UNIVERSITY OF CAMBRIDGE

GATES Cambridge

GausSN: Bayesian Time Delay Estimation for Strongly Lensed Supernovae

Erin Hayes

University of Cambridge

with Kaisey Mandel, Stephen Thorp (OKC, Stockholm),

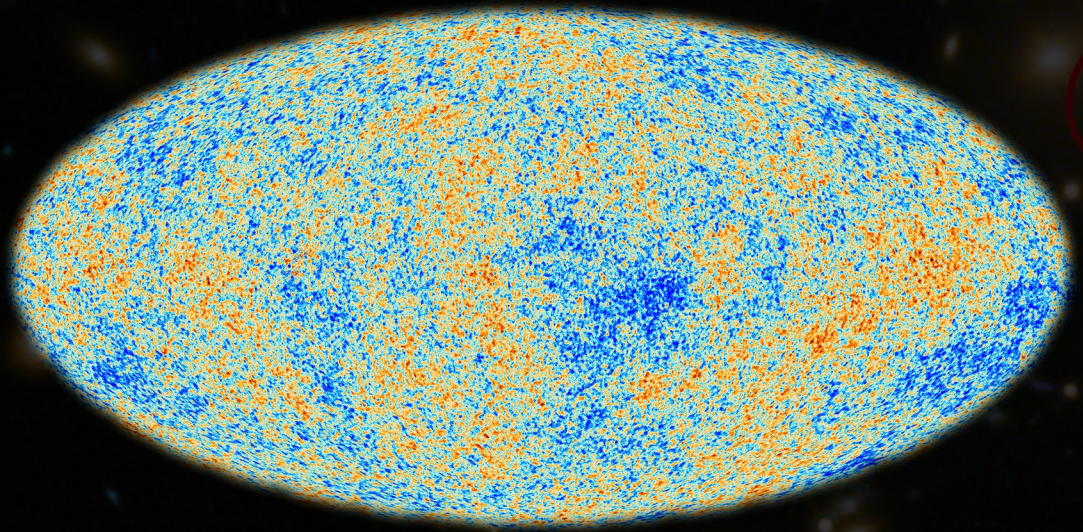
Nikki Arendse (OKC, Stockholm), Matthew Grayling, and Suhail Dhawan

arXiv: 2311.17997

The Current State of Affairs

CMB (Planck Collaboration+18)

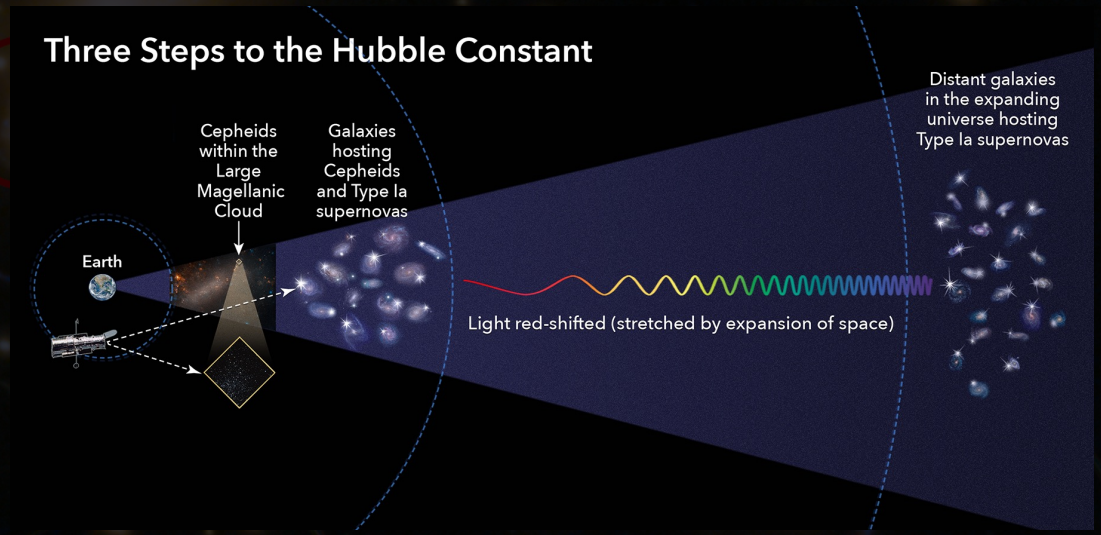
$$H_0 = 67.4 \pm 0.5 \text{ km/s/Mpc}$$



Credit: ESA and the Planck Collaboration

Local Distance Ladder (Riess+22)

$$H_0 = 73.04 \pm 1.04 \text{ km/s/Mpc}$$



Credit: NASA, ESA, and A. Field (STScI)

New physics or systematics?

We need a local probe of H_0 that is **independent** of the distance ladder to cross-check the local H_0 estimate.

Time Delay Cosmography

Time Delay Cosmography

Credit: ESA/Hubble and L. Calçada
https://esahubble.org/videos/heic1710a/

Ingredients for H_0 Estimate

$$\frac{\Delta t}{\phi_{lens}} \propto D_{\Delta t}$$

Ingredients for H_0 Estimate

$$\frac{\Delta t}{\phi_{lens}} \propto D_{\Delta t}$$

Δt = time delay

Ingredients for H_0 Estimate

$$\frac{\Delta t}{\phi_{lens}} \propto D_{\Delta t}$$

Δt = time delay

ϕ_{lens} = lensing potential

Ingredients for H_0 Estimate

$$\frac{\Delta t}{\phi_{lens}} \propto D_{\Delta t}$$

Δt = time delay

ϕ_{lens} = lensing potential

$D_{\Delta t}$ = distance traveled by delayed image light

Ingredients for H_0 Estimate

$$\frac{\Delta t}{\phi_{lens}} \propto D_{\Delta t} \propto \frac{1}{H_0}$$

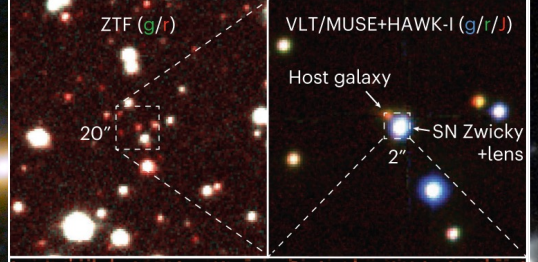
Δt = time delay

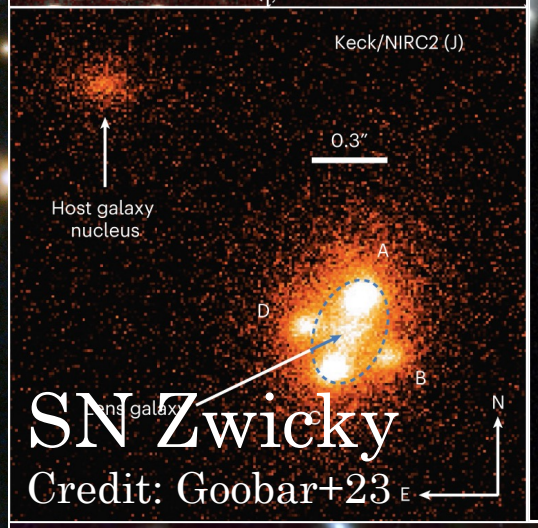
ϕ_{lens} = lensing potential

$D_{\Delta t}$ = distance traveled by delayed image light

SN Refsdal

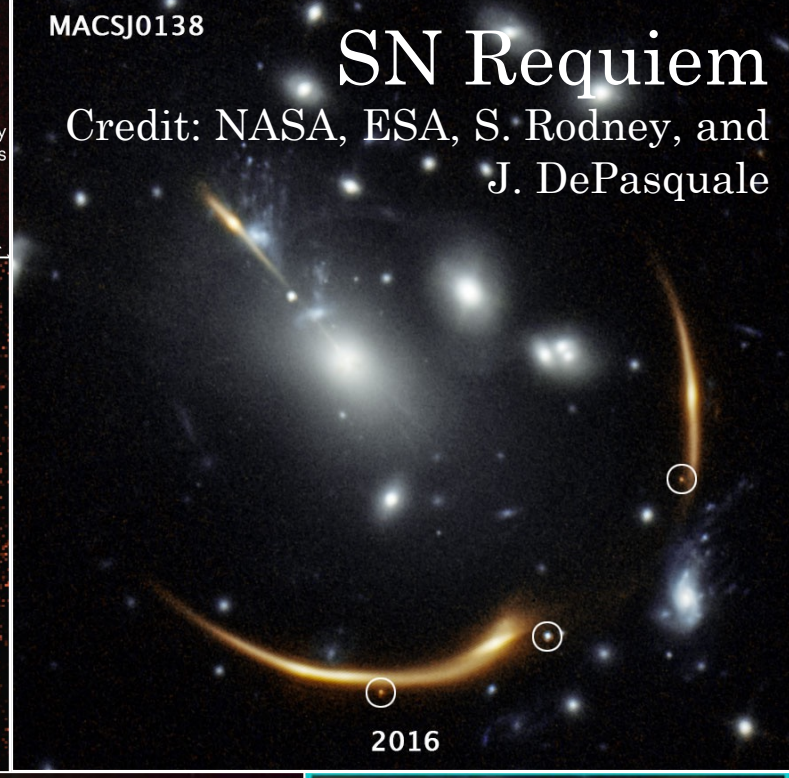
Credit: NASA, ESA, S. Rodney, and the FrontierSN Team





