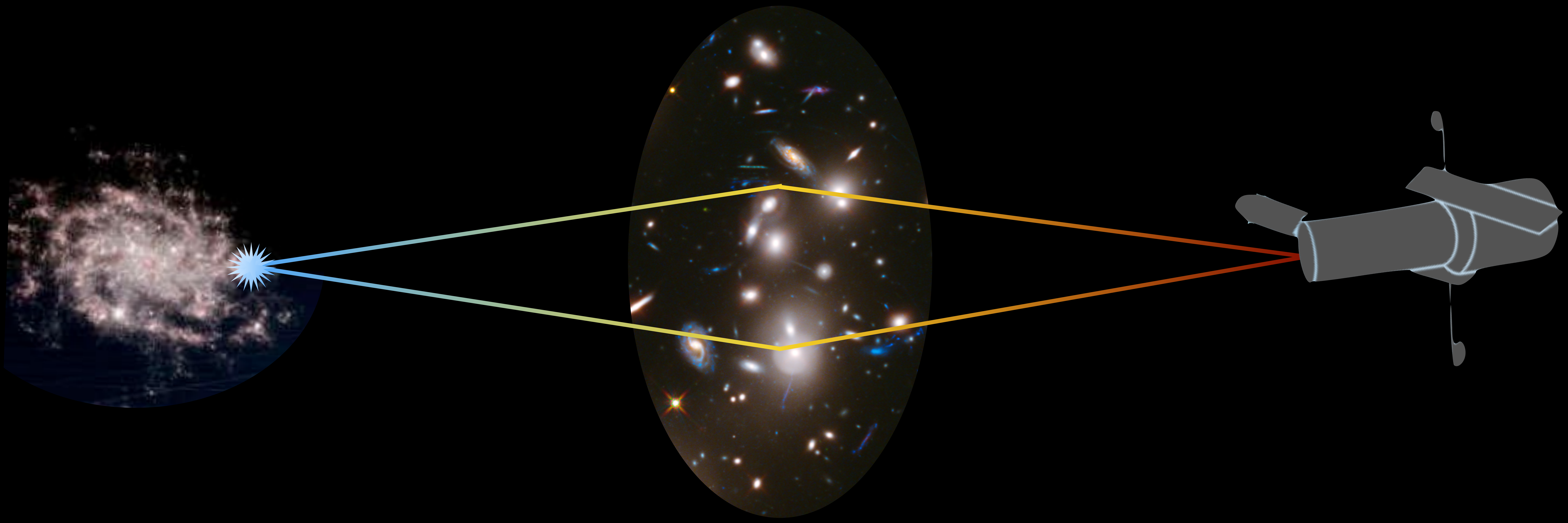
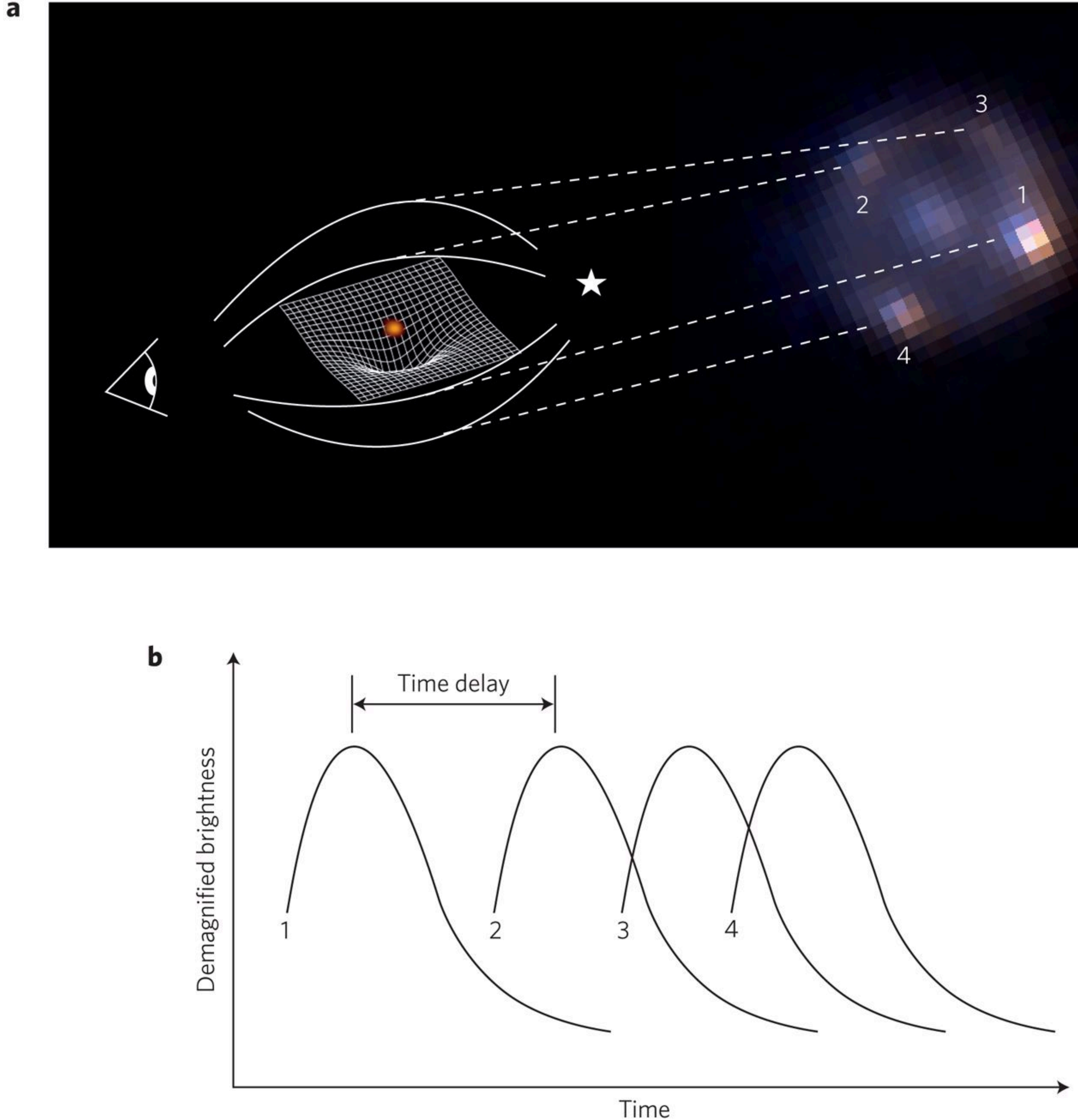
Turning Gravitationally Lensed Supernovae into Cosmological Tools

Steve Rodney
U. of South Carolina





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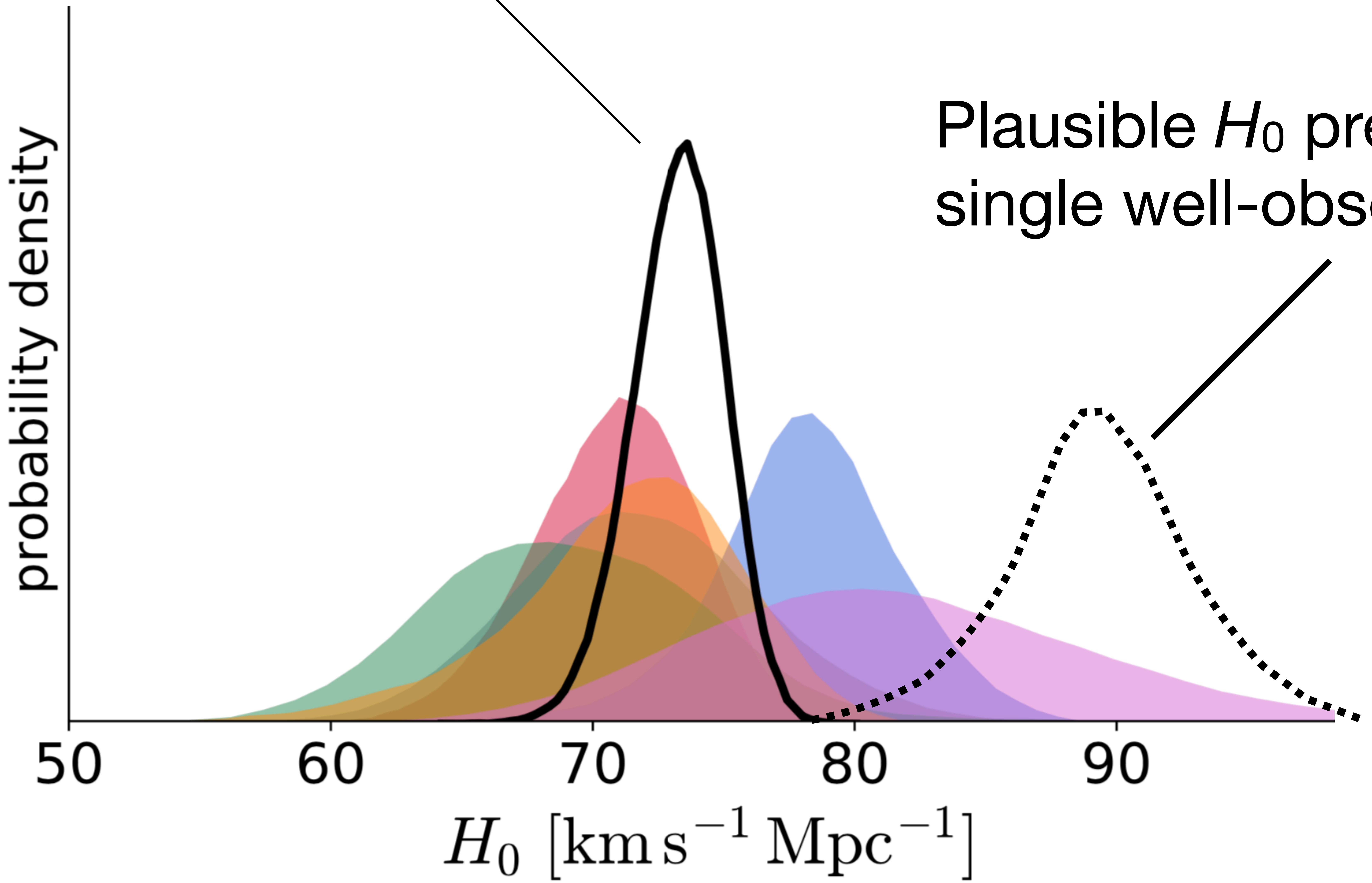
H_0 measured to 2.4%, combining 6 lensed QSOs from H0LiCOW, each with ~6-10% precision.

