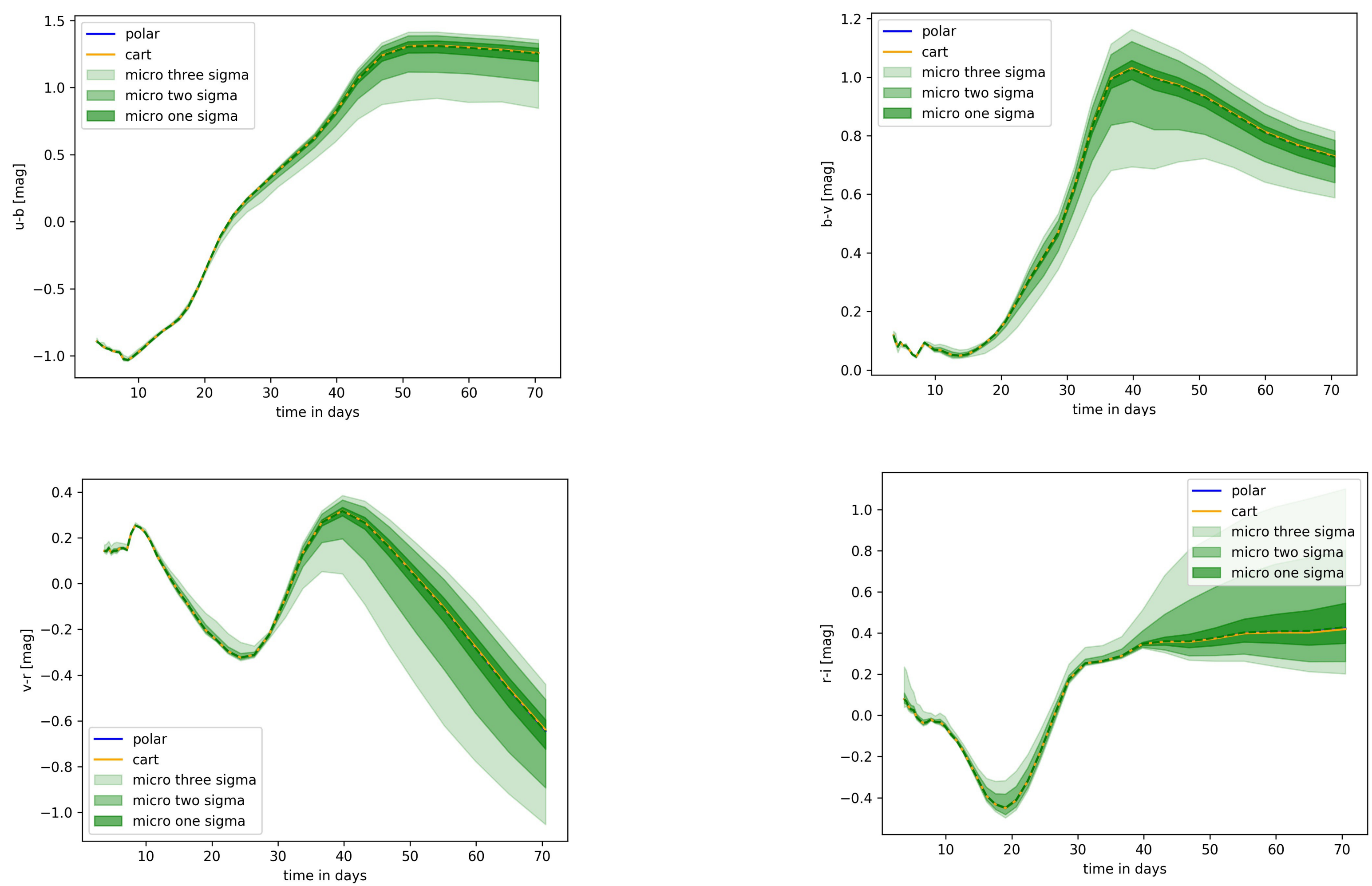




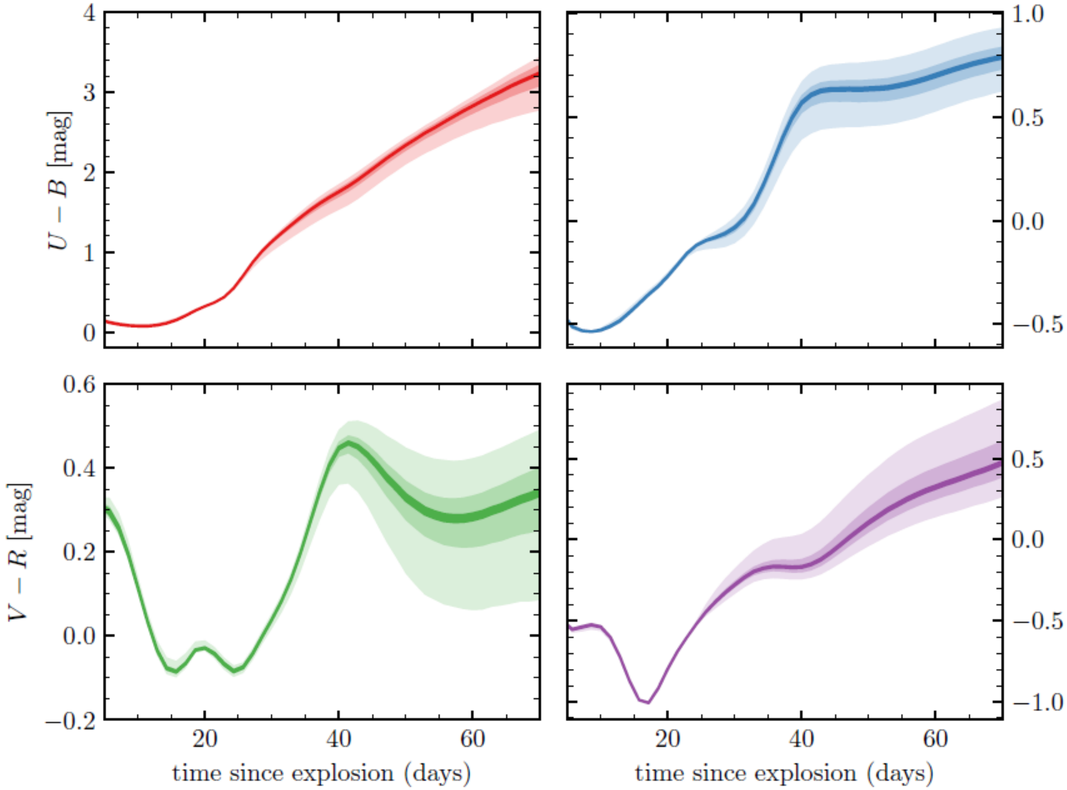




Johnson, kappa = 0.6, gamma = 0.6, s = 0.5

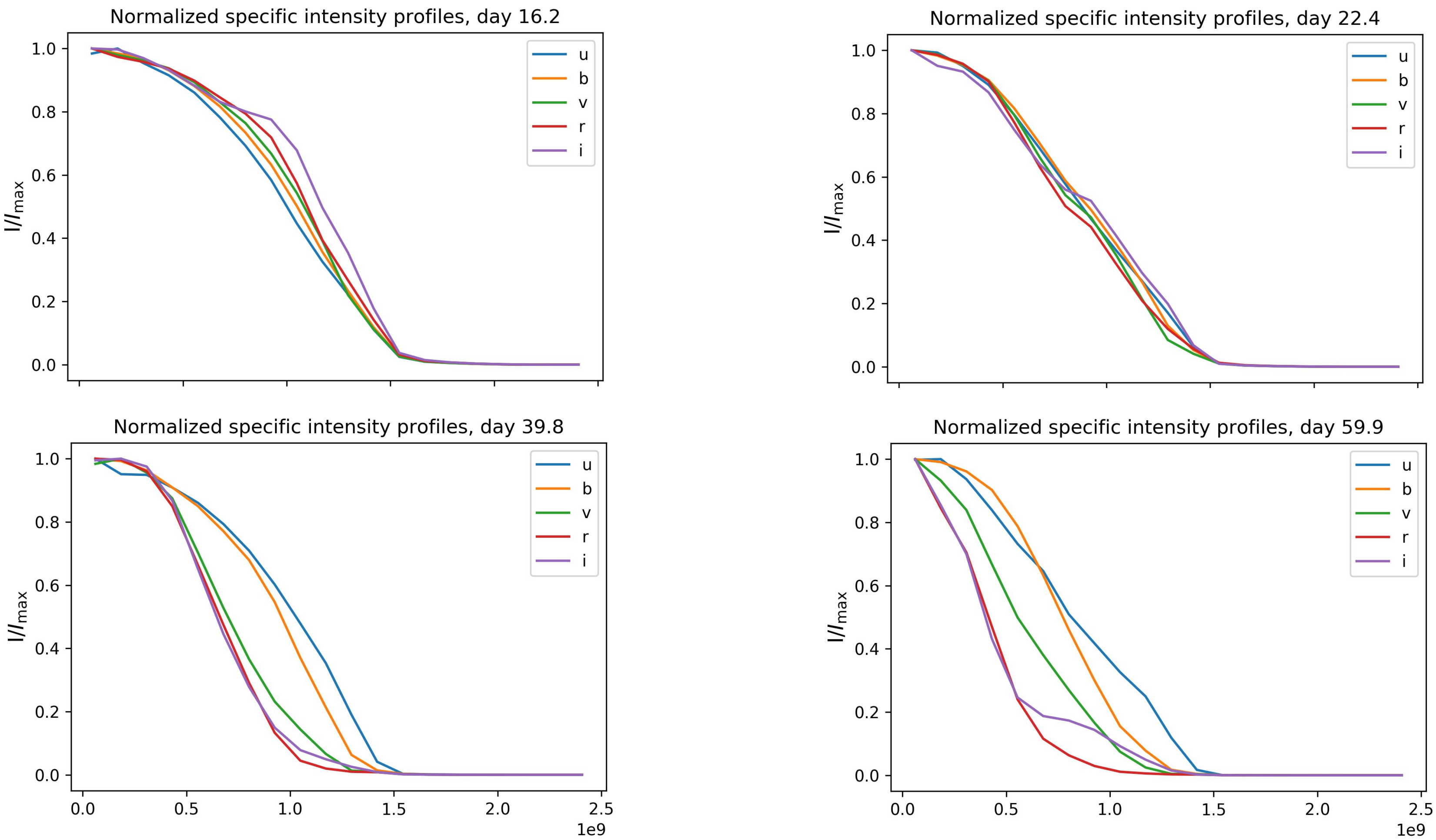