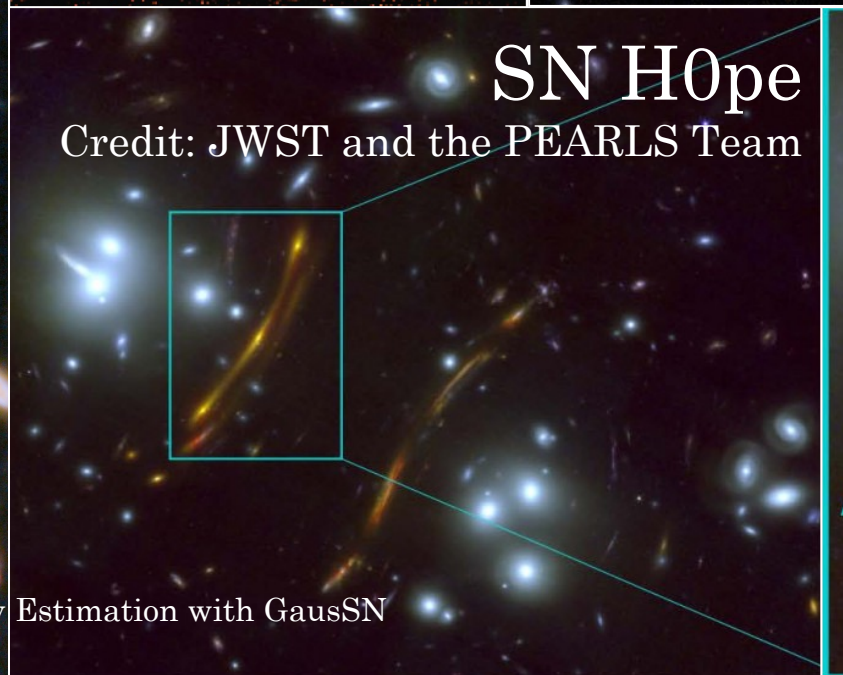
SN Zwicky

Credit: Goobar+23



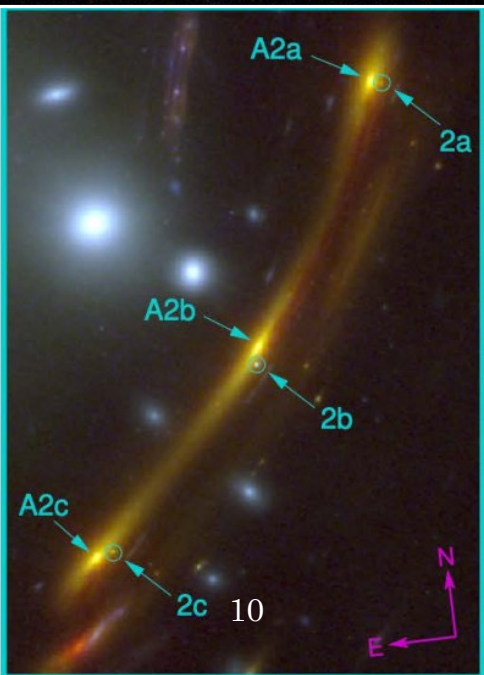
SN Requiem

Credit: NASA, ESA, S. Rodney, and J. DePasquale



SN H0pe

Credit: JWST and the PEARLS Team

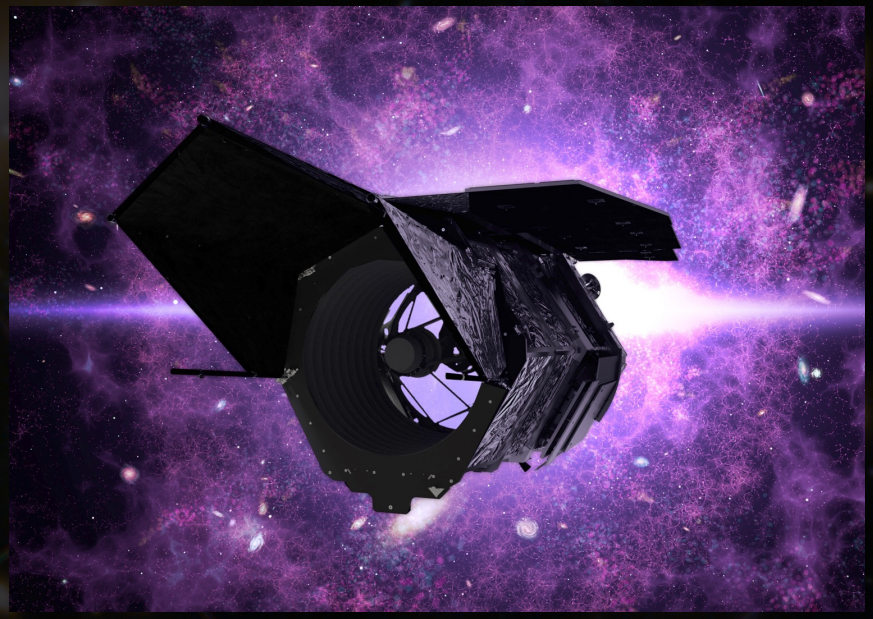


Next Generation Cosmological Surveys

Vera Rubin Observatory's Legacy Survey of Space and Time

Credit: Rubin Observatory, NSF, and AURA

Roman Space Telescope

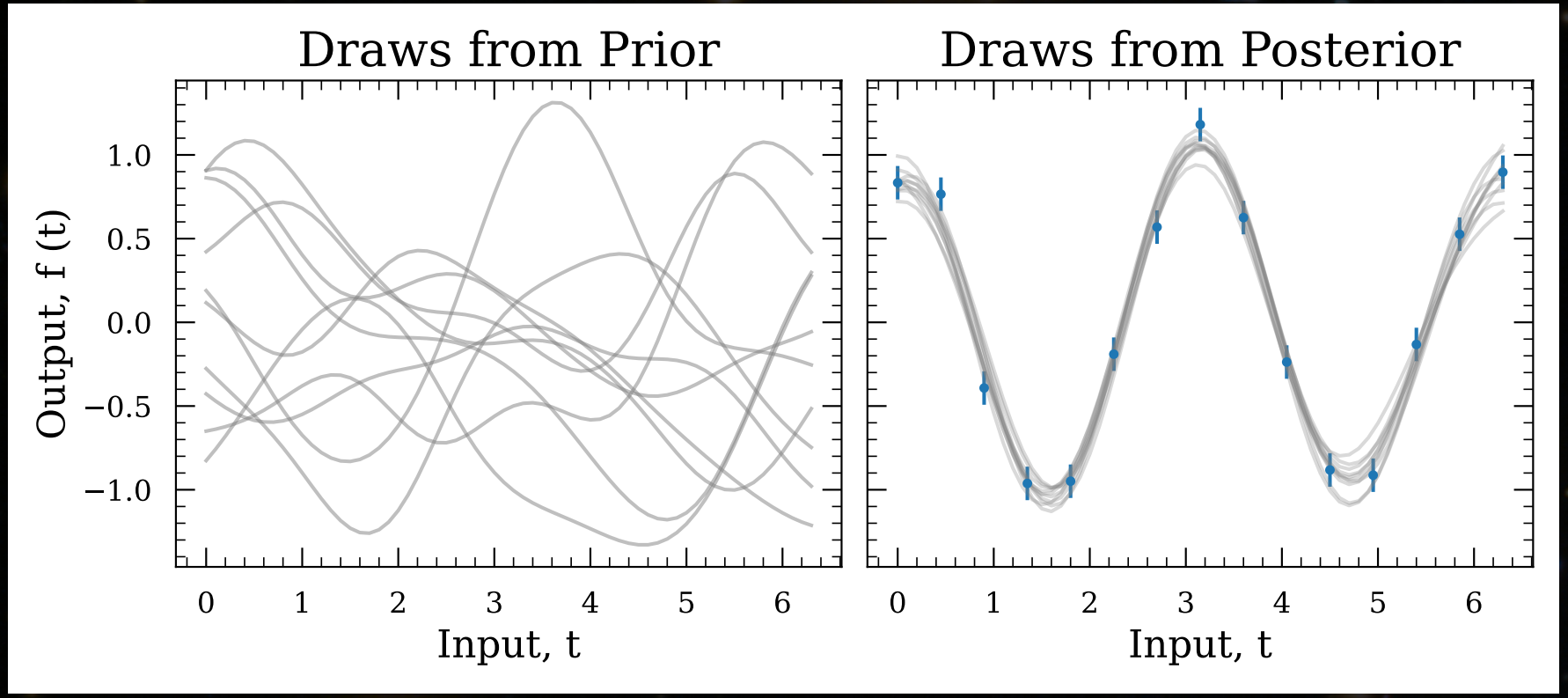


Credit: NASA

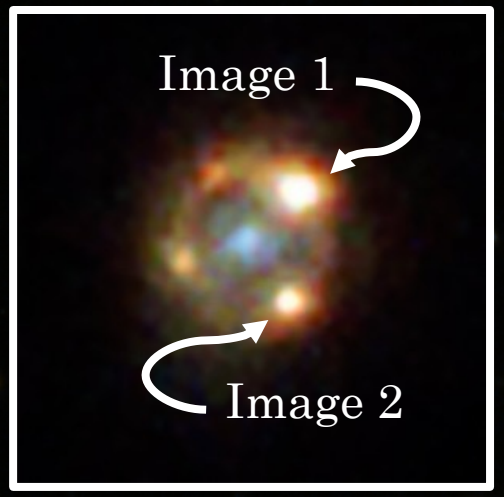
GausSN

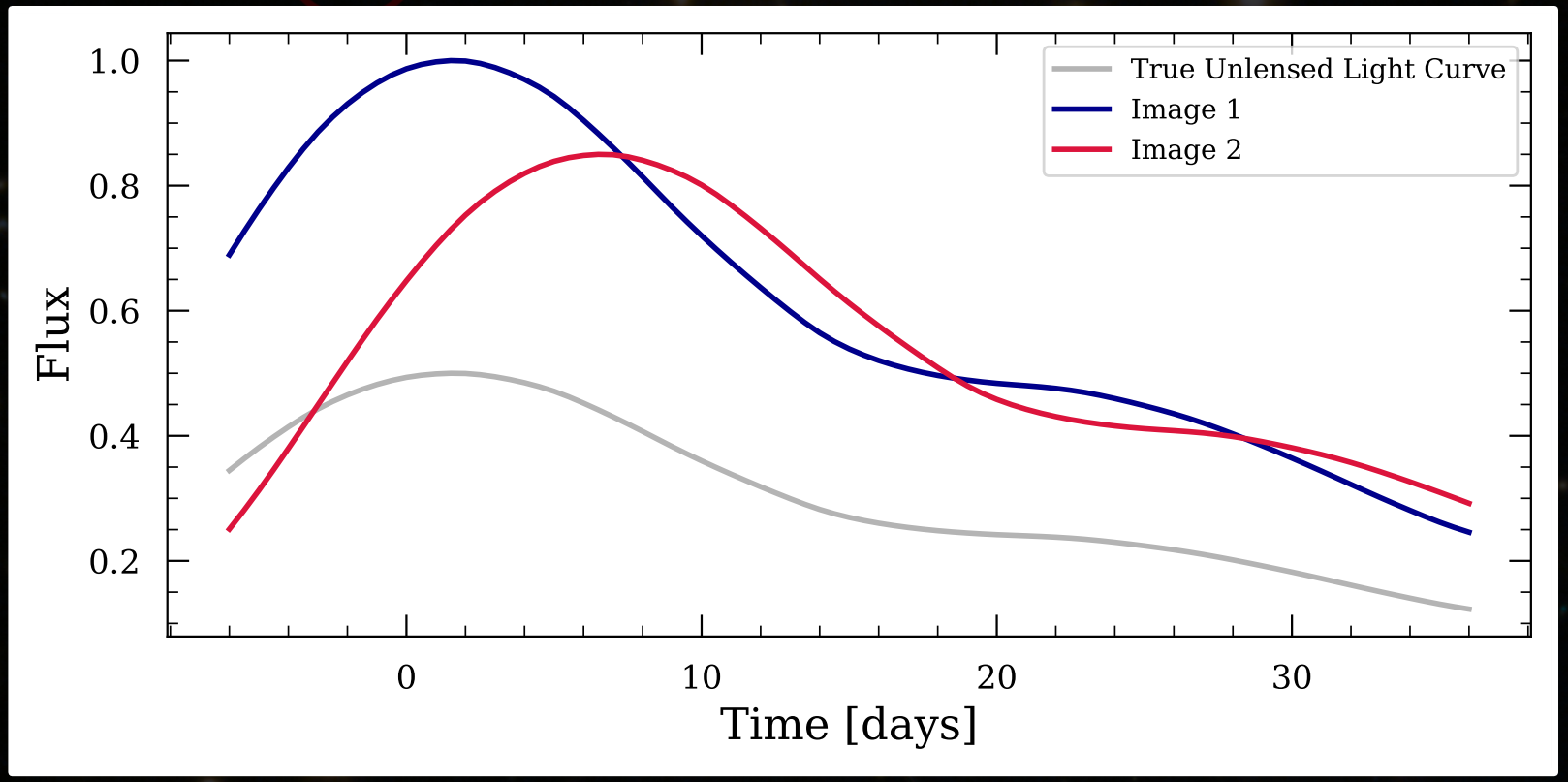
A Bayesian Gaussian Process (GP) Approach for Time Delay Estimation