Wong+ 2019



Plausible H_0 precision from a single well-observed GLSN : ~7%

See talk by Anowar Shajib after the break

Steve Rodney (UofSC)

1. Measuring time delays : SNTD

2. Time delay cosmography
   with SN Refsdal

3. How to find the next one

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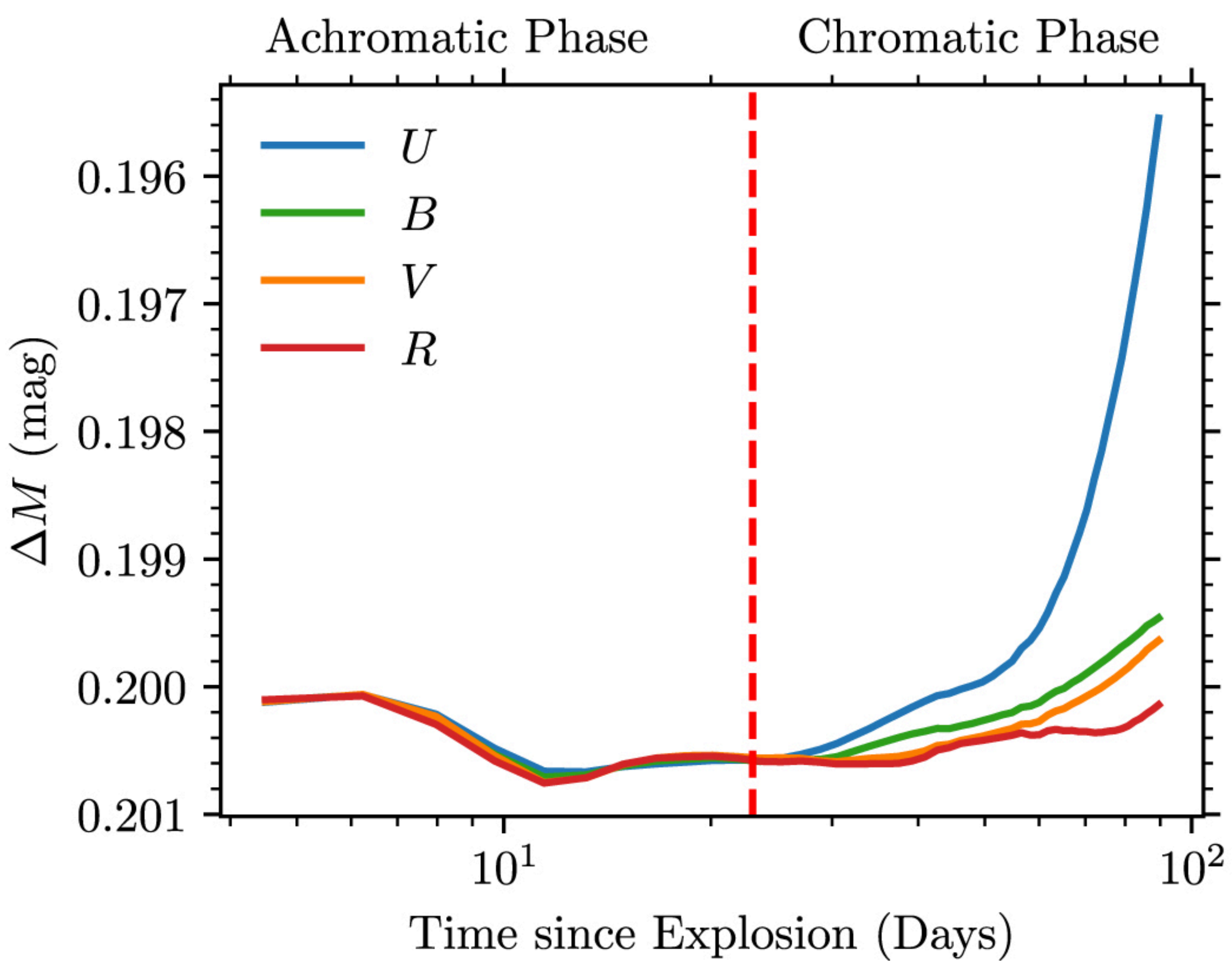

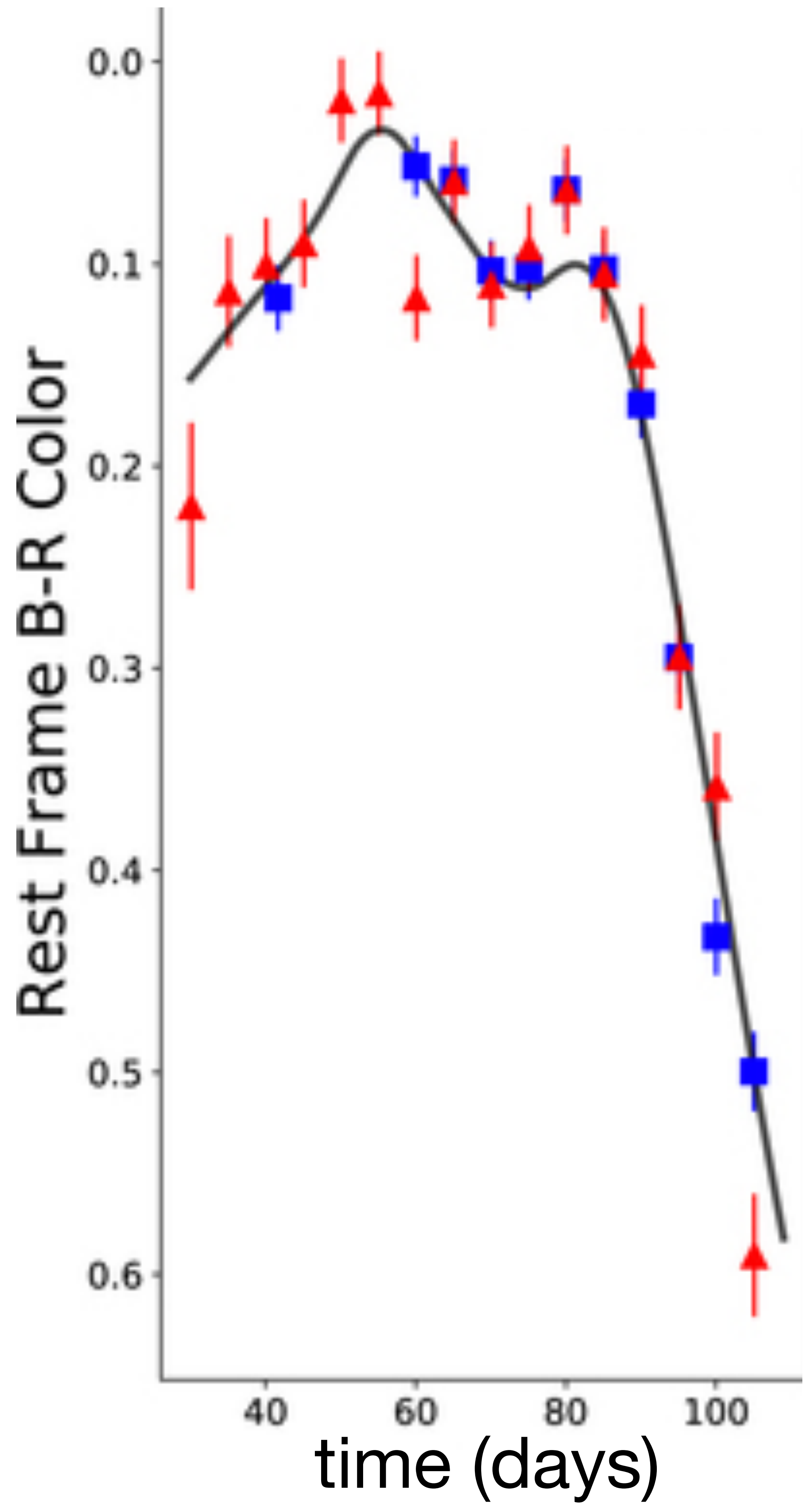

Steve Rodney (UofSC)