W7 SEDONA (Goldstein et al. 2017)



Achromatic phase before day 20

Intensity profiles Johnson (ARTIS)



Magnification map (GERLUMPH, Vernardos et al. 2015)

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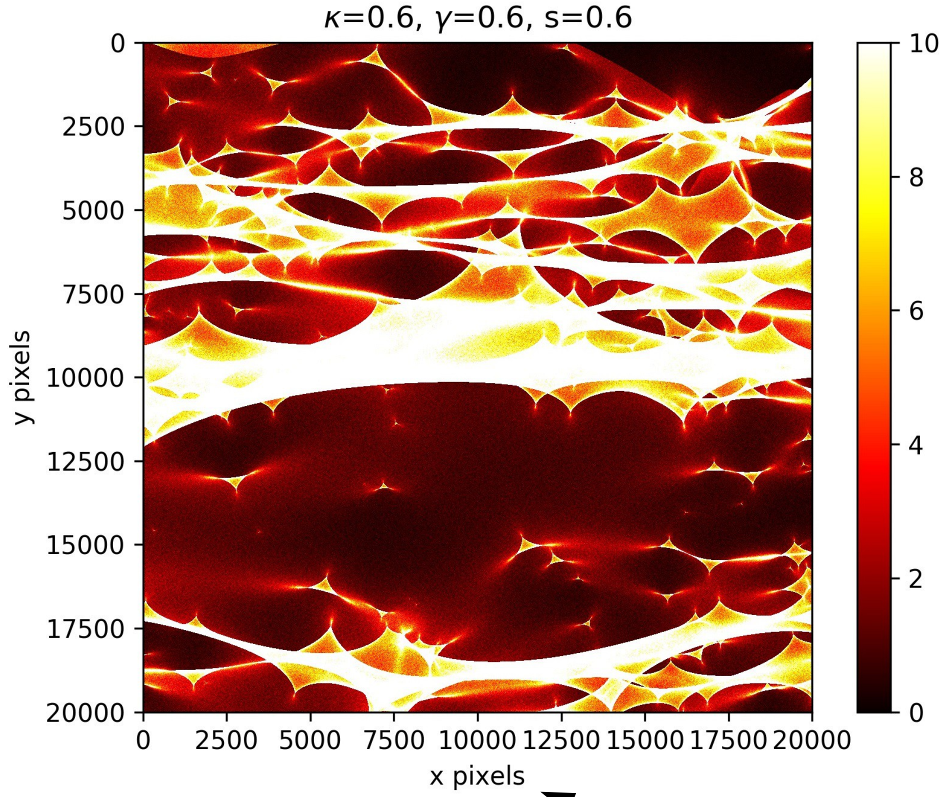
$$F_\lambda = \frac{1}{D_\mathrm{A}^2} \int_0^{2\pi} \mathrm{d}\phi \int_0^{p_\mathrm{S}} \mathrm{d}p\, p\, I_{\lambda,\mathrm{o}}$$