$$f(t) = N\big(m(t), K(t,t)\big)$$

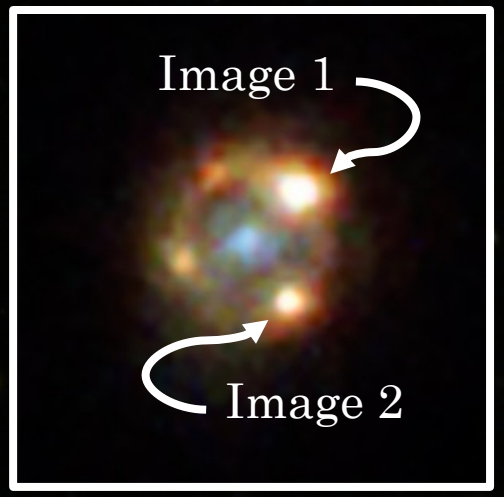


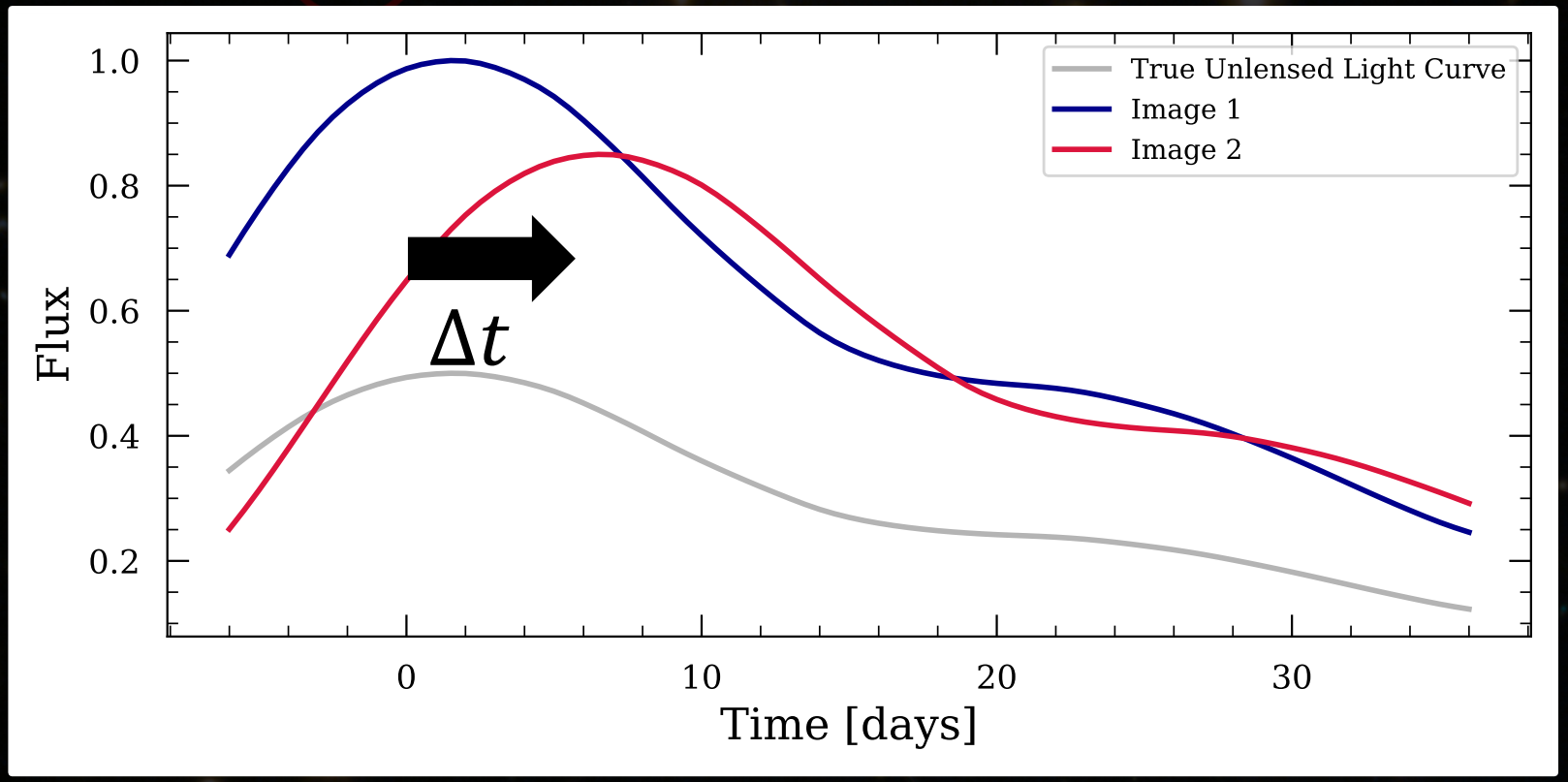
The GausSN Model



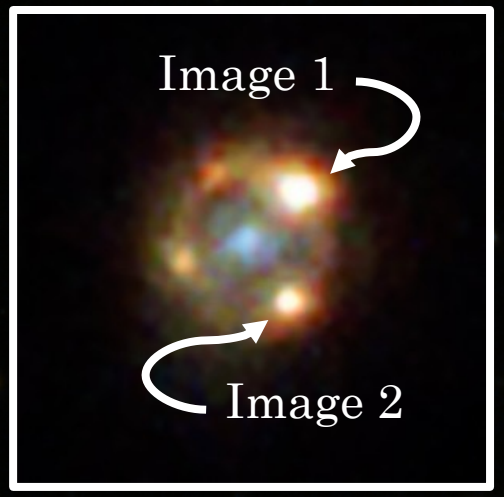


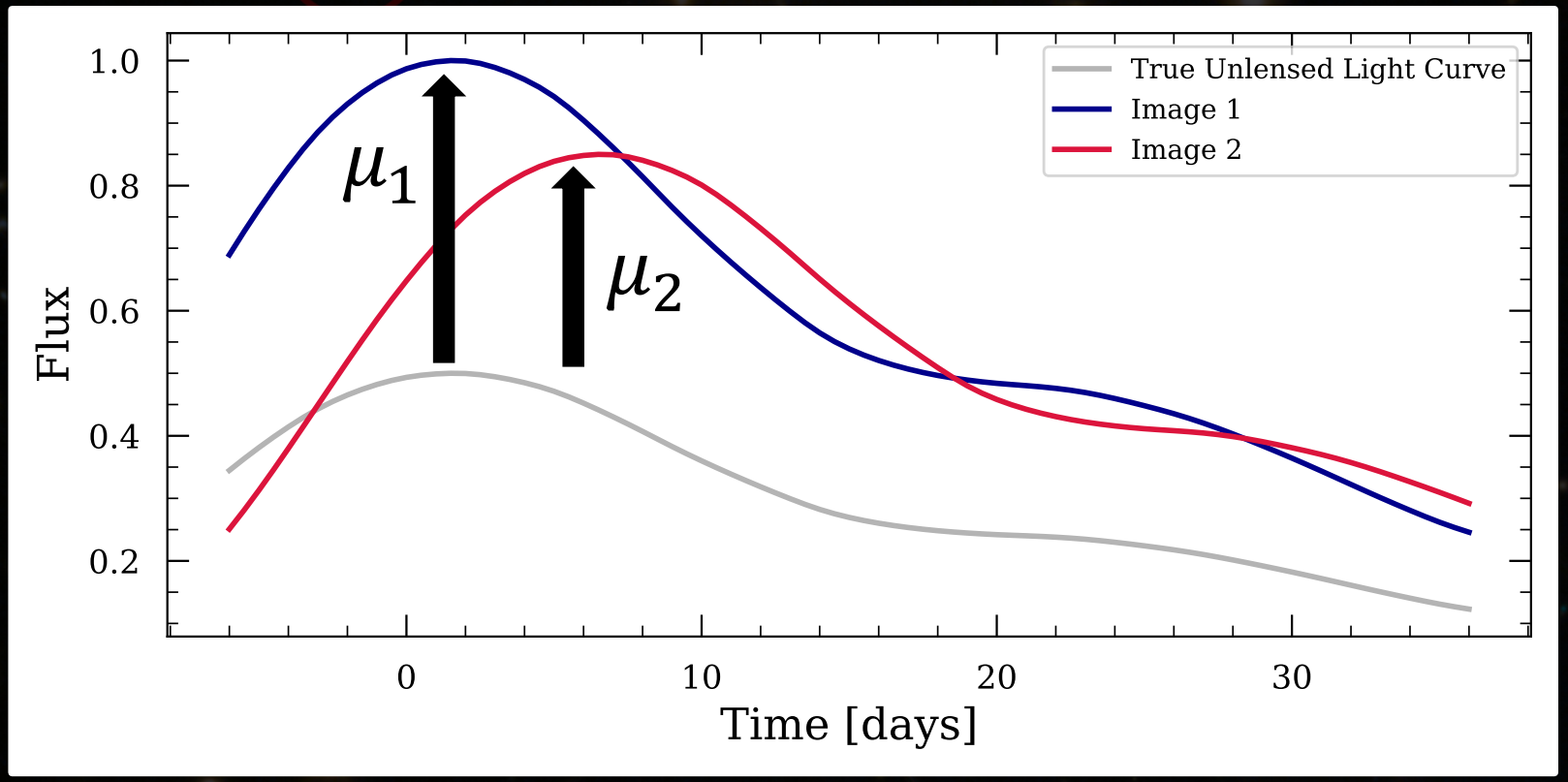
The Time Delay



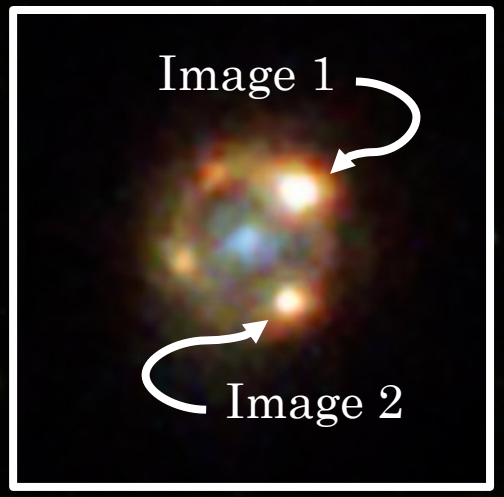


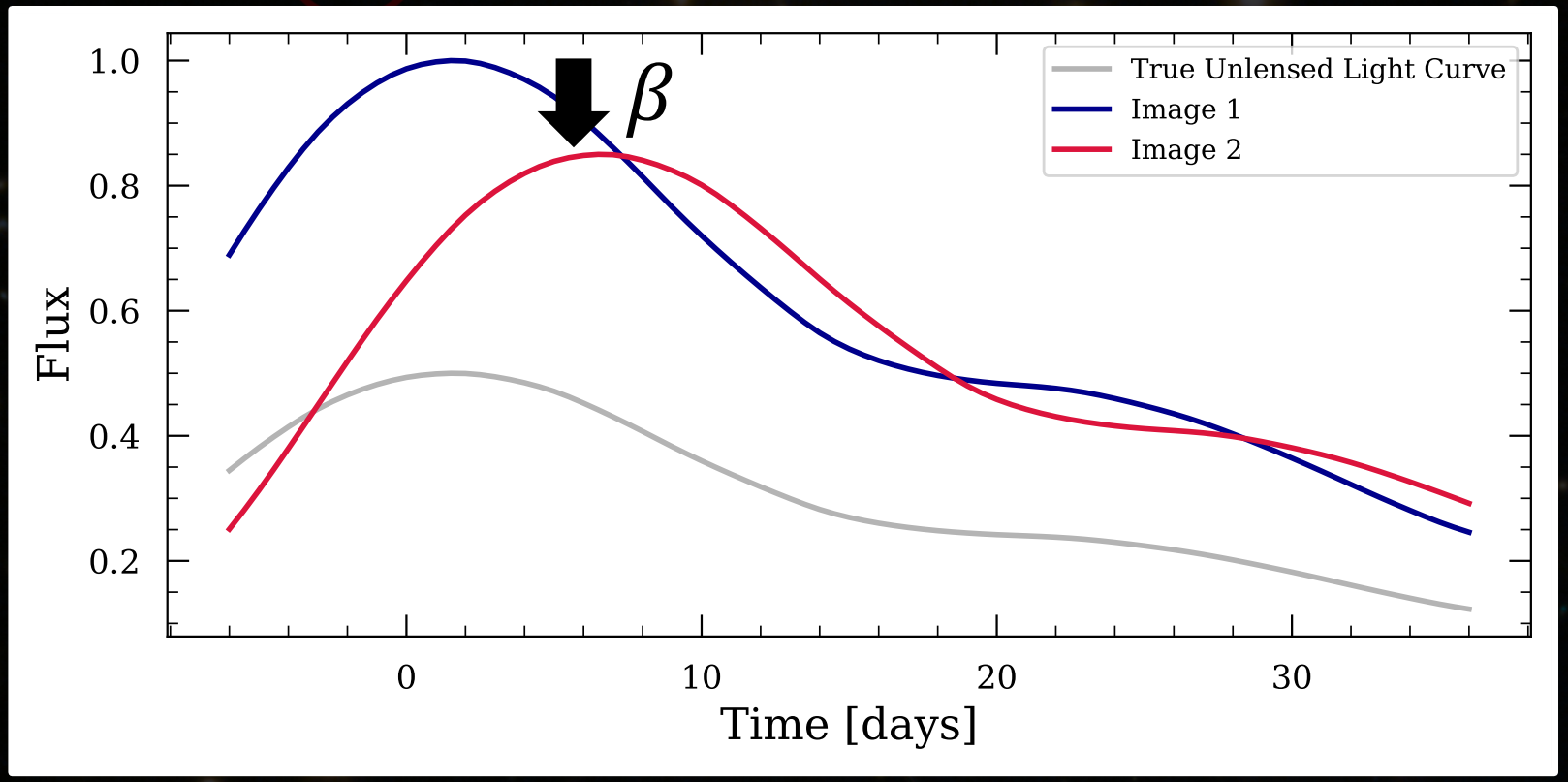
The Magnification



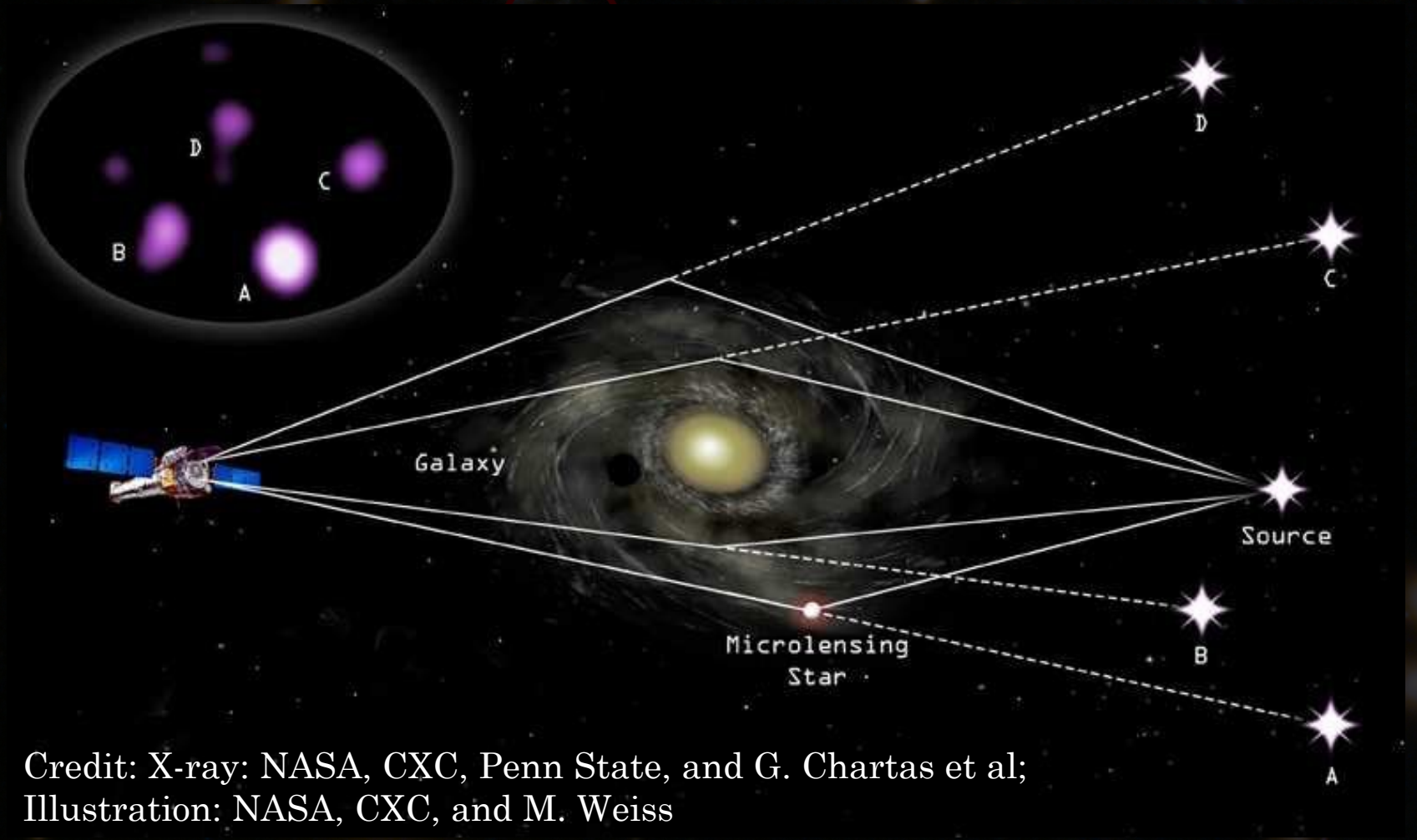


The (Relative) Magnification



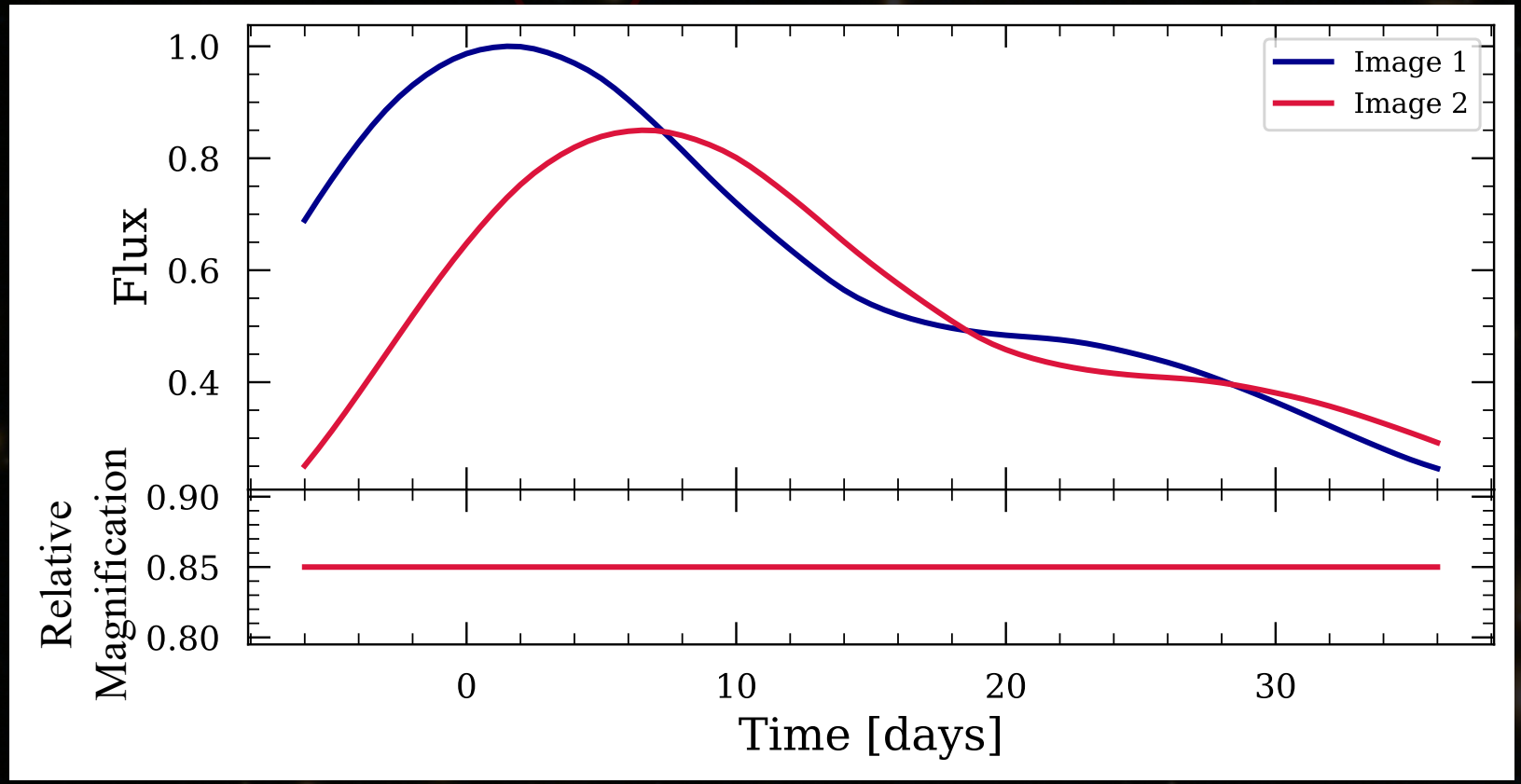


Microlensing

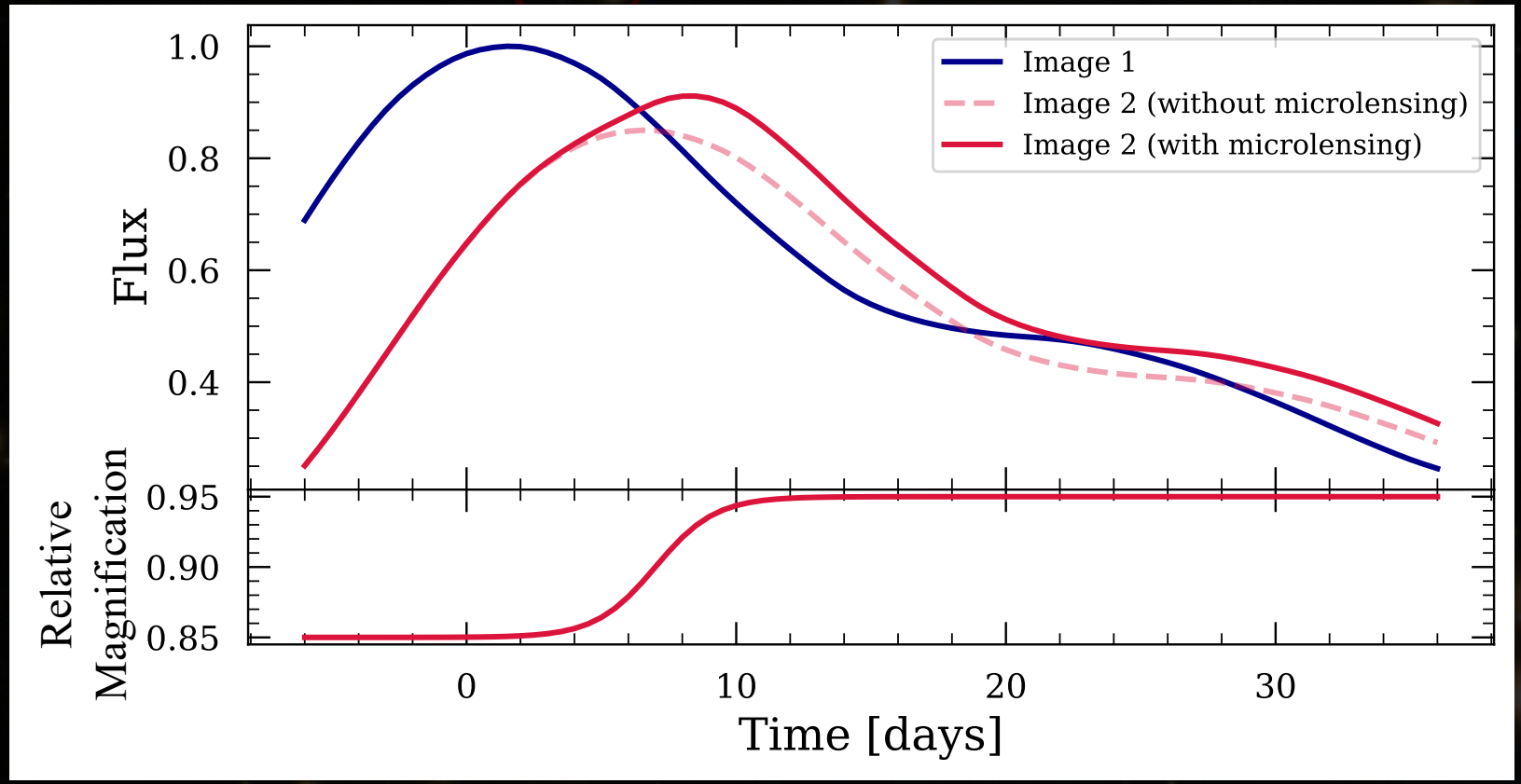


Credit: X-ray: NASA, CXC, Penn State, and G. Chartas et al;
Illustration: NASA, CXC, and M. Weiss