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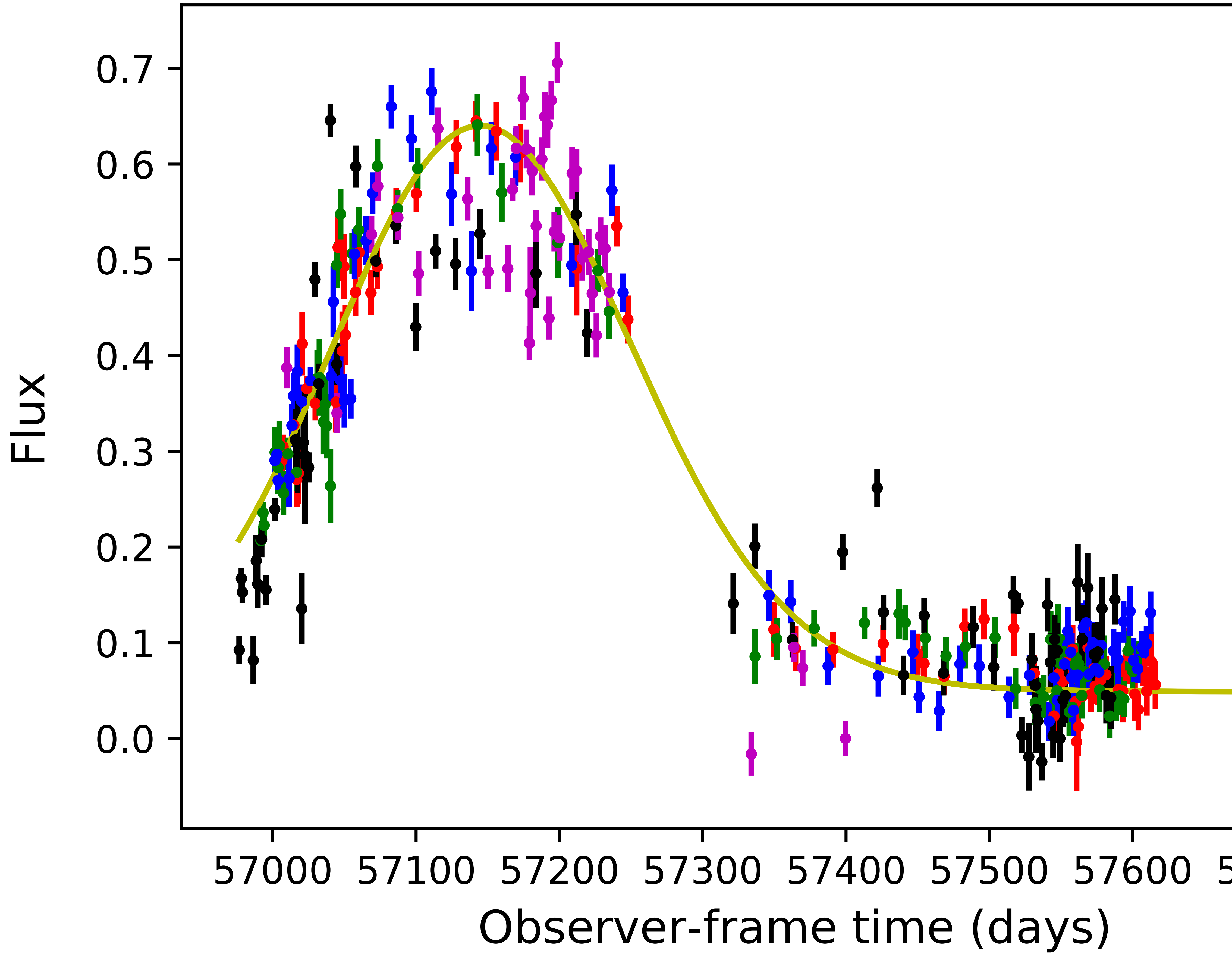

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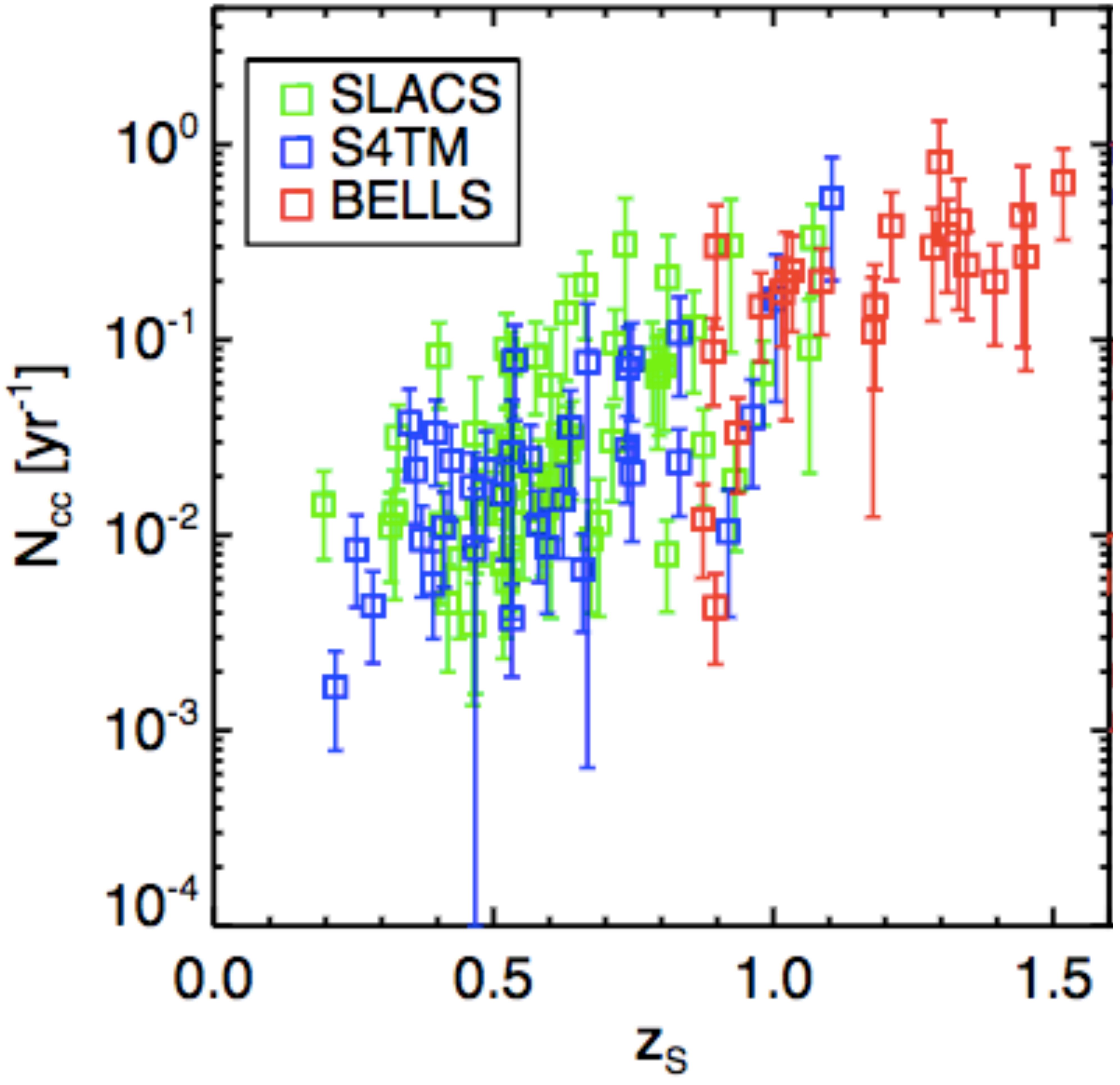