1 pixel = 1e13 cm

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Model parameters for iPTF16geu

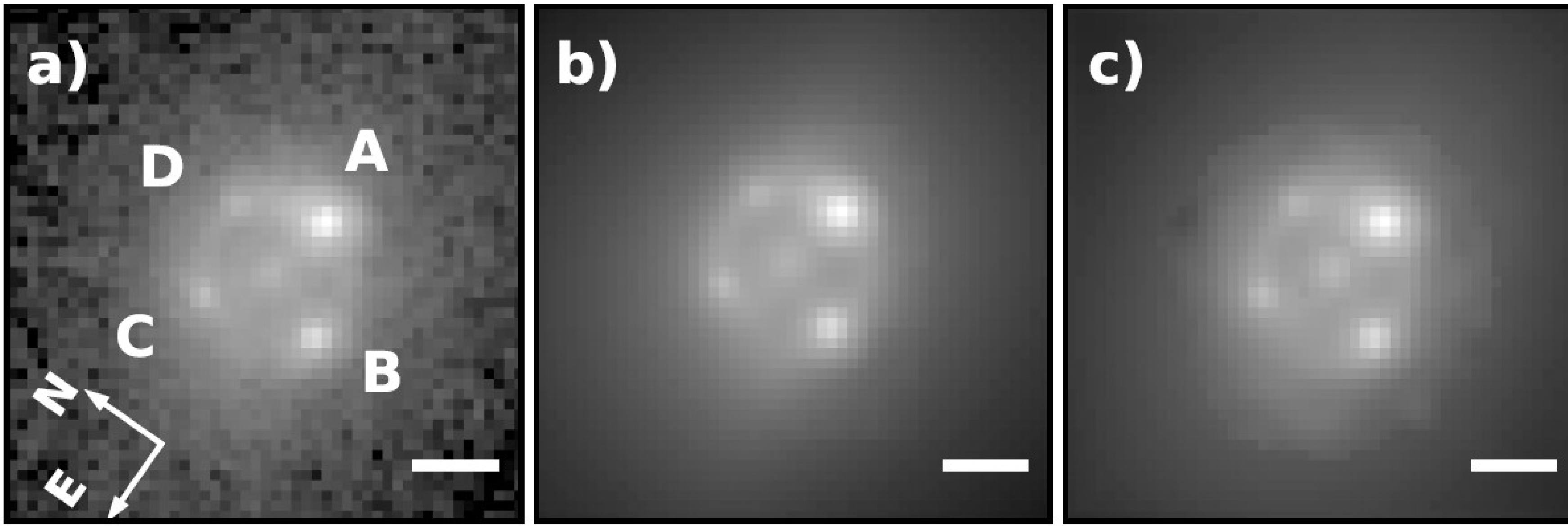
TABLE 1
MODEL PARAMETERS AND PREDICTIONS.