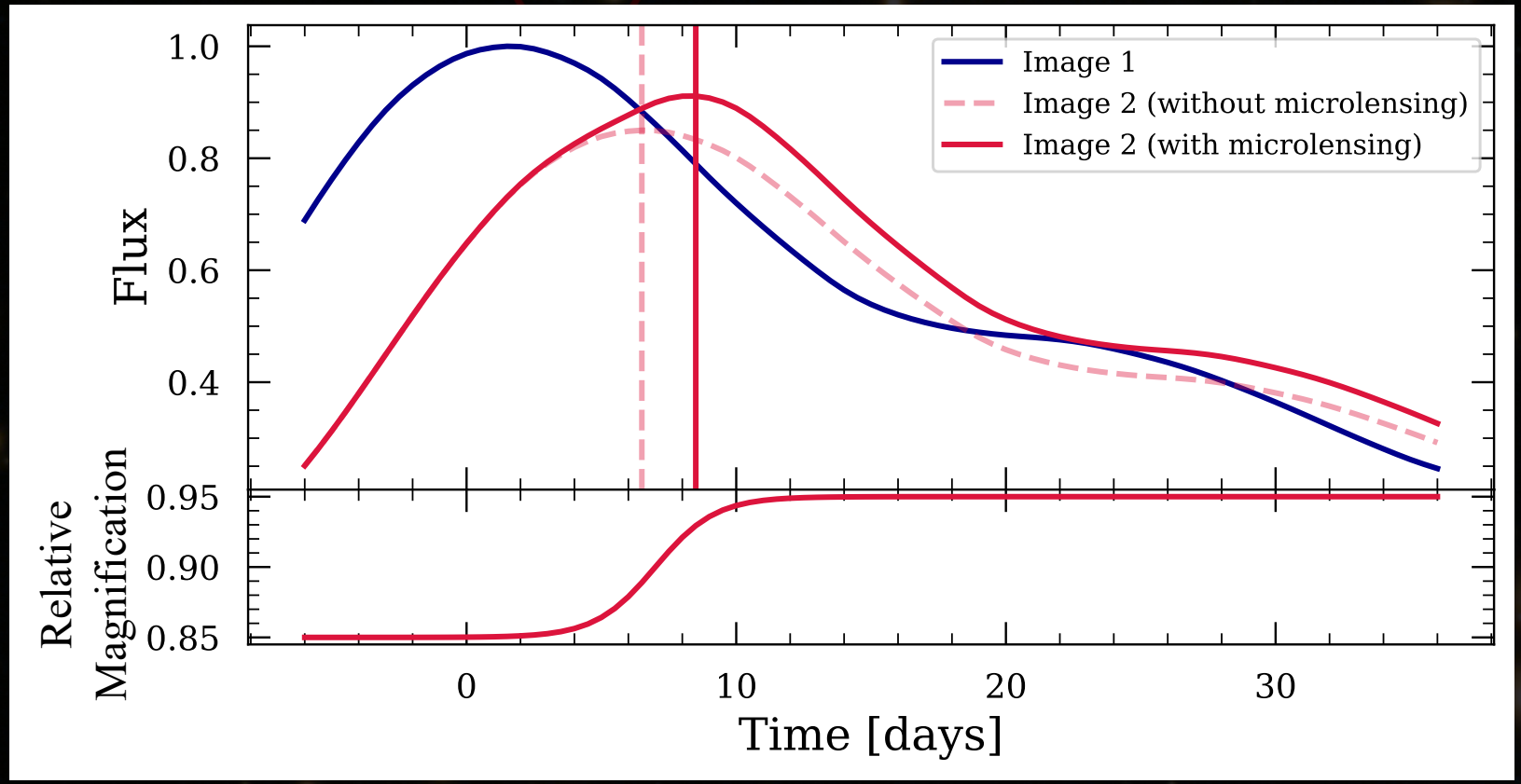
Microlensing



Microlensing



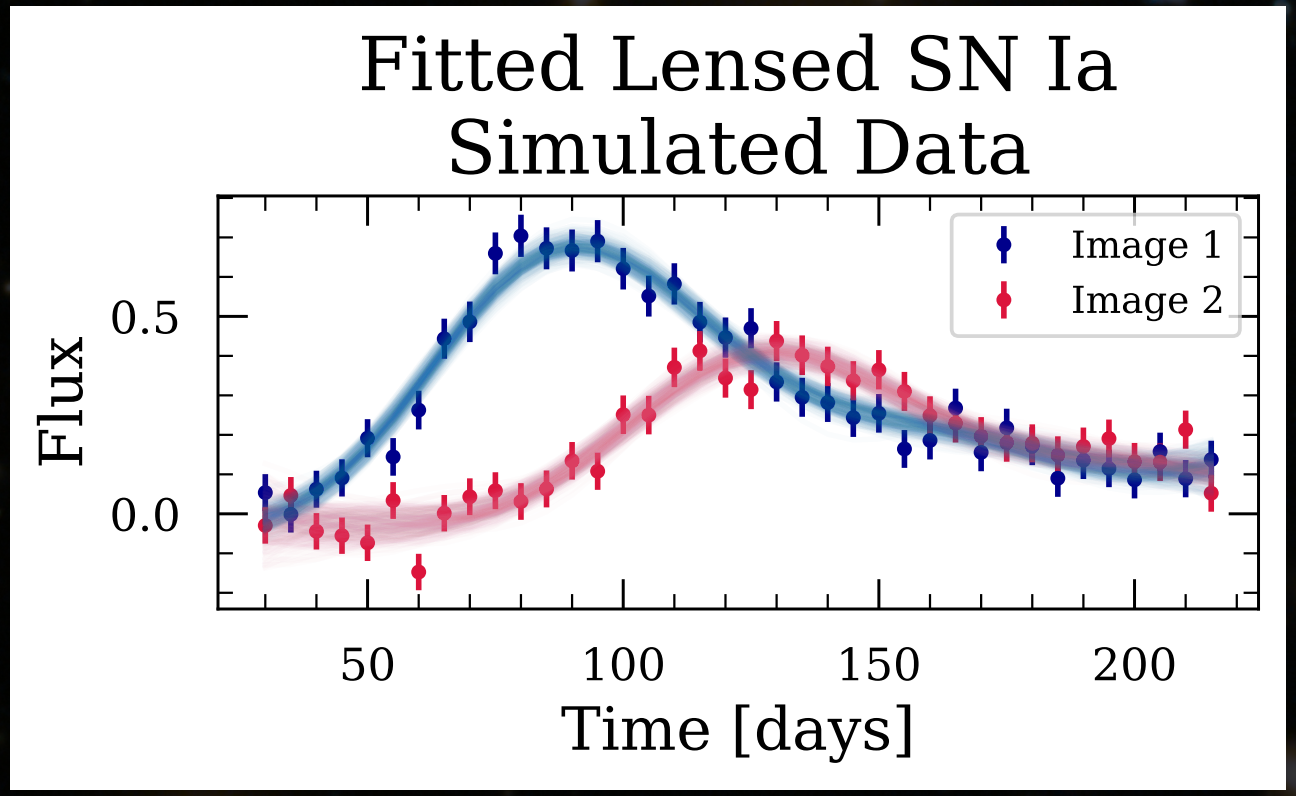
Microlensing



GausSN

A Bayesian Gaussian Process (GP) Approach for Time Delay Estimation

$$f(t) = N\big(m(t), K_\theta(t,t)\big)$$

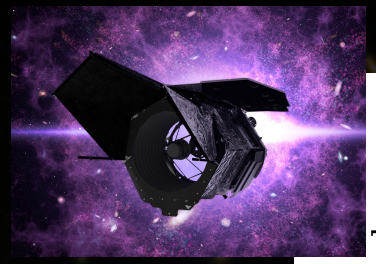


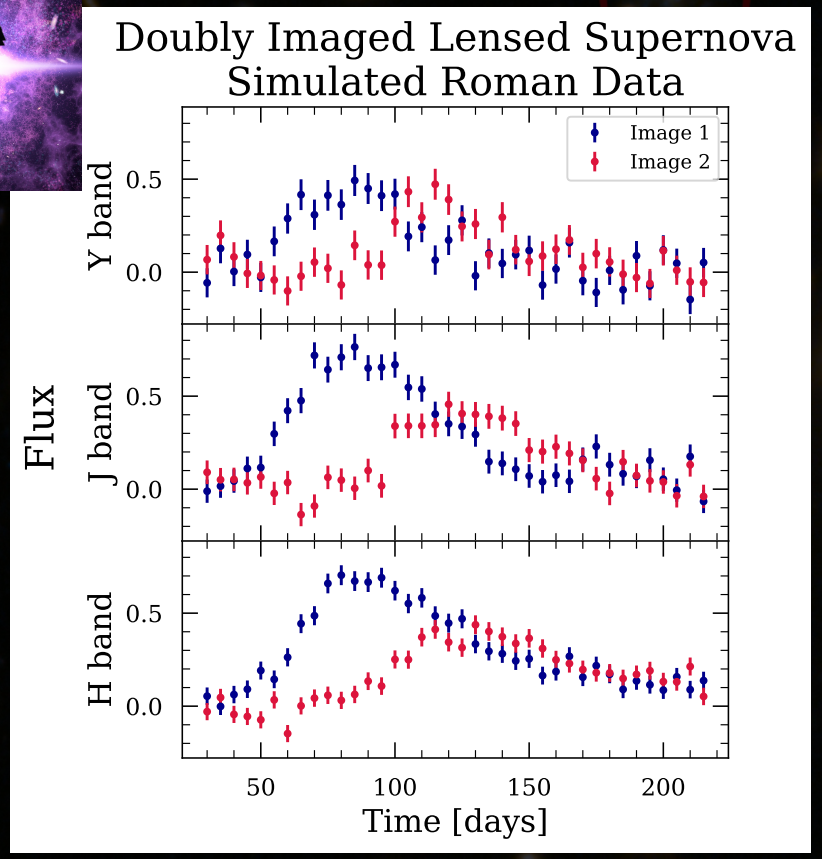
GausSN

A Bayesian Gaussian Process (GP) Approach for Time Delay Estimation

- Models the light curves of **any SN Type** as a draw from a Gaussian Process
- Treats macro- and micro-lensing together alongside time delay estimation
- Fits any number of images in any number of bands **simultaneously**
- Fully Bayesian treatment of system parameters
  - Sample posteriors using MCMC or nested sampling

Roman Space Telescope Simulations





- From Pierel, et. al., 2021
- Simulations of lensed supernovae (SNe)
- Cadence and depth emulate expected Roman data
- Realistic time delay and magnification distributions
- Realistic microlensing treatment

Roman Space Telescope Simulations

Constant Lensing Model

- Describes lensing as a constant in time:

$$\beta(t) = \beta_0$$

- Allows direct comparison to existing field standard template-based time delay estimation technique

Sigmoid Lensing Model

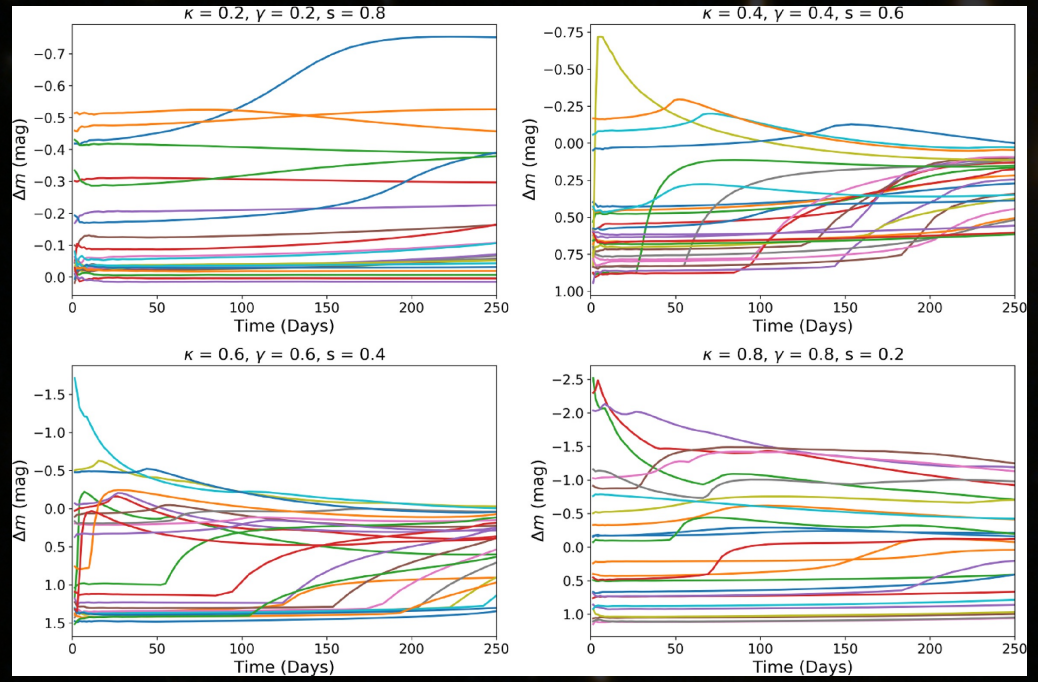
- Describes lensing as a sigmoid function:

$$\beta(t) = \beta_0 + \frac{\beta_1}{1 + \exp(-r(t - t_0))}$$

- Novel time-varying lensing treatment in time delay estimation

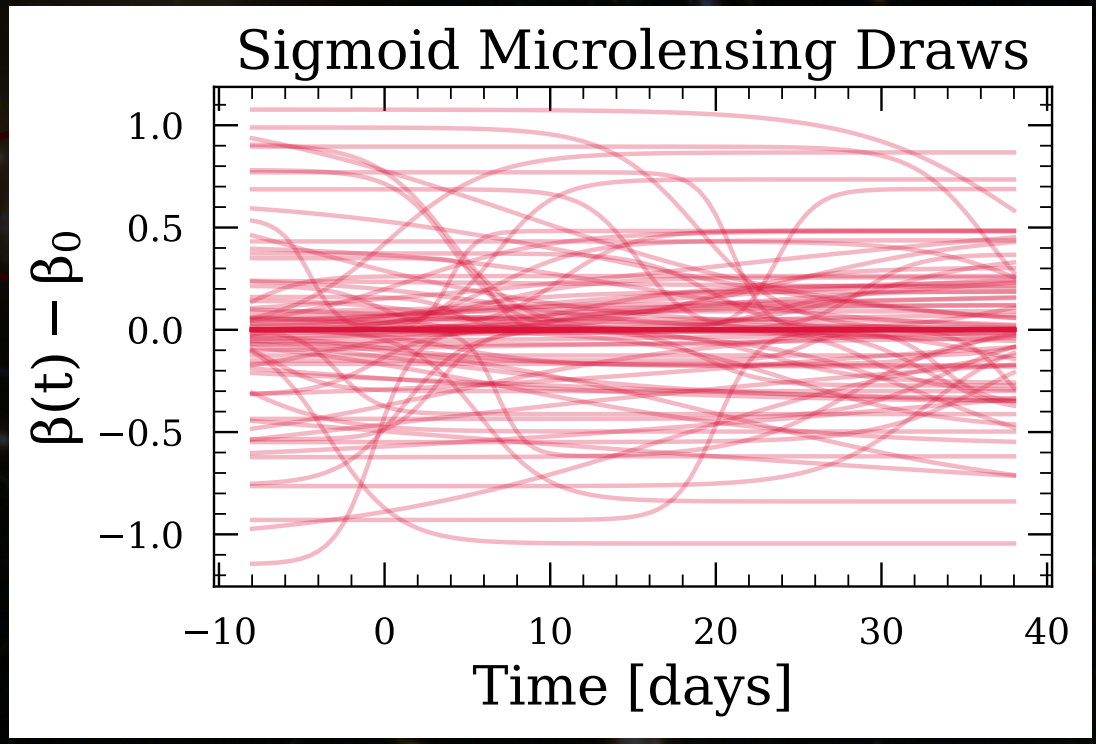
Roman Space Telescope Simulations

Realistic Microlensing Simulations

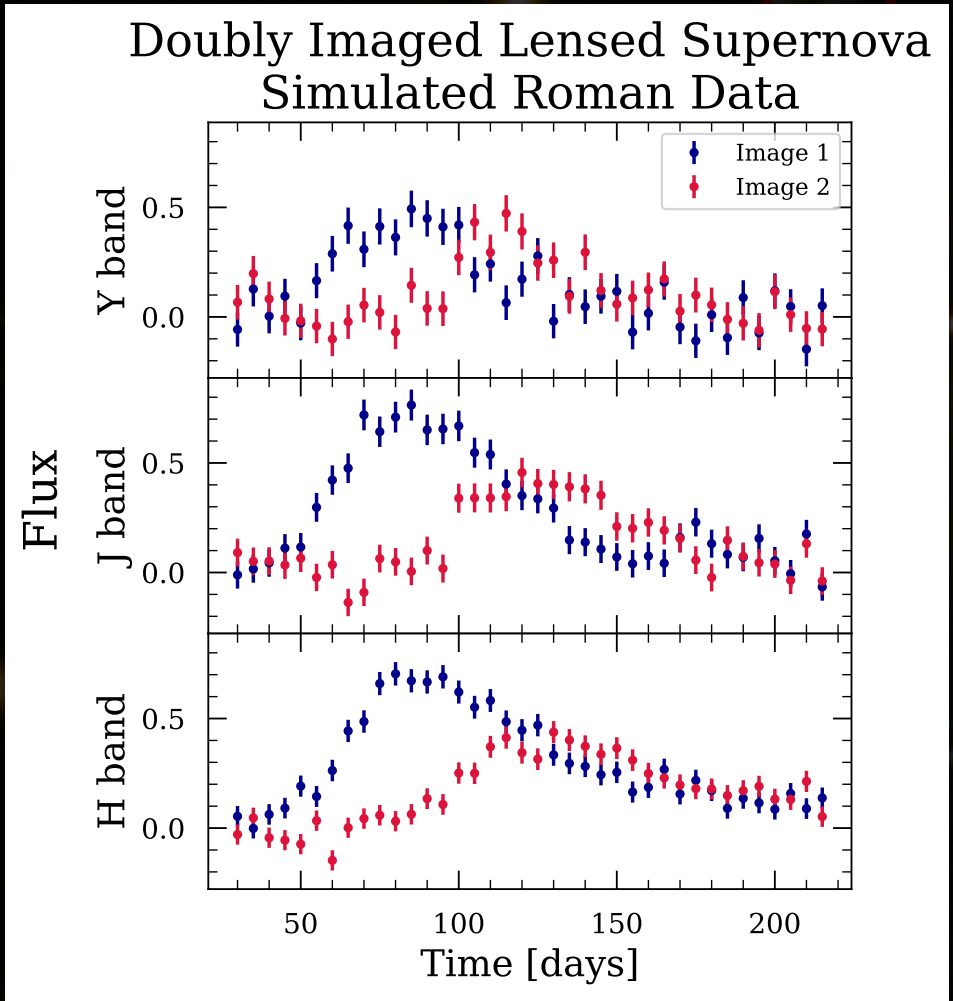


Credit: Foxley-Marrable+18

Sigmoid Lensing Model

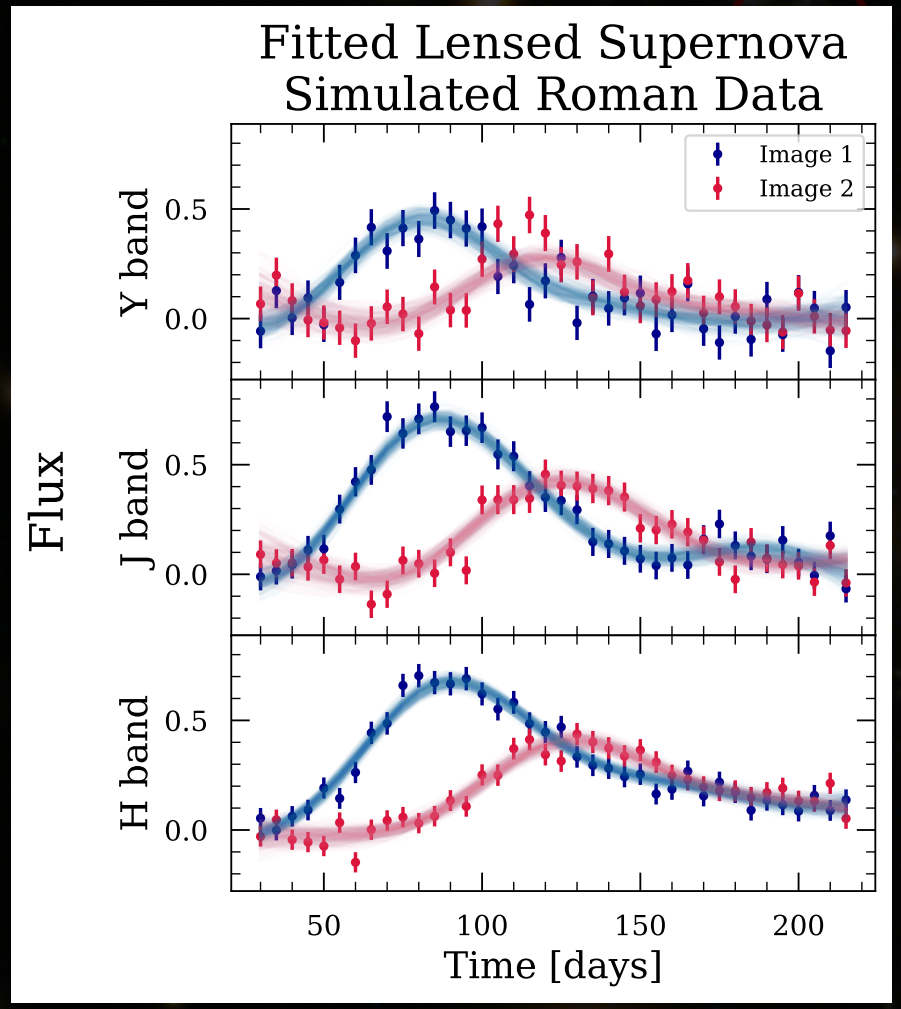


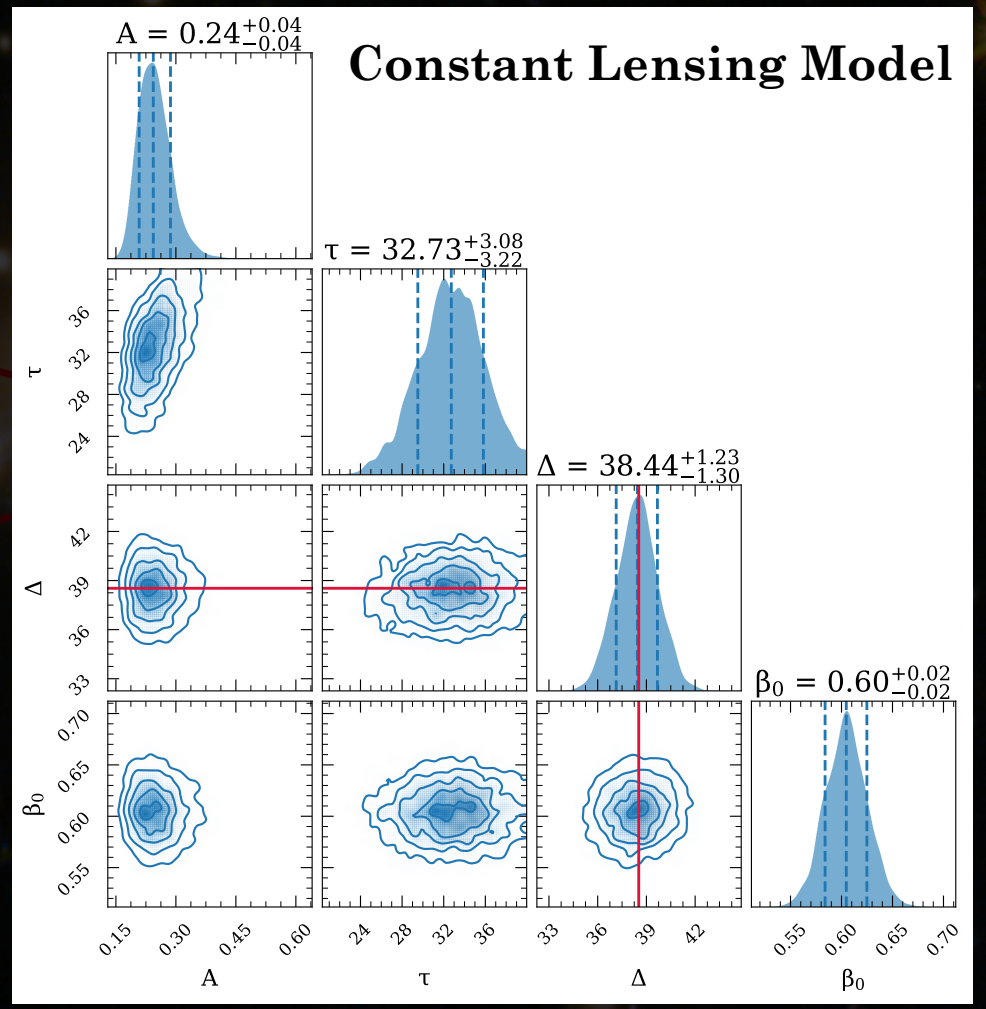
Results: Individual Object Level



- Doubly-imaged lensed Type Ia Supernova (SN Ia) at $z = 1.93$
- Time delay, $\Delta = 38.53$ days
- Observed in Roman's *Y*-, *J*-, and *H*-bands
- Fitting 304 data points takes:
  - 13 minutes for constant lensing model (4 parameters)
  - 18 minutes for sigmoid lensing model (7 parameters)

Results: Individual Object Level





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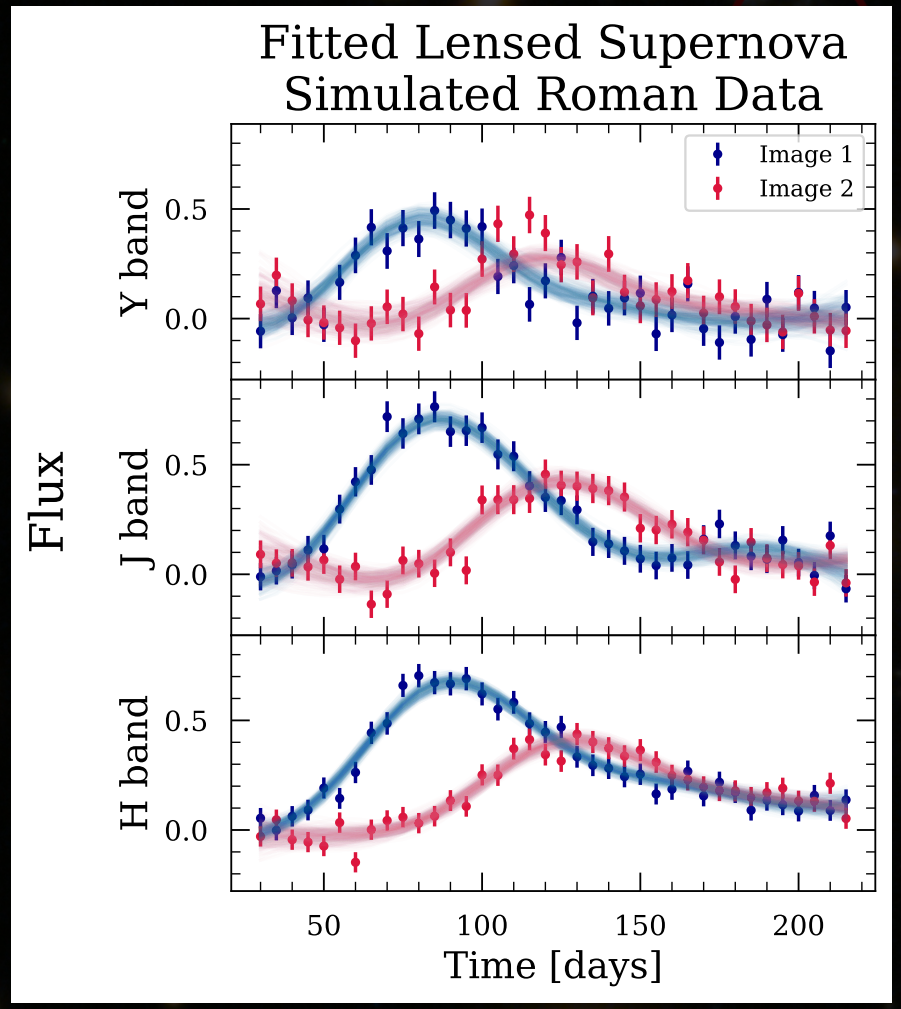

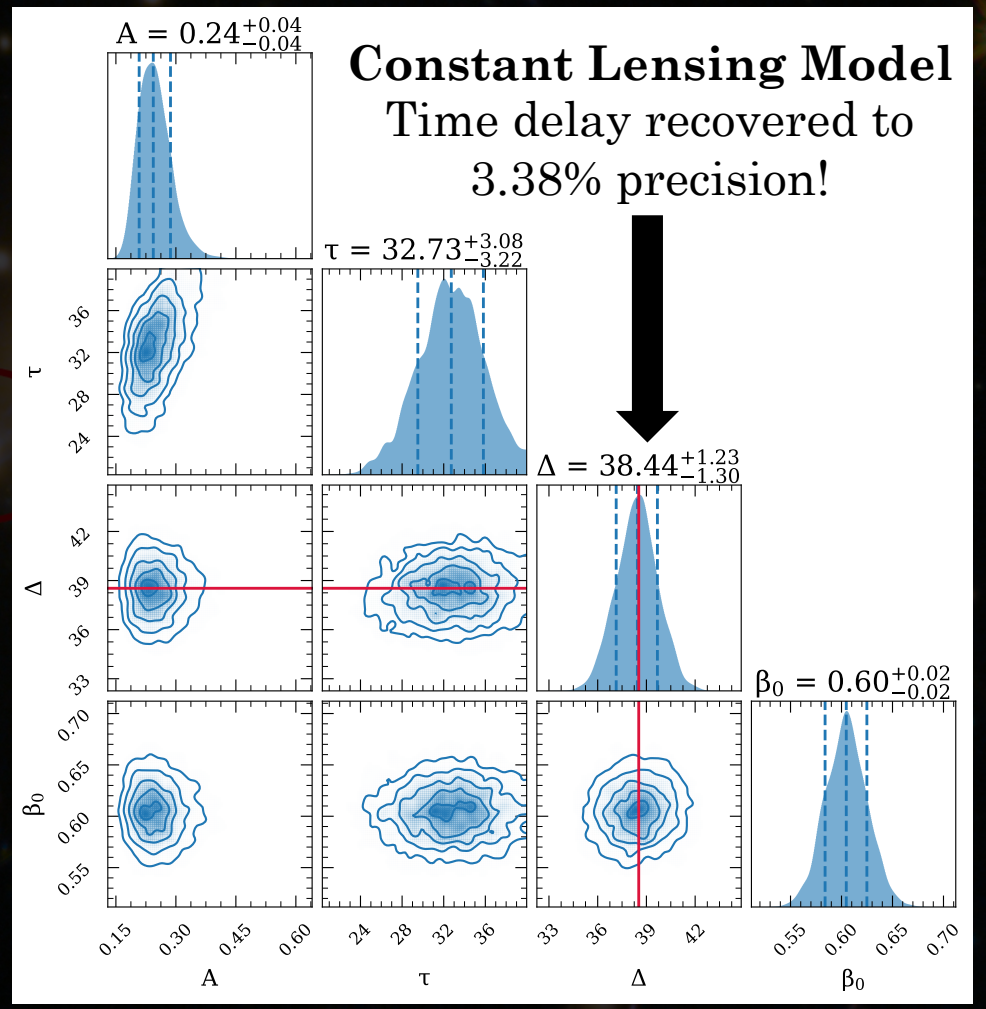

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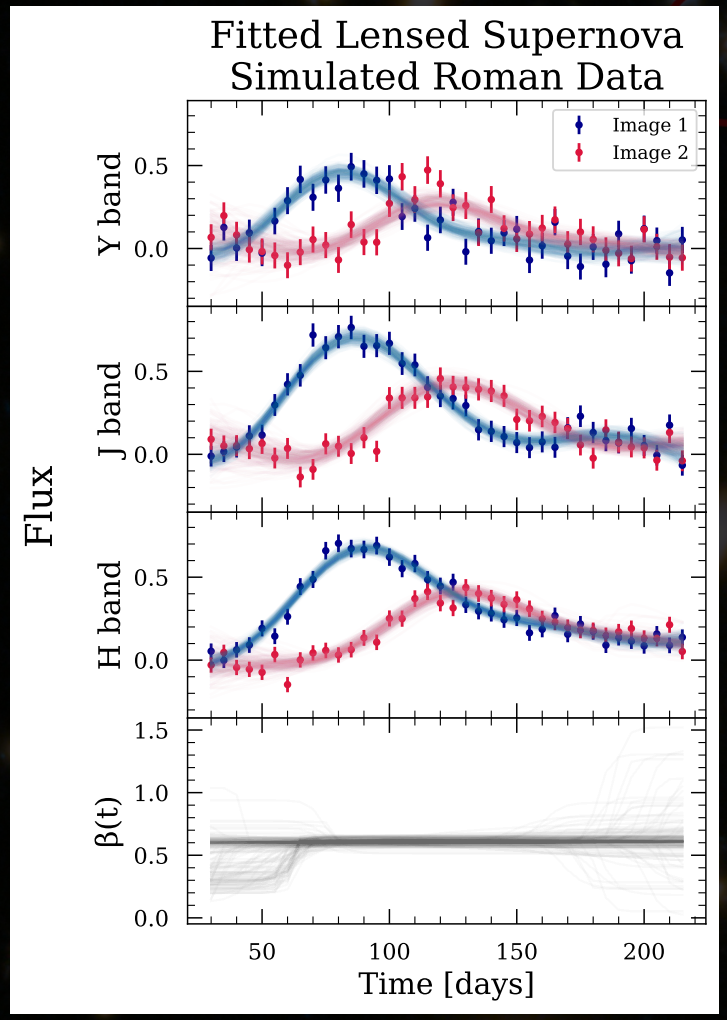
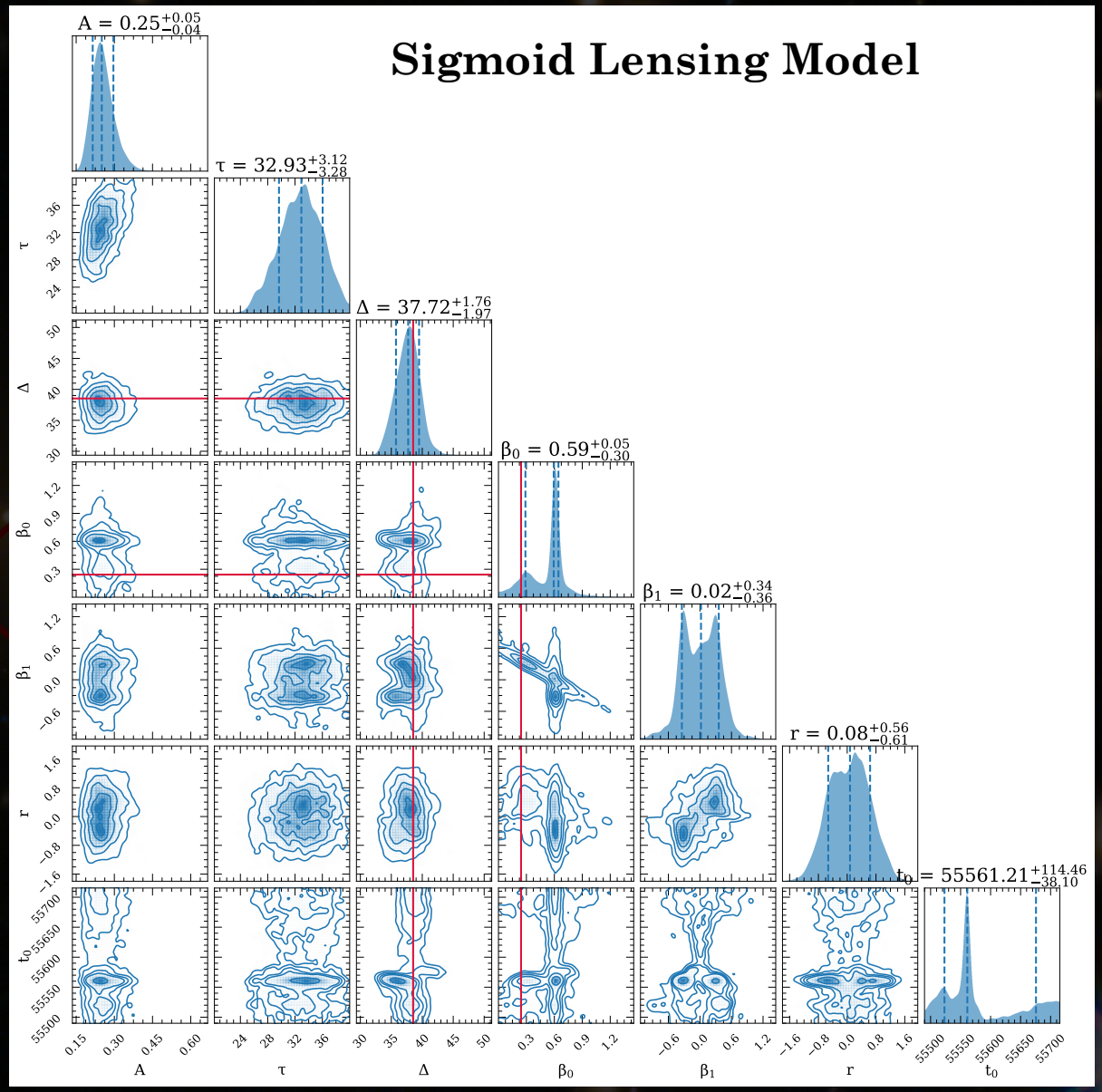
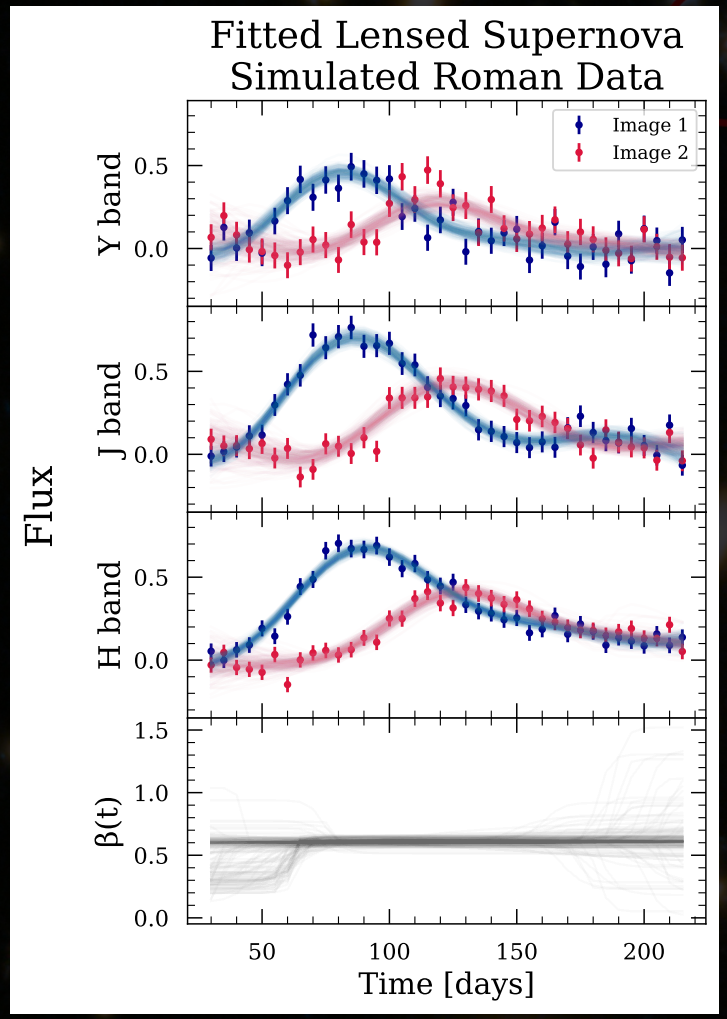
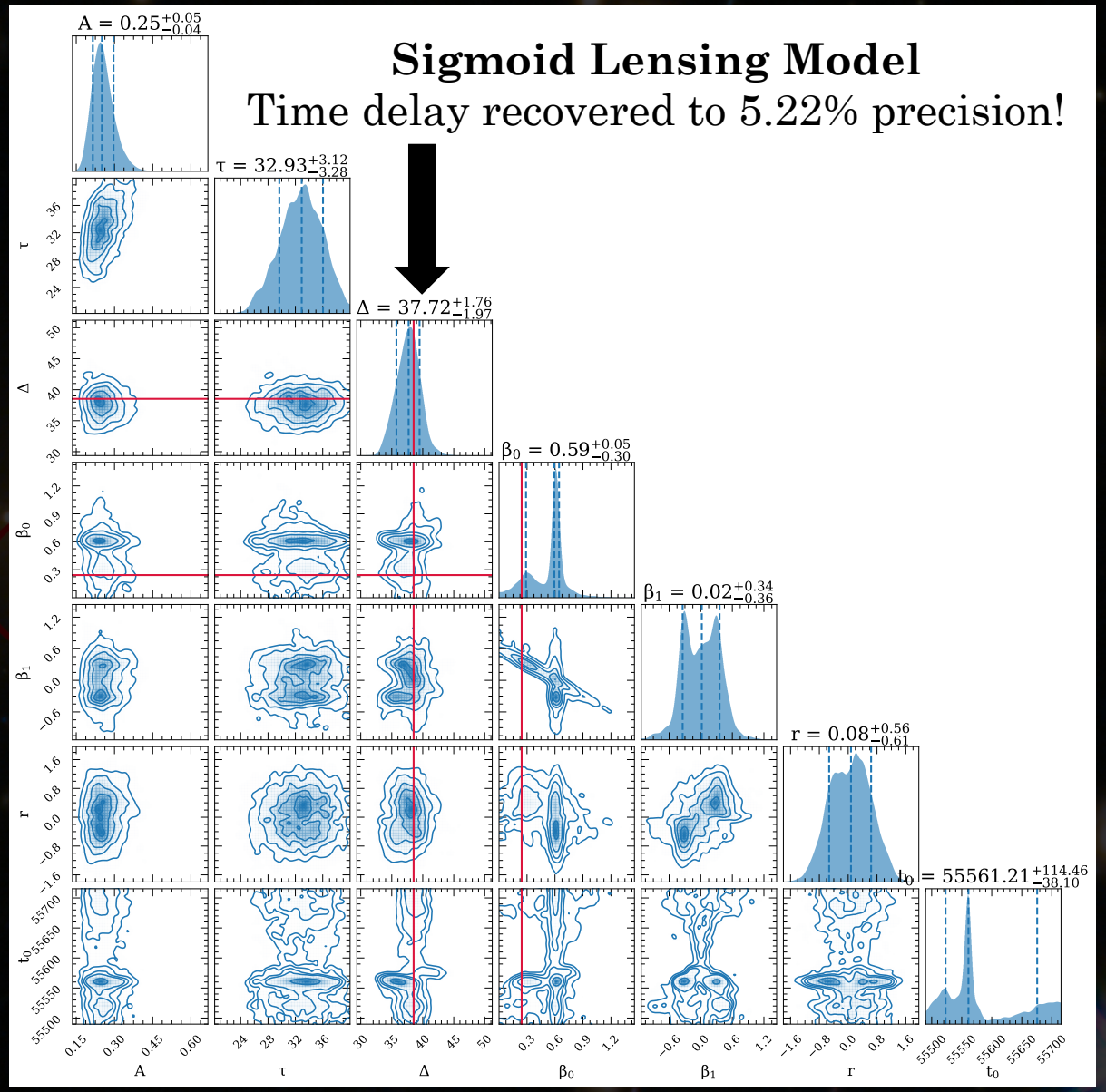