SNTD : The open-source toolkit for SN Time Delay measurement

Justin Pierel (UofSC)

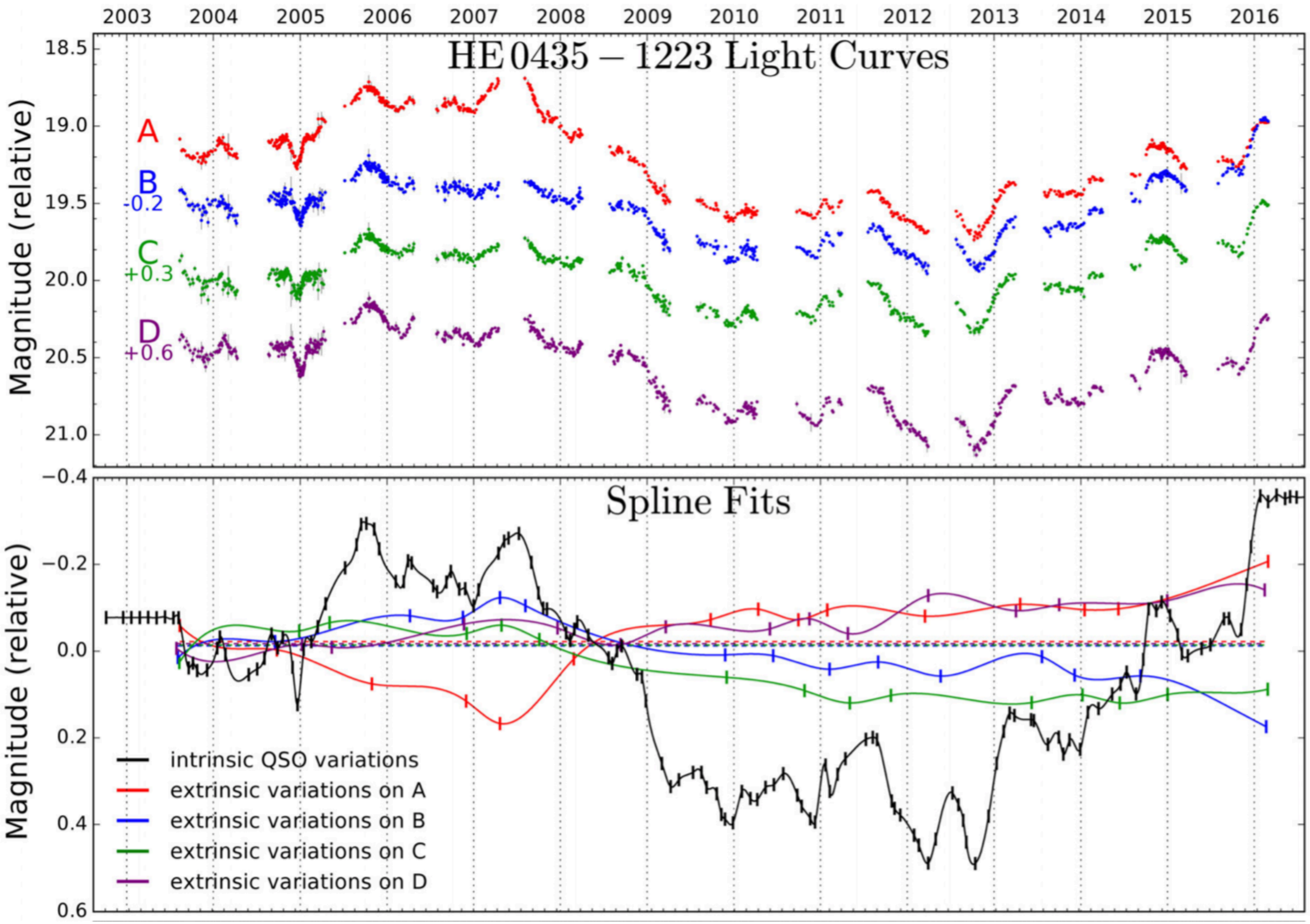
Pierel & Rodney 2019, ApJ, 876, 107.

```
pip install sntd
```

sntd.readthedocs.io

Steve Rodney (UofSC)

Quasar light curves are stochastic and unpredictable...



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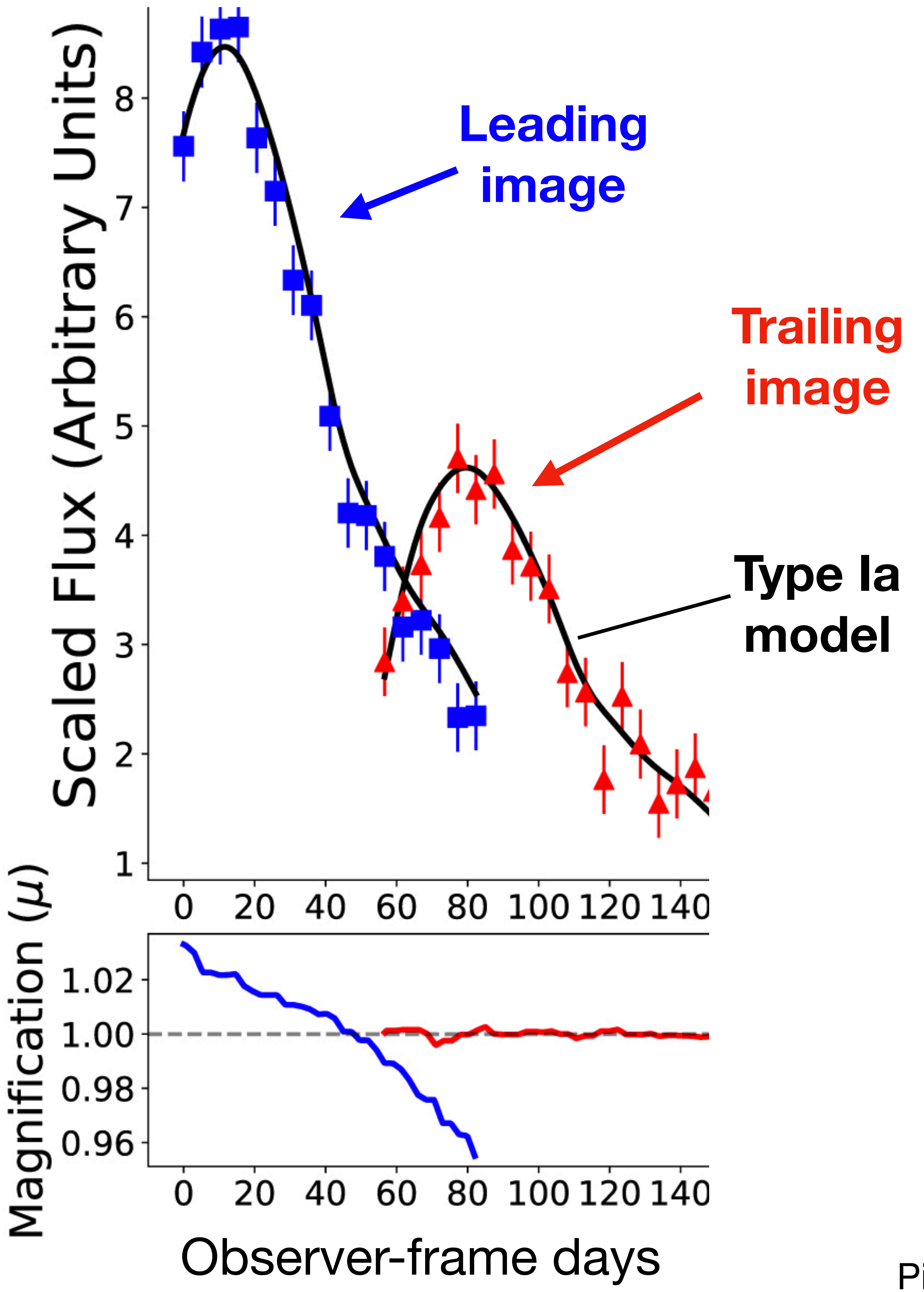
(most) SN Light curves are fast, simple, and predictable