Lens Model						κ, γ			
Model Profile	$\theta_{\rm E}('')$	$q_{\rm m}$	φ_e	γ'	$\gamma_{\rm ext}, \varphi_{\rm ext}$	A	B	C	D
GLAFIC SIE	0.29 ± 0.01	0.83 ± 0.01	65 ± 1	$\equiv 2.0$	–	0.56,0.56	0.43,0.43	0.57,0.56	0.46,0.45
GLEE SIE	0.294 ± 0.002	$0.77^{+0.03}_{-0.02}$	66 ± 1	$\equiv 2.0$	–	0.60,0.60	0.40,0.40	0.62,0.62	0.43,0.43
GLEE PL	0.30 ± 0.01	0.73 ± 0.04	66 ± 1	2.1 ± 0.1	–	0.56,0.66	0.35,0.44	0.58,0.68	0.38,0.48
GLEE PL+$\gamma_{\rm ext}$	0.30 ± 0.01	$0.66^{+0.08}_{-0.04}$	68^{+4}_{-2}	2.1 ± 0.1	$0.02^{+0.03}_{-0.01}, 79^{+8}_{-14}$	0.63,0.61	0.36,0.44	0.64,0.64	0.40,0.47

Model Predictions								
Model	Magnification factors				Δt (days)			
Profile	A	B	C	D	A	B	C	D
GLAFIC SIE	$-8.2^{+0.4}_{-0.5}$	$7.2^{+0.2}_{-0.2}$	$-7.1^{+0.3}_{-0.3}$	$10.8^{+0.4}_{-0.4}$	$0.40^{+0.02}_{-0.02}$	$\equiv 0$	$0.47^{+0.01}_{-0.02}$	$0.25^{+0.01}_{-0.01}$
GLEE SIE	$-6.7^{+1.2}_{-1.0}$	$5.6^{+0.6}_{-0.6}$	$-4.5^{+0.6}_{-0.6}$	$8.7^{+1.1}_{-1.3}$	$0.52^{+0.08}_{-0.05}$	$\equiv 0$	$0.65^{+0.07}_{-0.07}$	$0.35^{+0.05}_{-0.05}$
GLEE PL	$-5.5^{+0.9}_{-1.5}$	$4.8^{+0.9}_{-0.6}$	$-3.7^{+0.5}_{-0.9}$	$7.4^{+1.6}_{-0.9}$	$0.56^{+0.06}_{-0.06}$	$\equiv 0$	$0.70^{+0.06}_{-0.07}$	$0.37^{+0.03}_{-0.04}$
GLEE PL+$\gamma_{\rm ext}$	$-5.2^{+1.7}_{-1.9}$	$4.7^{+1.3}_{-1.2}$	$-3.6^{+1.2}_{-1.3}$	$7.4^{+1.9}_{-2.0}$	0.6 ± 0.1	$\equiv 0$	0.7 ± 0.1	0.4 ± 0.1

NOTE. — $\theta_{\rm E}$ is the Einstein radius. $q_{\rm m}$ is the axis ratio of the lens mass. The PAs (φ_e and $\varphi_{\rm ext}$) are in degrees measured East of North. A shear angle of $\varphi_{\rm ext} = 0$ corresponds to shearing of the lens system along the north-south direction. The most-probable convergence (κ) and shear (γ) values are given at the location of each SN image. Negative magnification (μ) means opposite parity and Δt is time delay relative to image B.

Observation iPTF16geu (More, Suyu et al.)



Observation (HST Image 28.10.16)