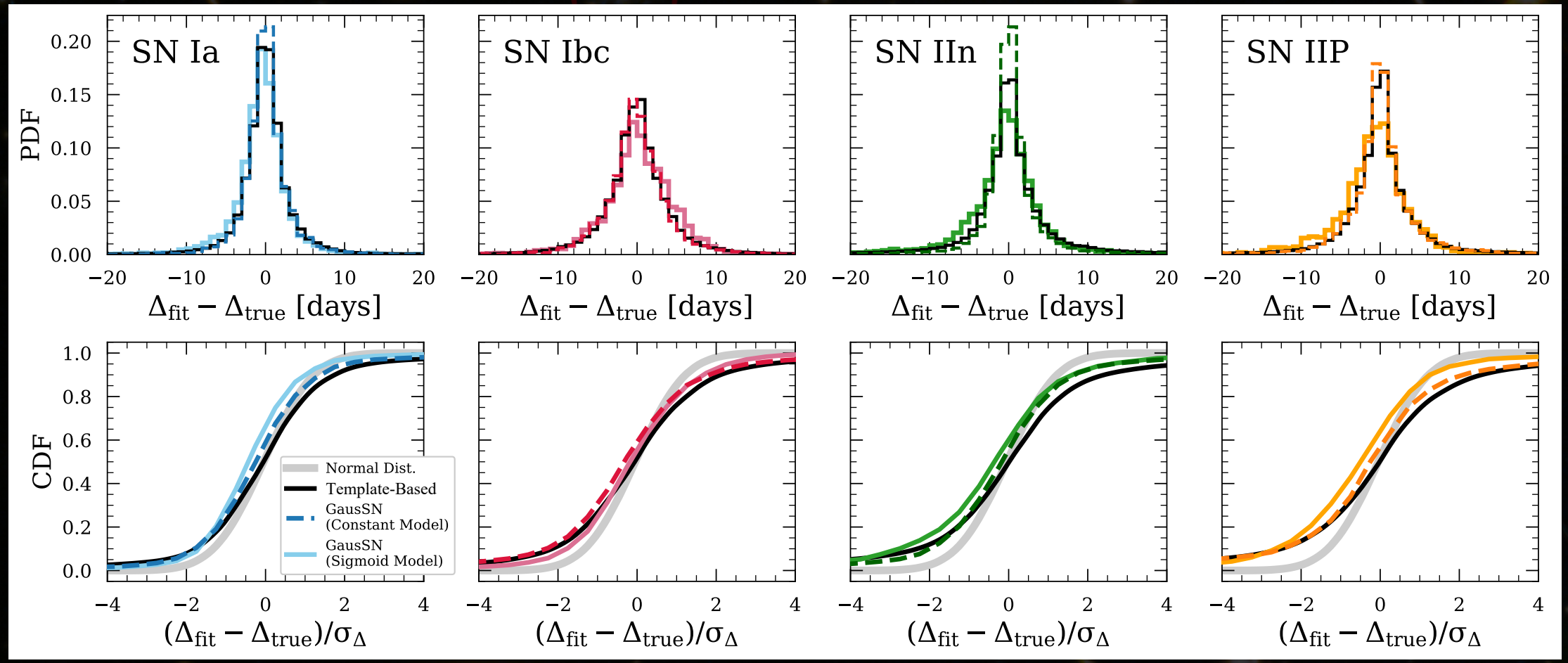


Results: Individual Object Level





Results: Population Level



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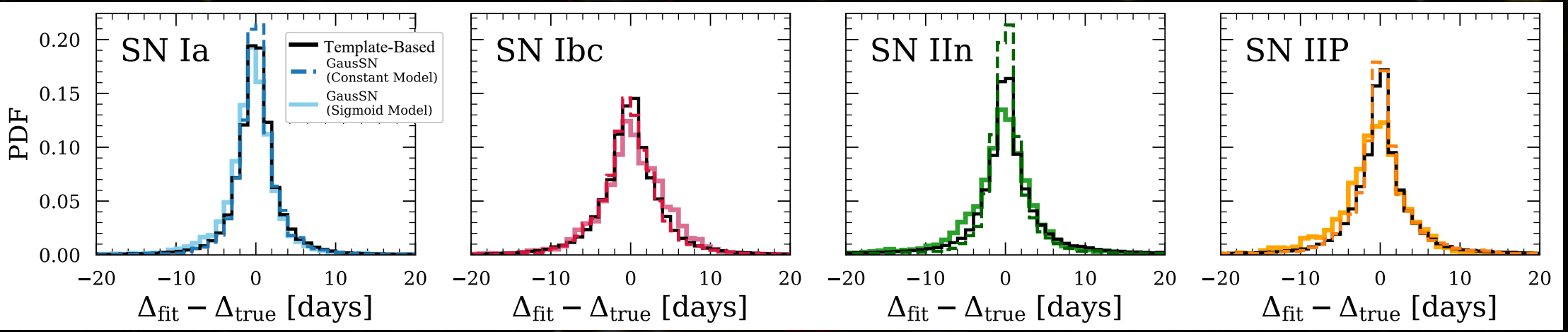
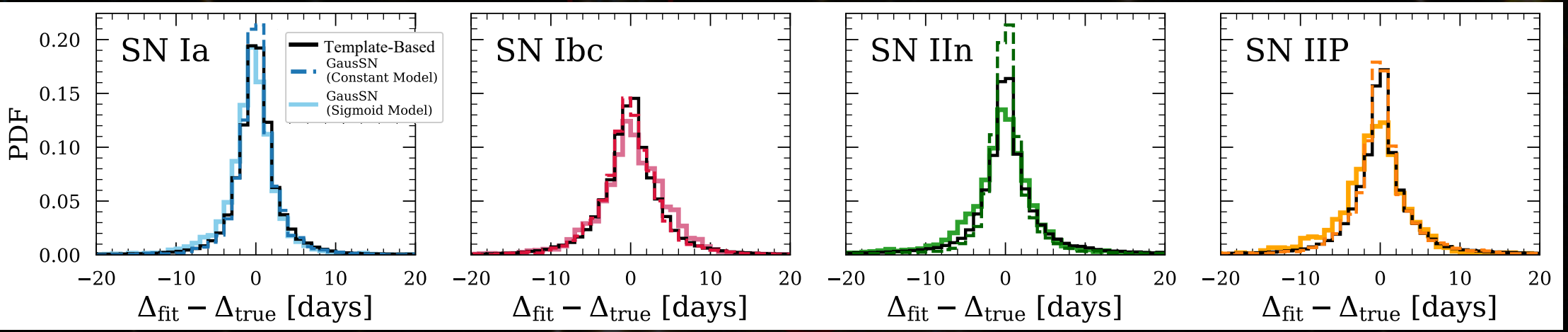


GausSN Sigmoid: 27.7% within 1 day, 62.7% within 3 days

GausSN Constant: 35.3% within 1 day, 70.4% within 3 days

Template-Based: 33.2% within 1 day, 61.6% within 3 days

Results: Population Level



GausSN makes fewer assumptions than leading template-based approach, while maintaining similar performance in time delay recovery!

Conclusions

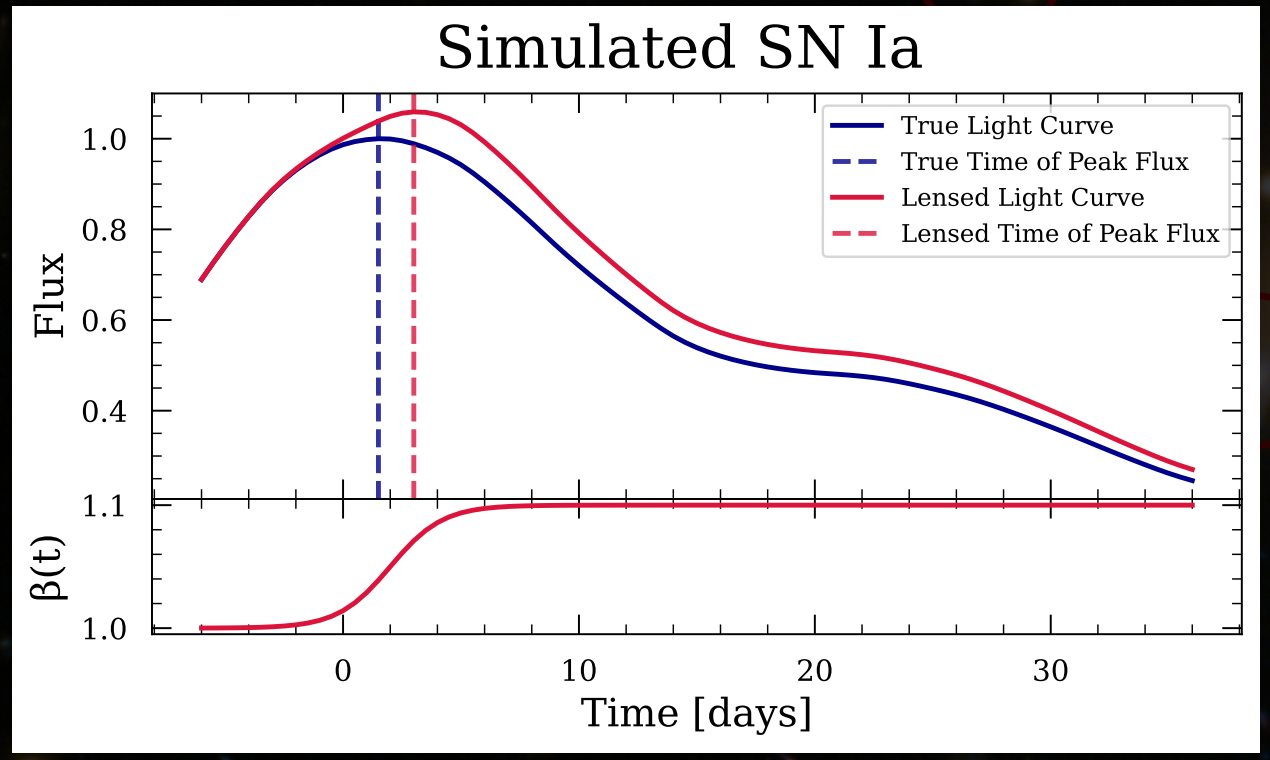
- GausSN provides competitive time delay estimates that:
  - have fully Bayesian uncertainties, with uncertainties due to microlensing baked in
  - are not sensitive to fine tuning
  - make minimal assumptions about the underlying light curve shape, therefore minimizing sources of systematic uncertainties
- Lensing treatment is novel and robust, with modular implementation for easy testing of other parameterizations
- Scalable given current projections of lensed SN discovery rate from current and upcoming telescopes