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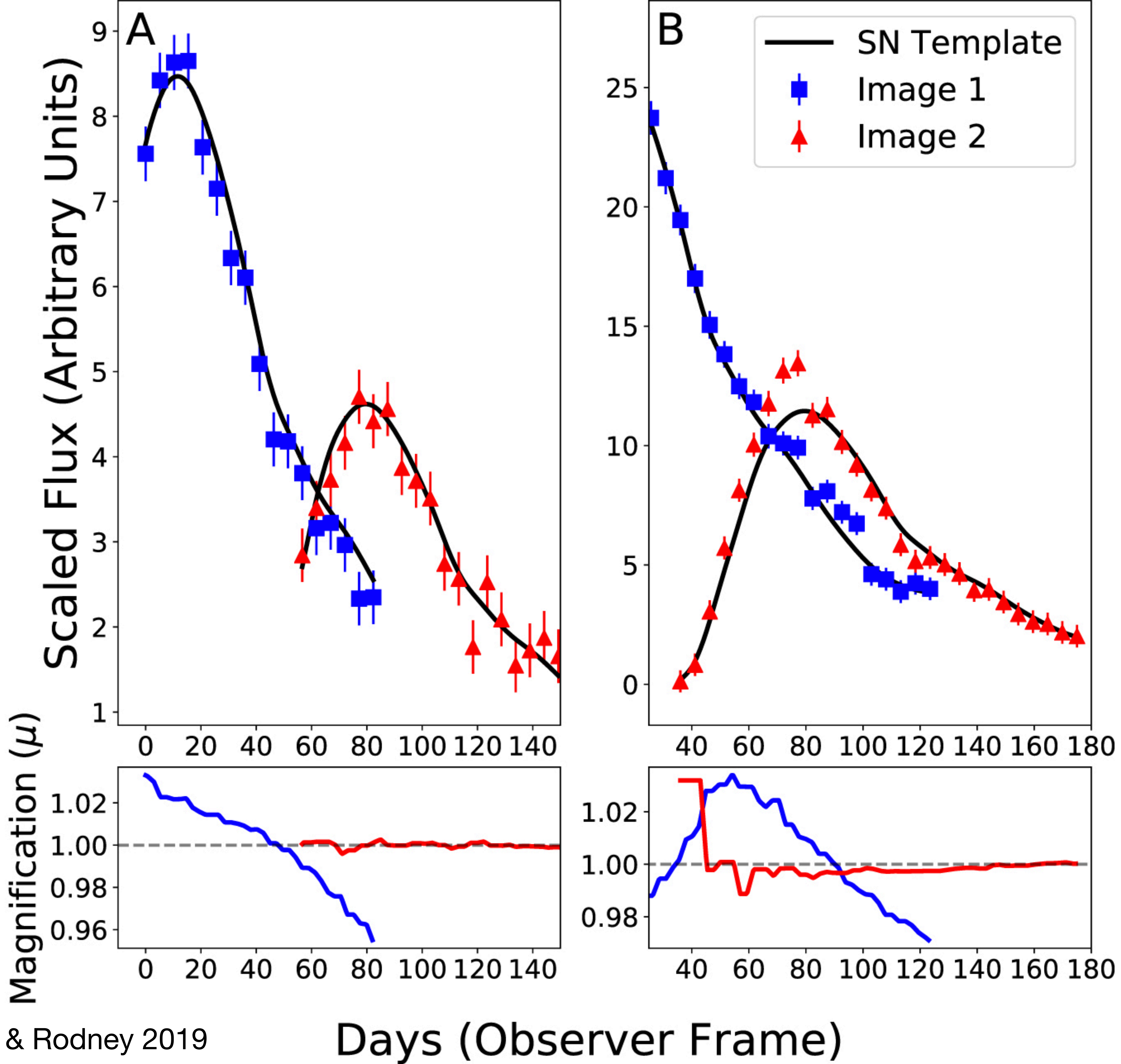
Pierel & Rodney 2019

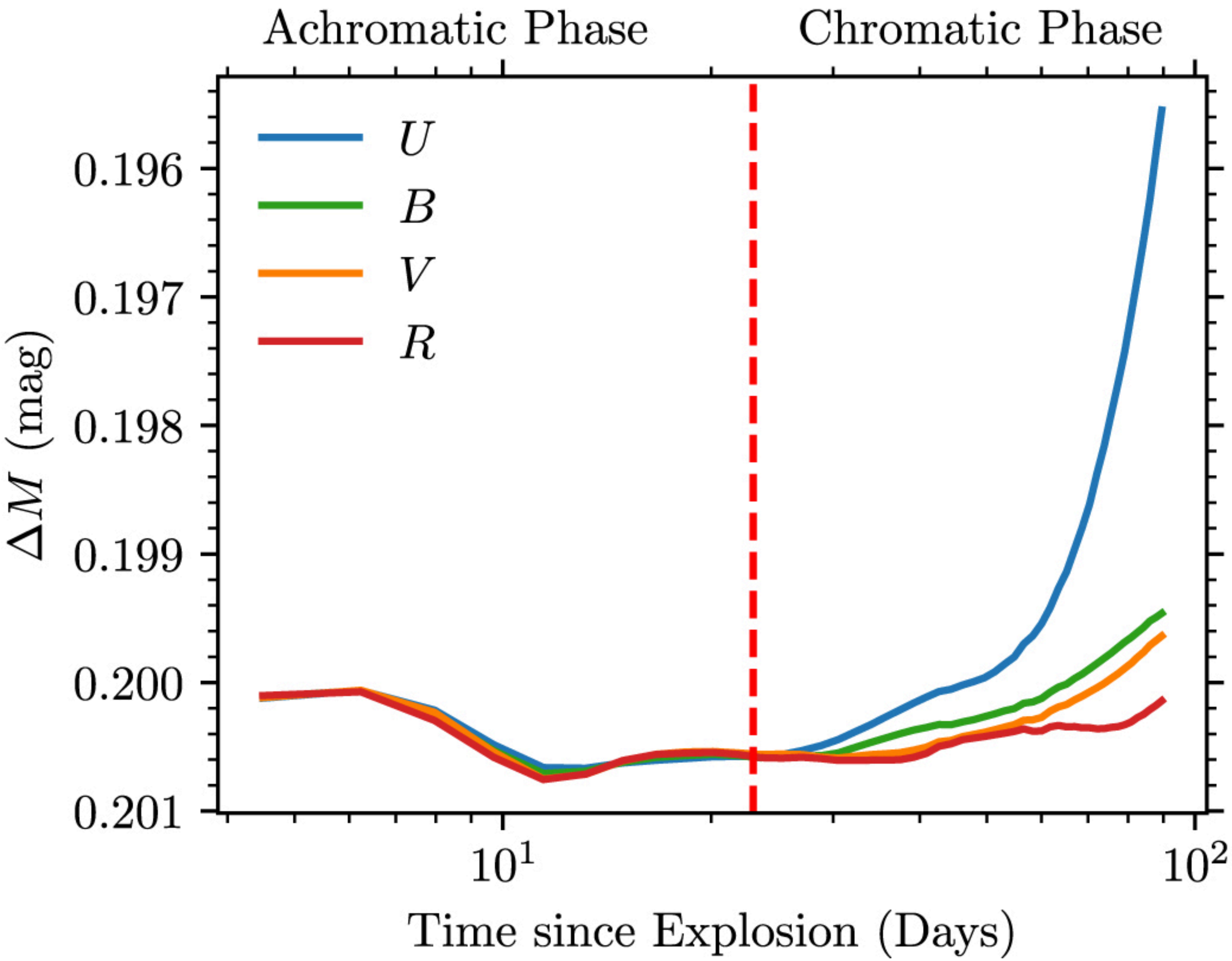
SNTD multiband light curve fitting:

measure time delays even if we miss the peak



Pierel & Rodney 2019

Early color curves of SNIa can be insensitive to microlensing



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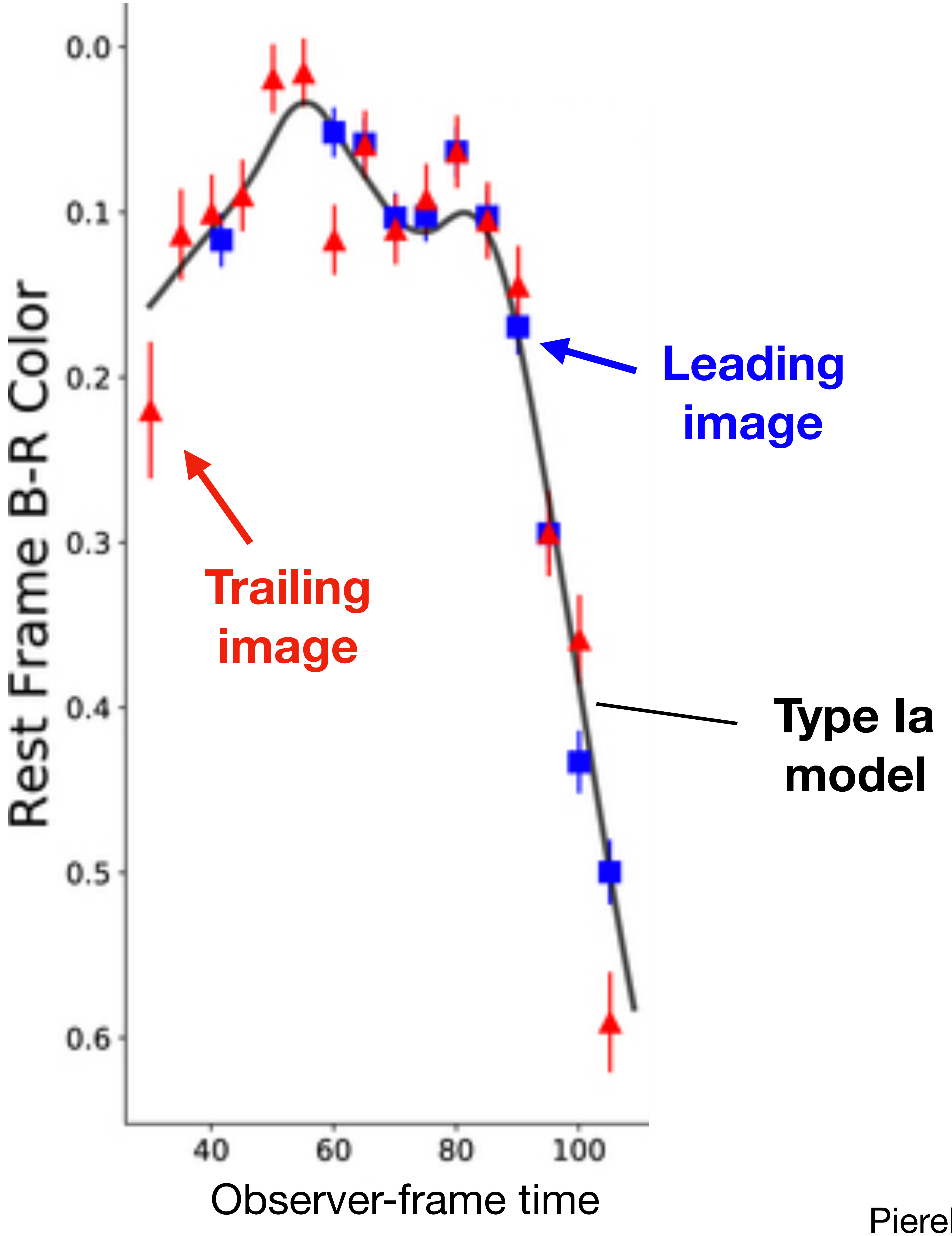
Goldstein+ 2018

SNTD "color curve" method:

Measure time delays directly from color curves



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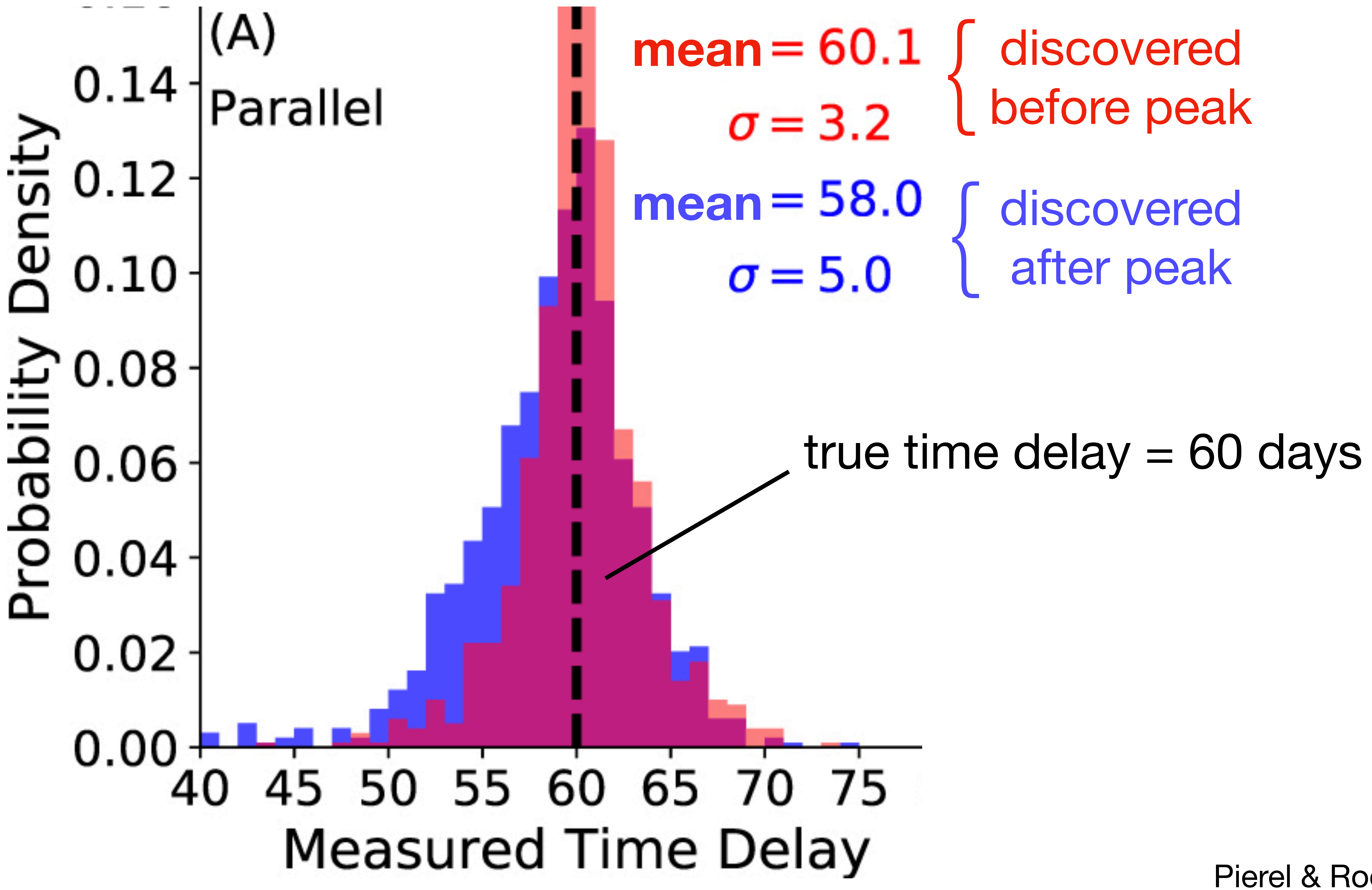
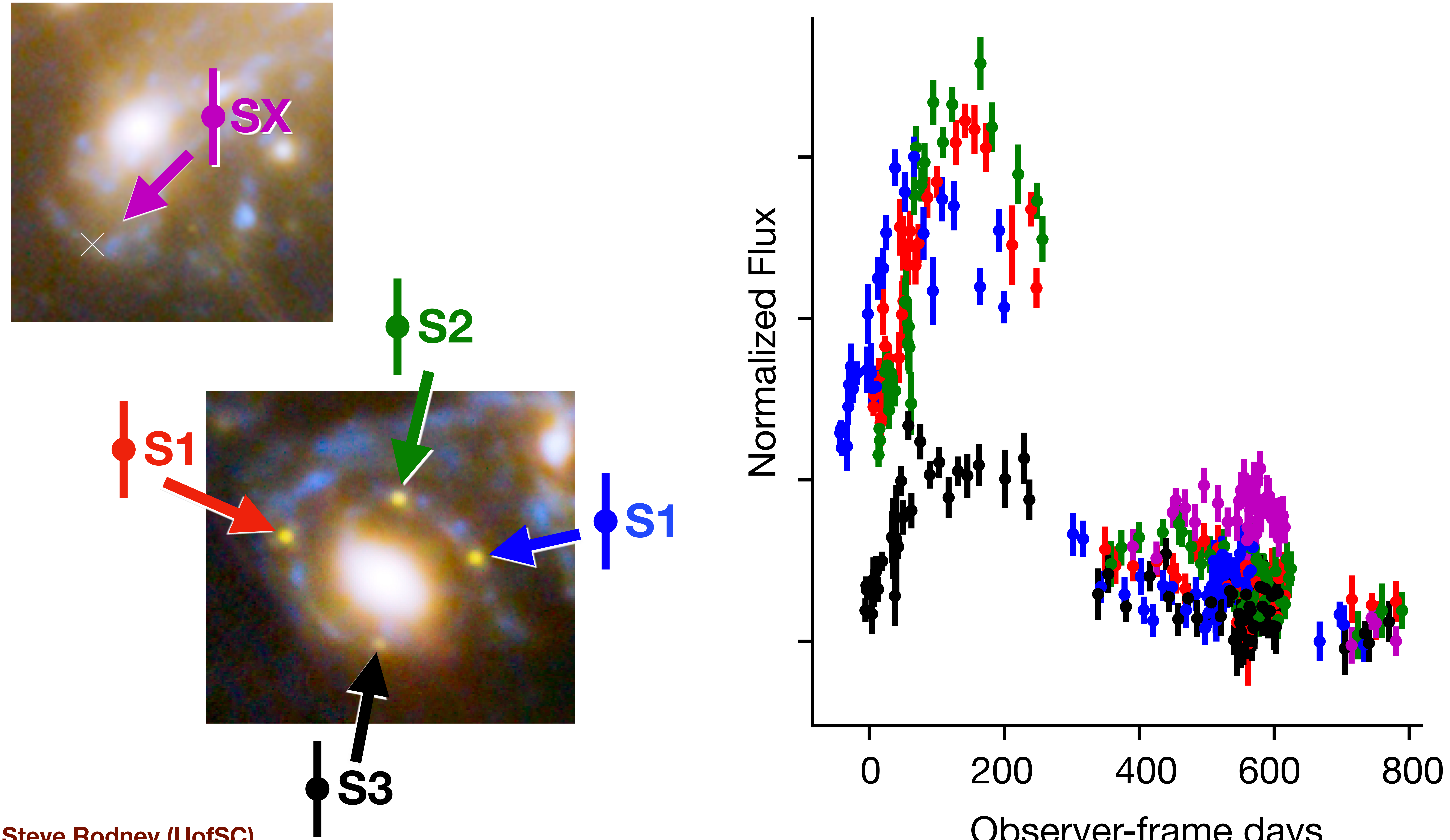
Pierel & Rodney 2019