Model

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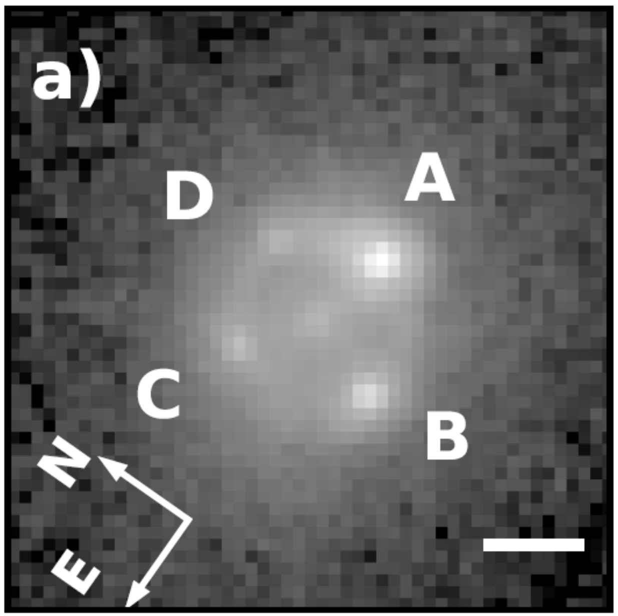
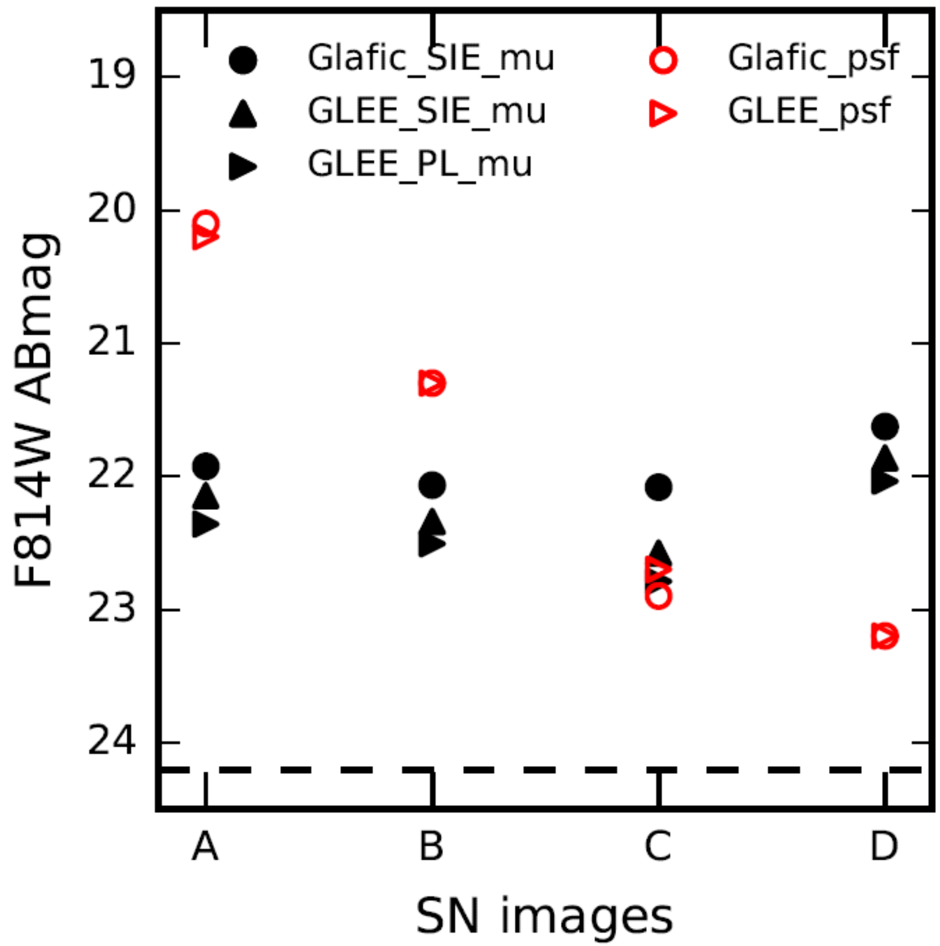
Observation iPTF16geu (Goobar et al. 2017)





- Model deviates from observation:
  - dust extinction
  - millilensing
  - microlensing

(More, Suyu et al. 2017)