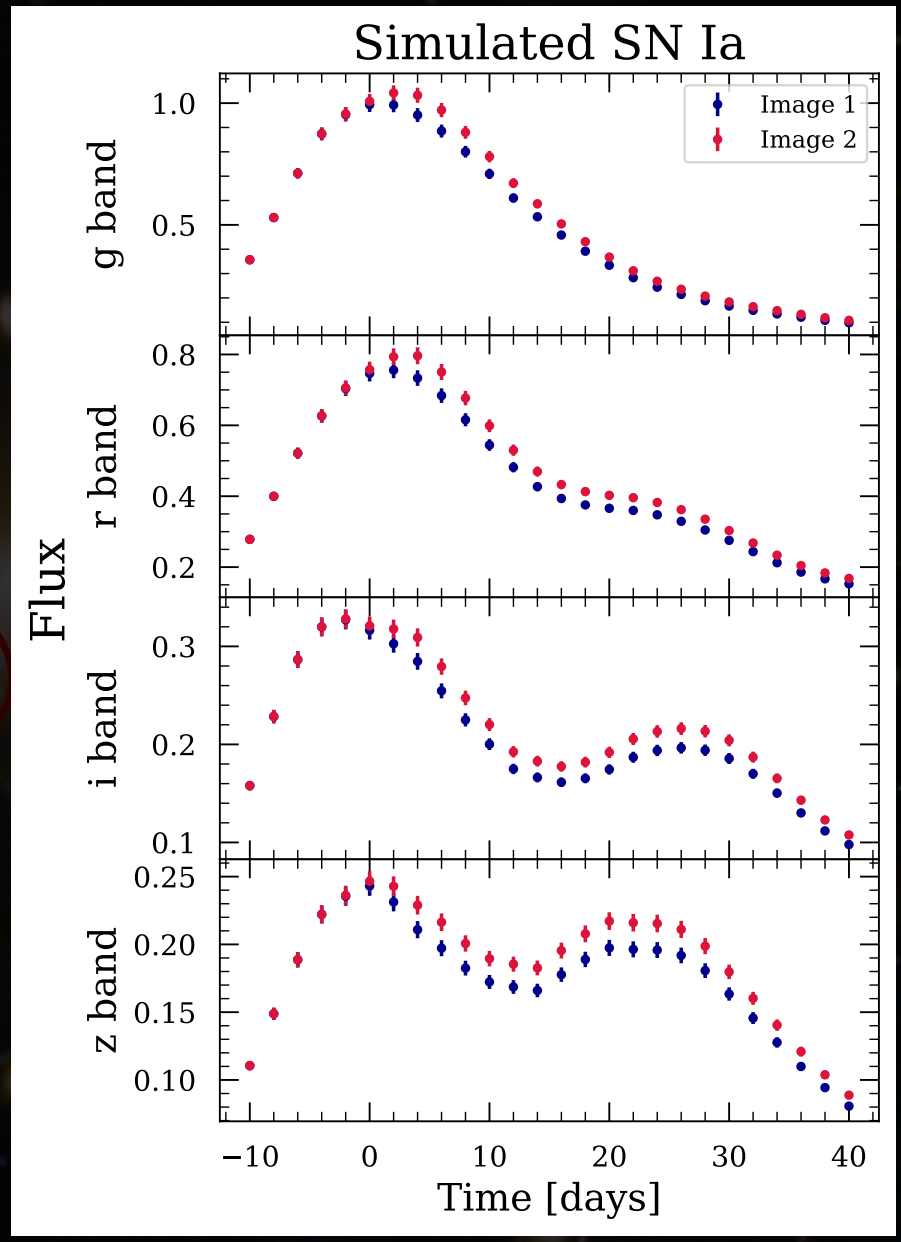
arXiv: 2311.17997

We expect an exciting next decade for lensed supernova cosmography!

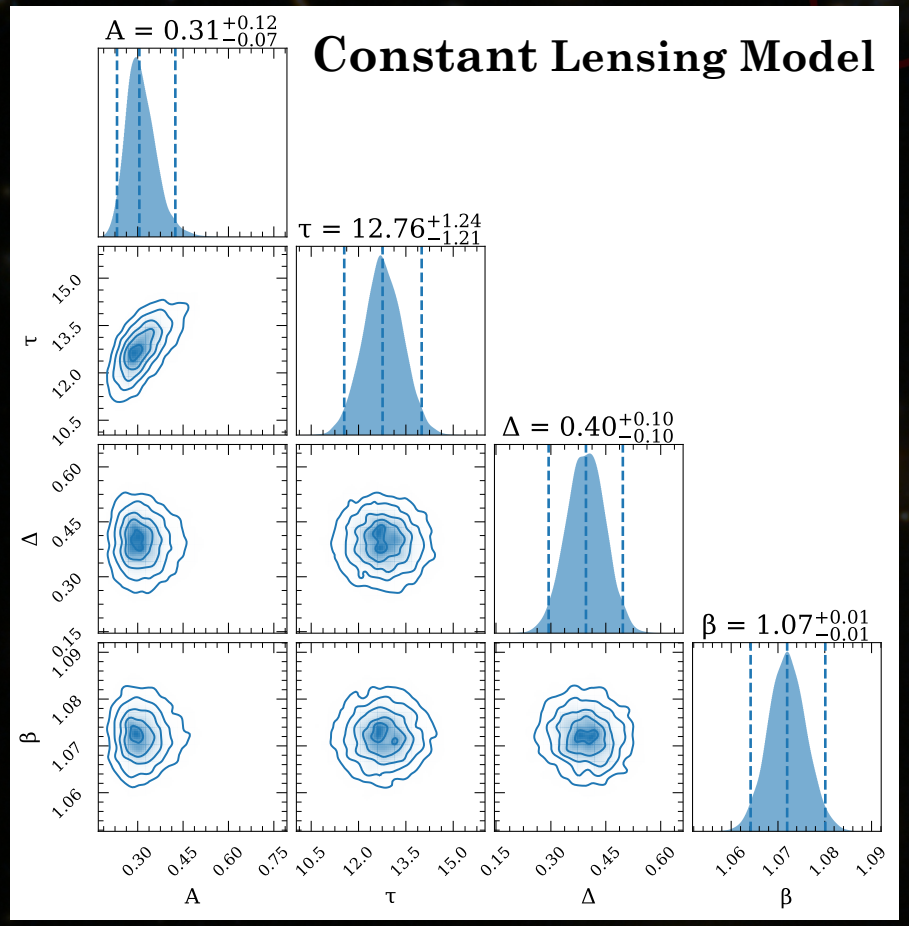
Credit: Rubin Observatory, NSF, and AURA