Precision of ±3 days is achievable with well-sampled light curves



Pierel & Rodney 2019

Turning SN Refsdal into a Cosmological Tool



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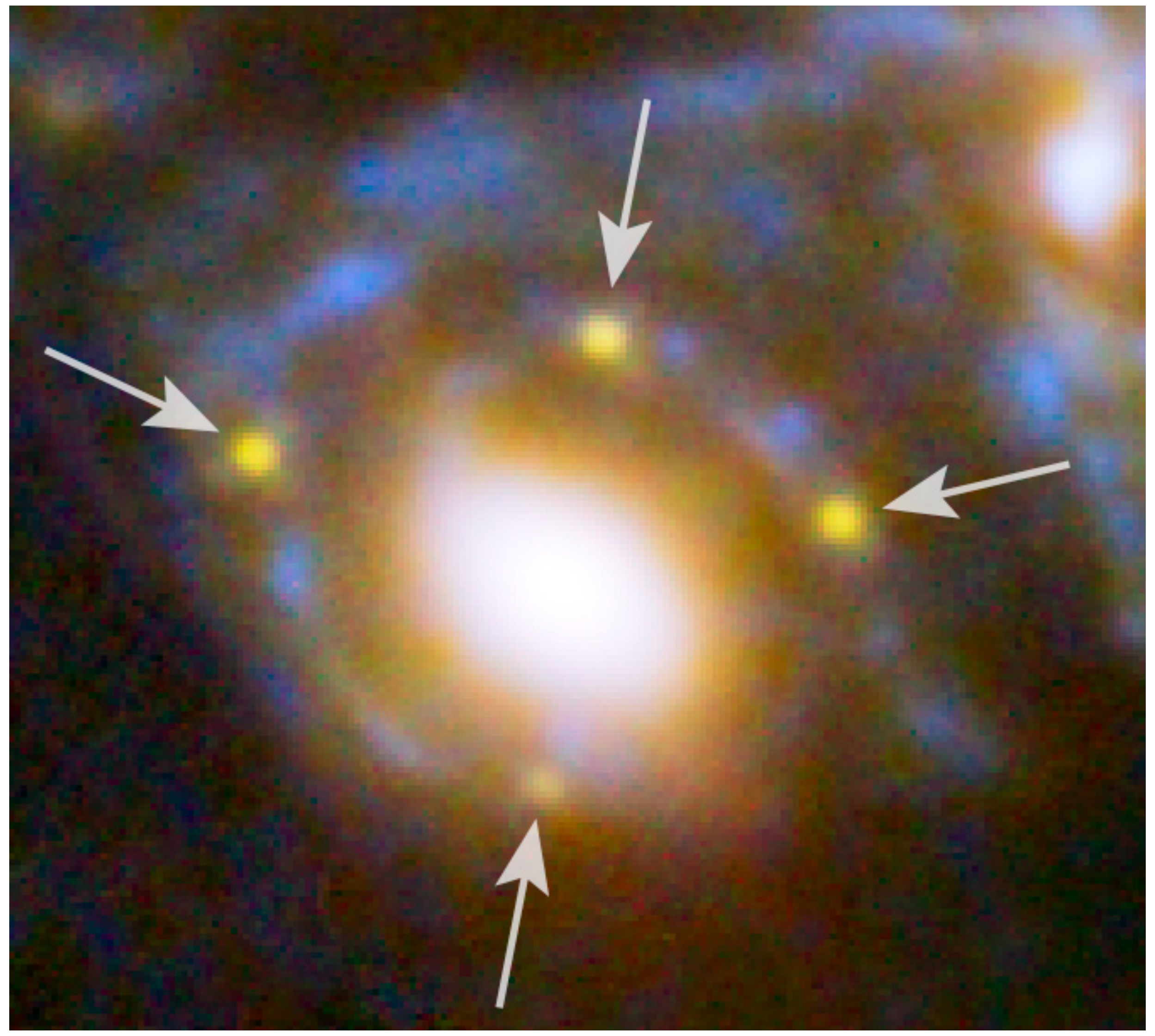
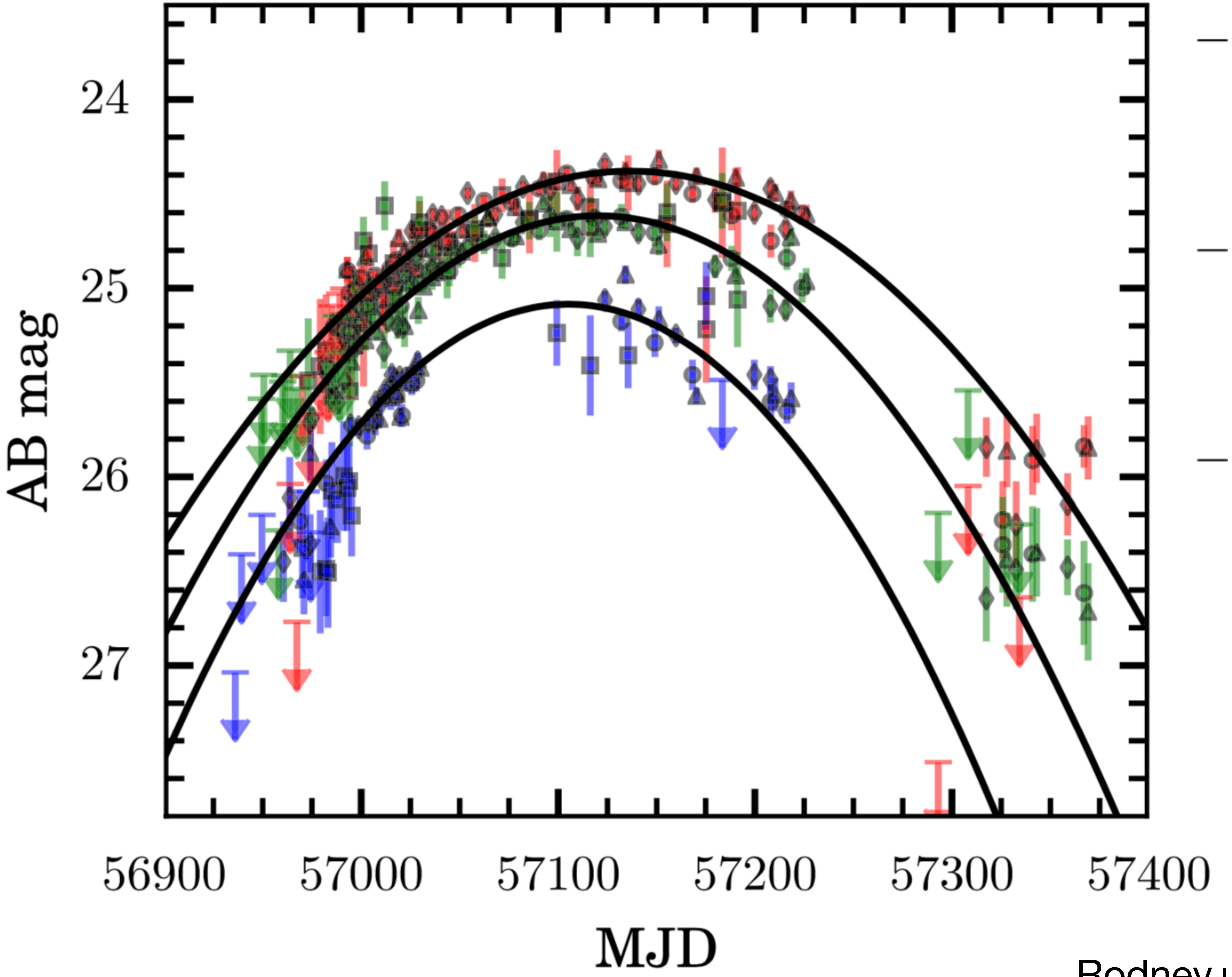
First attempt: precision of 2 to 7 days for images S1–S4