W7 ARTIS + Microlensing

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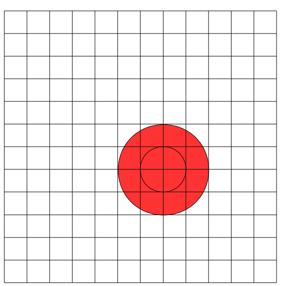
$$F_\lambda = \frac{1}{{D_\mathrm{L}}^2} \int_0^{2\pi} \mathrm{d}\phi \int_0^{p_\mathrm{S}} \mathrm{d}p\, p\, \mu\, I_\lambda$$

$$F_{\lambda,\mathrm{polar}}(t) = \frac{2\pi}{{D_\mathrm{L}}^2} \sum_i I_\lambda(t, p_i)\, p_i(t)\, \Delta p_i(t)$$

no microlensing

$$F_{\lambda,\mathrm{cart}}(t) = \frac{1}{{D_\mathrm{L}}^2} \sum_j \sum_k I_\lambda(t, x_j, y_k)\, \Delta d^2_\mathrm{mag}$$

- Magnification map stored in cartesian bins
- Specific intensity stored in radial bins



Linear interpolation of specific intensity

Calculate specific intensity at each grid point → cartesian grid for specific intensity

$$\Delta_\mathrm{d}(t) \equiv \sqrt{\frac{1}{N_\lambda} \sum_\lambda \left(\frac{F_{\lambda,\mathrm{cart}}(t) - F_{\lambda,\mathrm{polar}}(t)}{F_{\lambda,\mathrm{polar}}(t)} \right)^2}$$

→ interpolate magnification map to a finer grid until deviation < 1 %

W7 ARTIS + Microlensing

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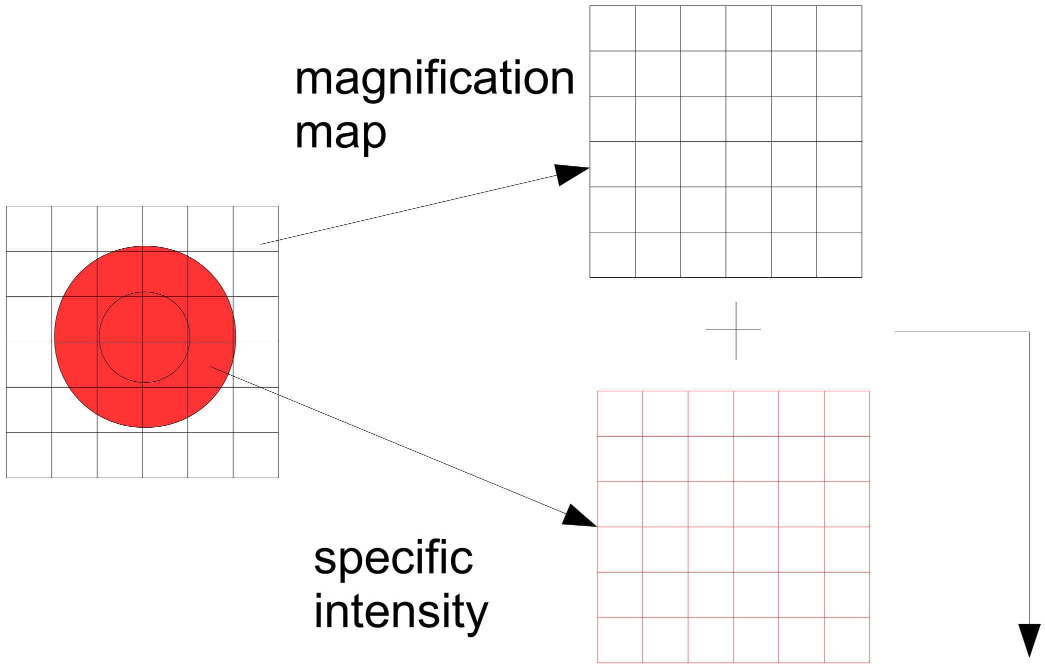
$$F_\lambda = \frac{1}{{D_\mathrm{L}}^2}\int_0^{2\pi}\mathrm{d}\phi\int_0^{p_\mathrm{S}}\mathrm{d}p\,p\,\mu\,I_\lambda$$



$$F_{\lambda,\mathrm{micro}}(t) = \frac{1}{{D_\mathrm{L}}^2}\sum_j\sum_k I_\lambda(t,x_j,y_k)\,\mu(x_j,y_k)\,\Delta d_\mathrm{mag}^2$$