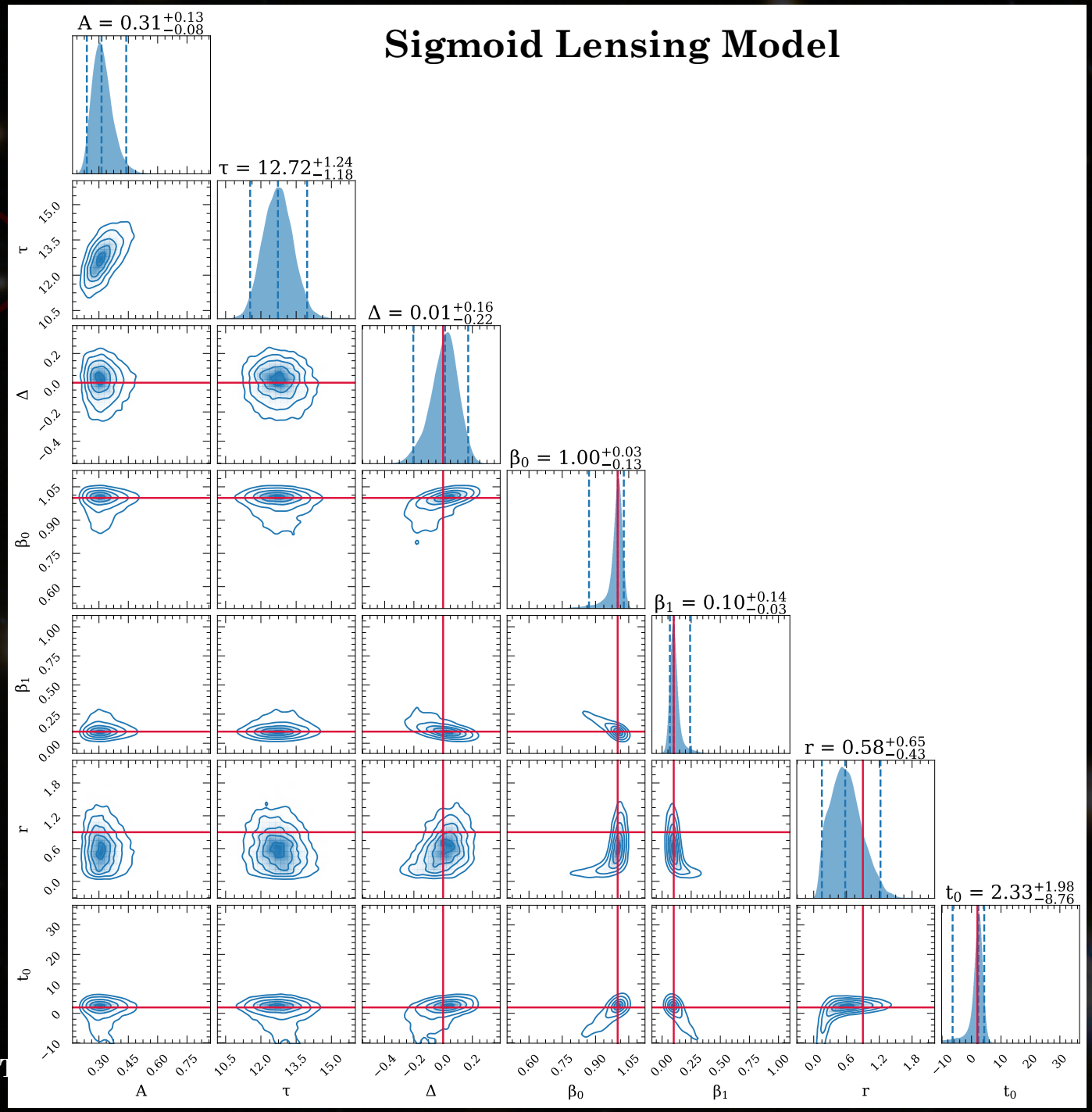
Microlensing



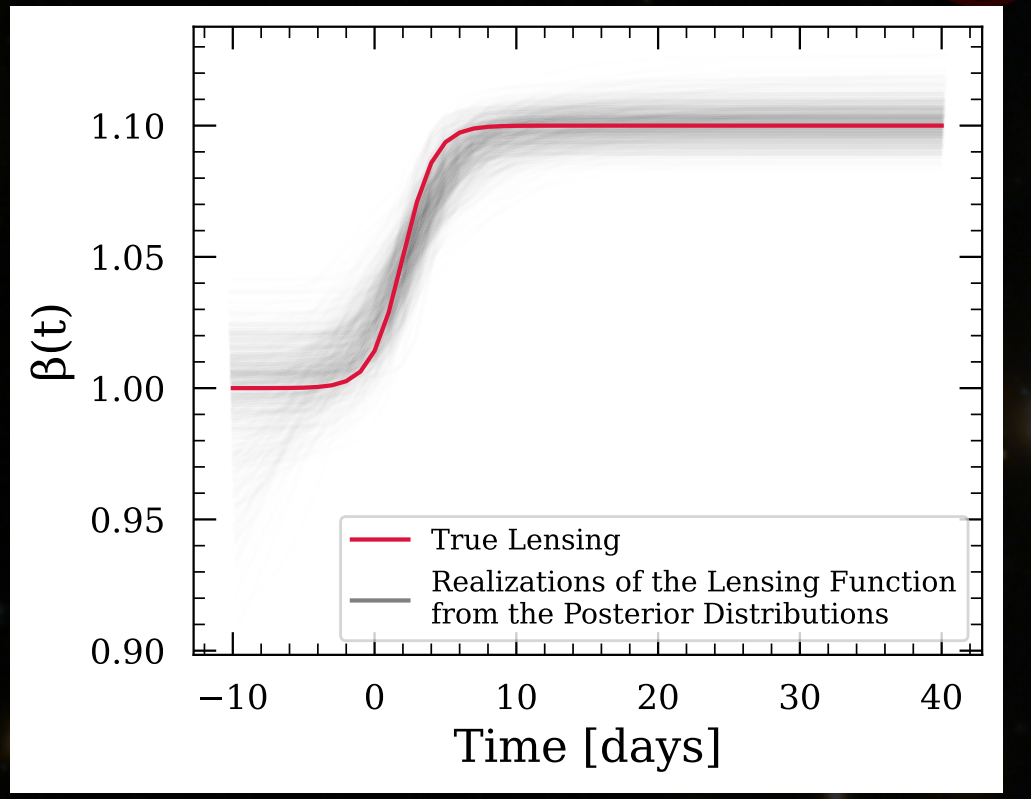


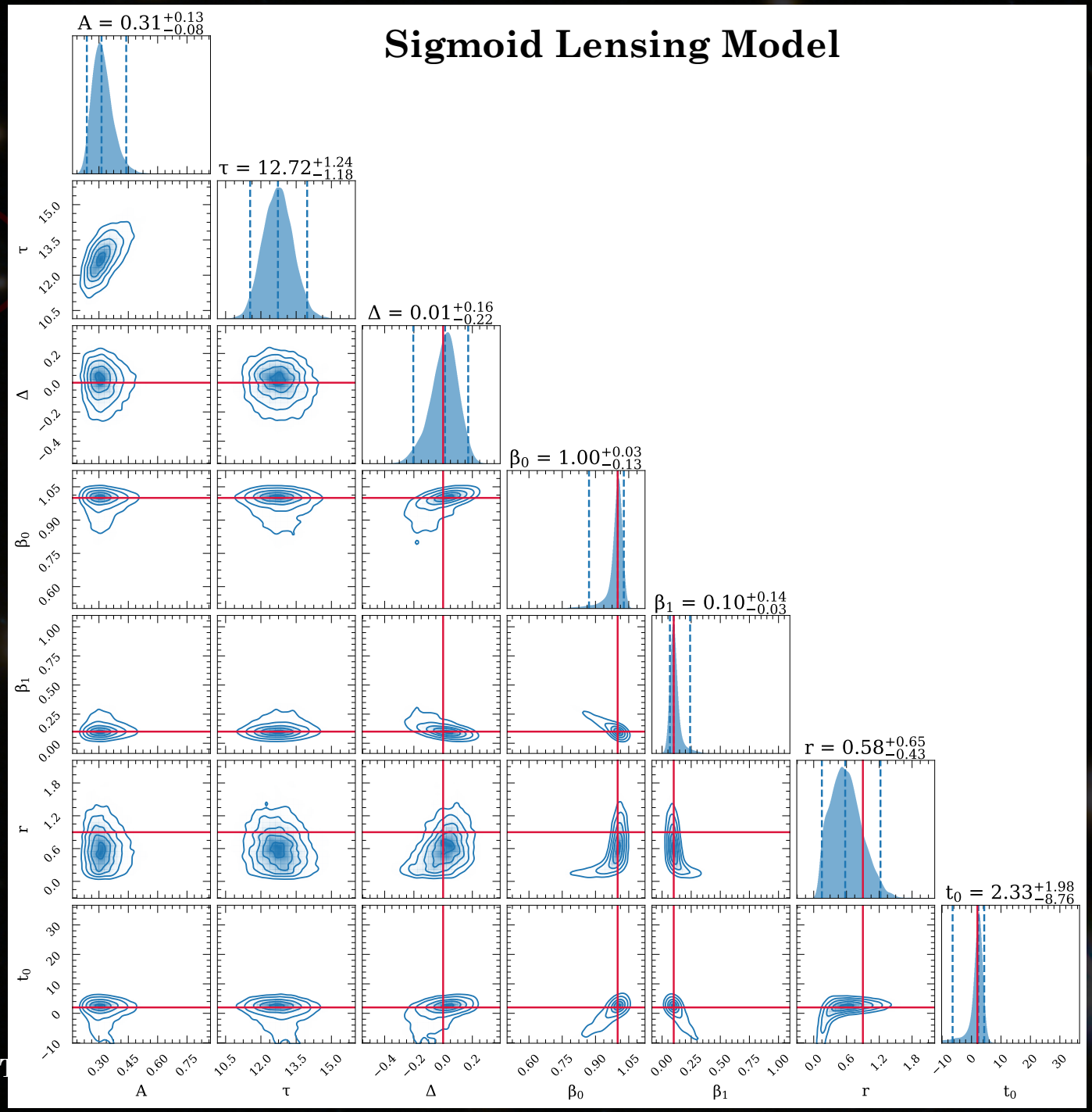
Microlensing



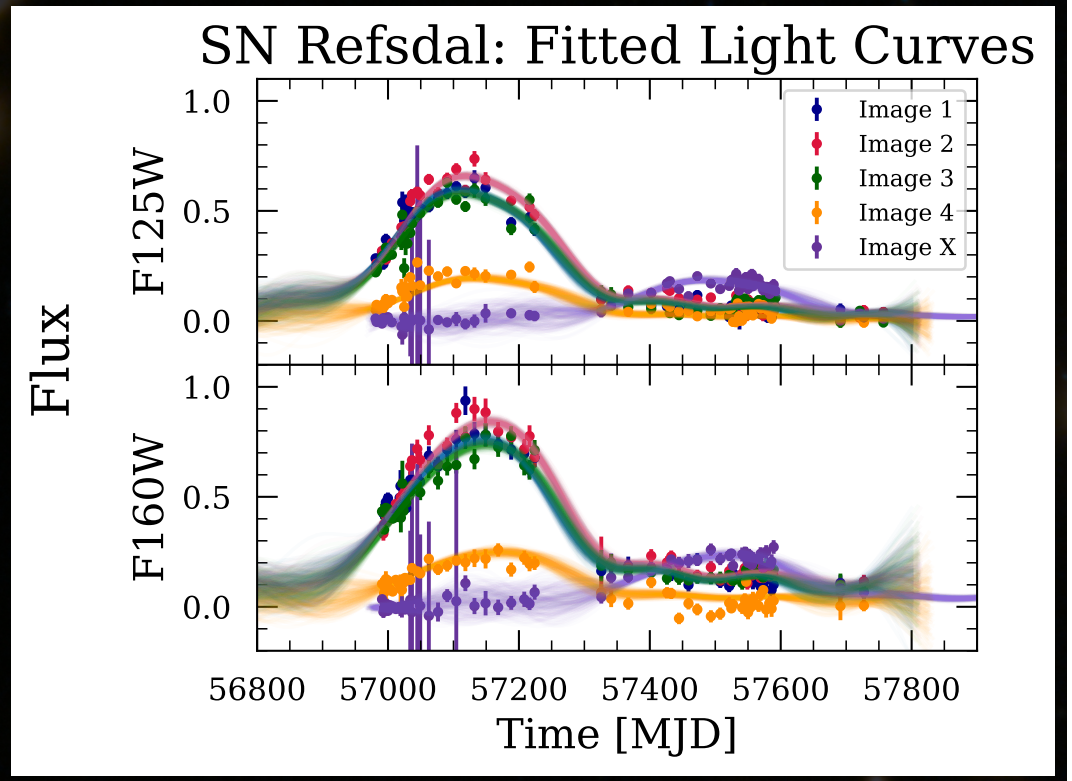


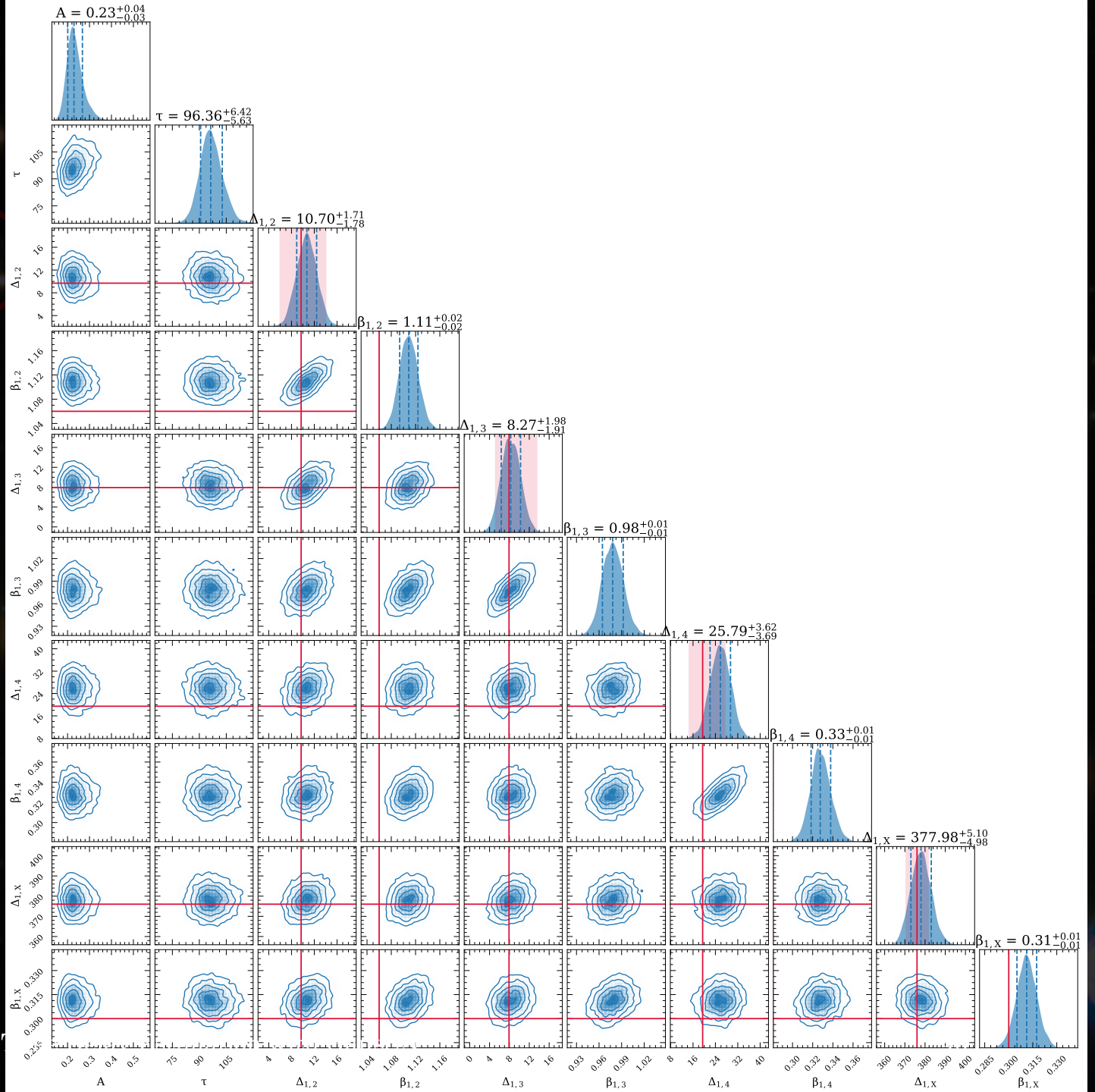
Microlensing



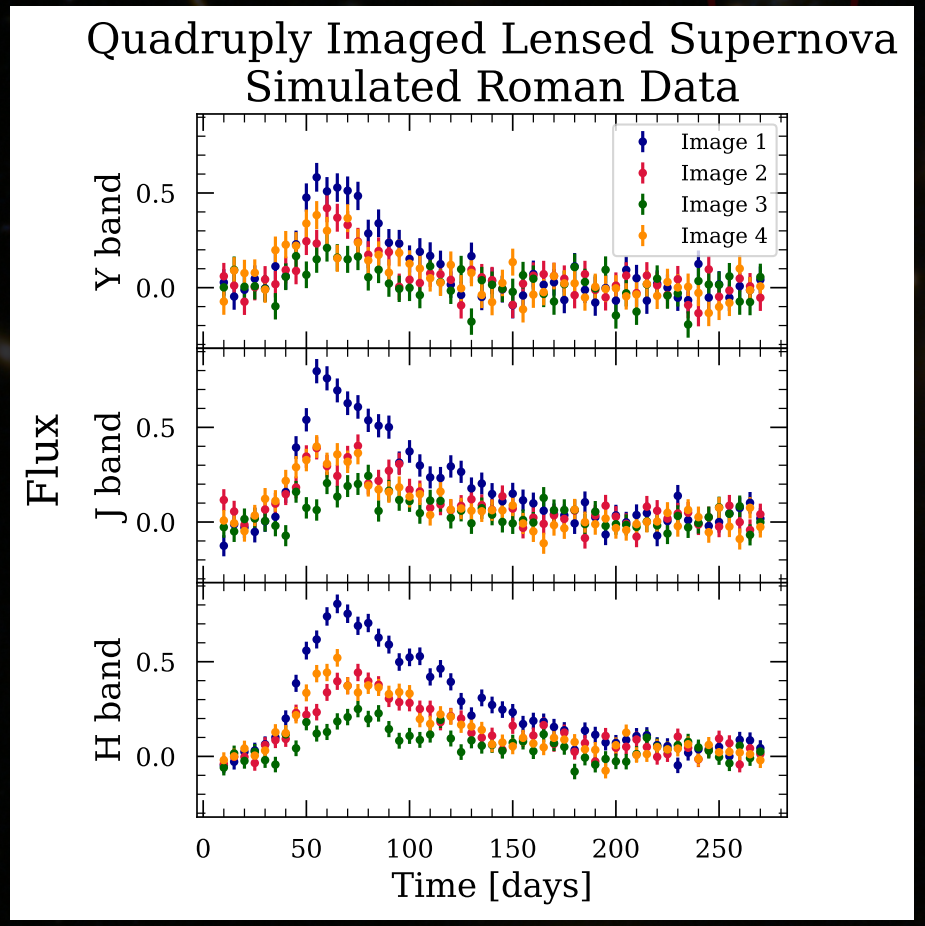


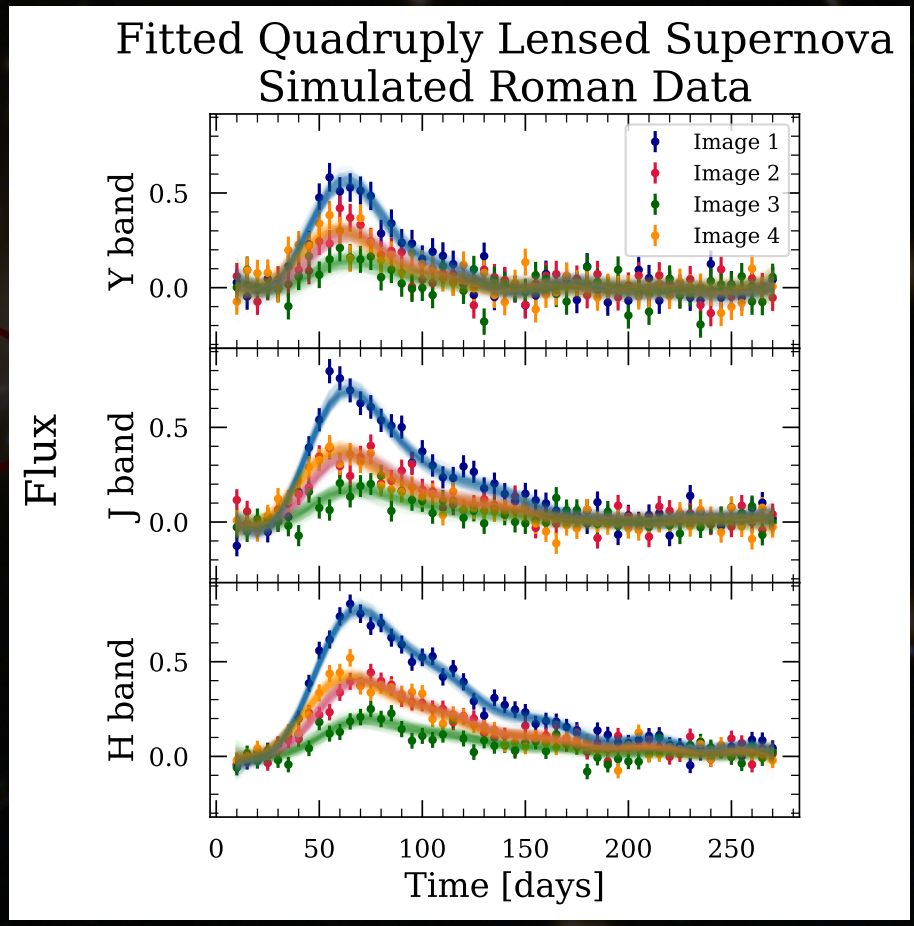
SN Refsdal


SN Refsdal: Fitted Light Curves
Flux
F125W
F160W
1.0
0.5
0.0
Image 1
Image 2
Image 3
Image 4
Image X
56800
57000
57200
57400
57600
57800
Time [MJD]

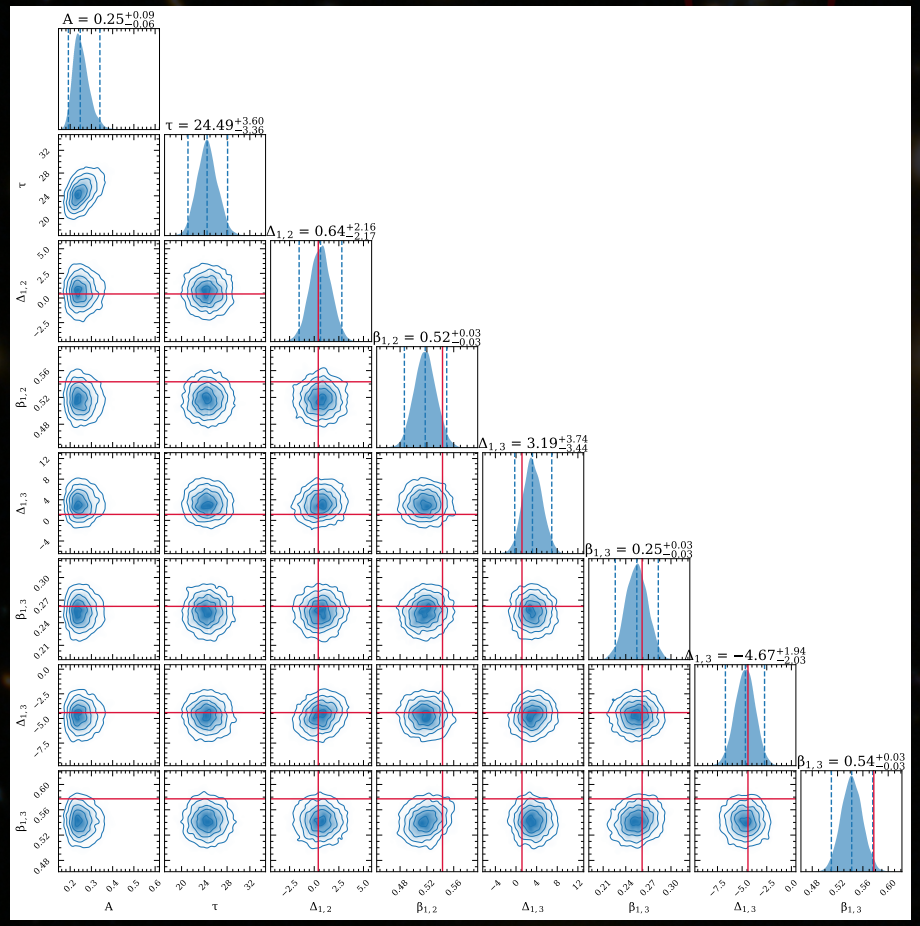

A = 0.23$^{+0.04}_{-0.03}$
τ = 96.36$^{+6.42}_{-5.63}$
Δ1,2 = 10.70$^{+1.71}_{-1.78}$
β1,2 = 1.11$^{+0.02}_{-0.02}$
Δ1,3 = 8.27$^{+1.98}_{-1.91}$
β1,3 = 0.98$^{+0.01}_{-0.01}$
Δ1,4 = 25.79$^{+3.62}_{-3.69}$
β1,4 = 0.33$^{+0.01}_{-0.01}$
Δ1,X = 377.98$^{+5.10}_{-4.98}$
β1,X = 0.31$^{+0.01}_{-0.01}$
A
τ
Δ1,2
β1,2
Δ1,3
β1,3
Δ1,4
β1,4
Δ1,X
β1,X

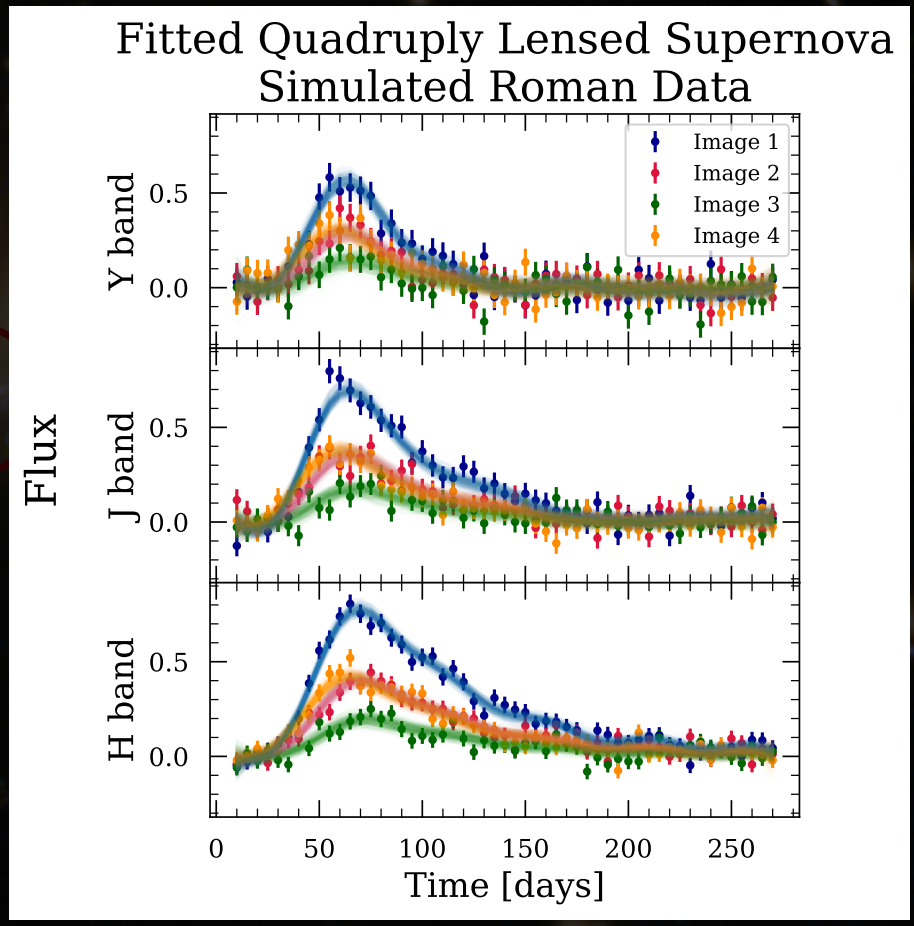
Quadruply-Imaged Supernova





Quadruply-Imaged Supernova





Results: Population Level

GausSN Constant: 54.5% within 1σ, 80.8% within 2σ
GausSN Sigmoid: 55.2% within 1σ, 82.7% within 2σ
SNTD: 47.5% within 1σ, 72.8% within 2σ