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Rodney+ 2016

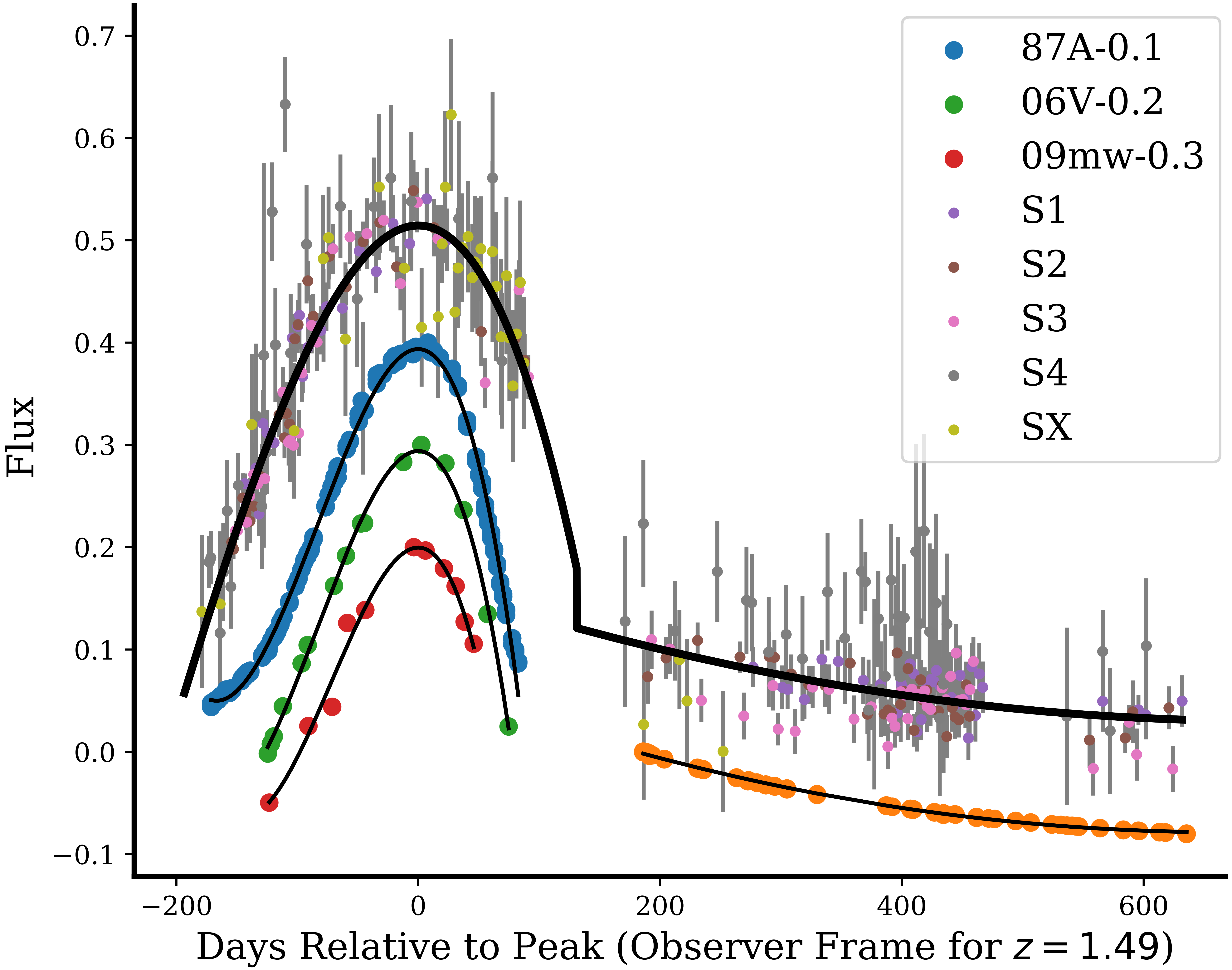
Time delays with the full light curves of all 5 images

- Apply four time delay fitting methods
- Measure each method's accuracy and precision using simulated data
- Combine results using image-by-image weights

Kelly ... SR et al. in prep

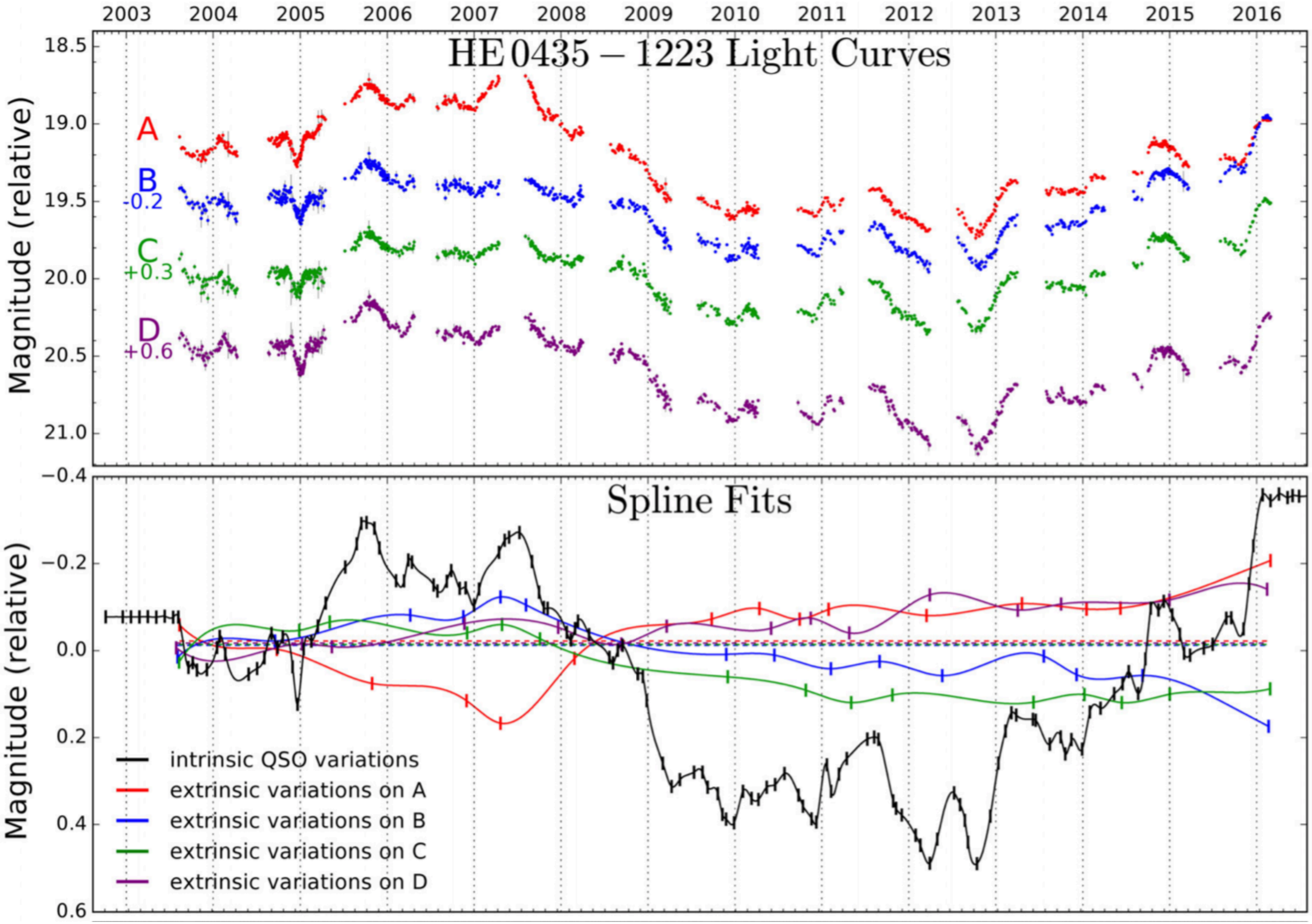
Method 1: piecewise polynomials

P. Kelly



Method 2: PyCS Splines

V. Bonvin



Bonvin+ 2017

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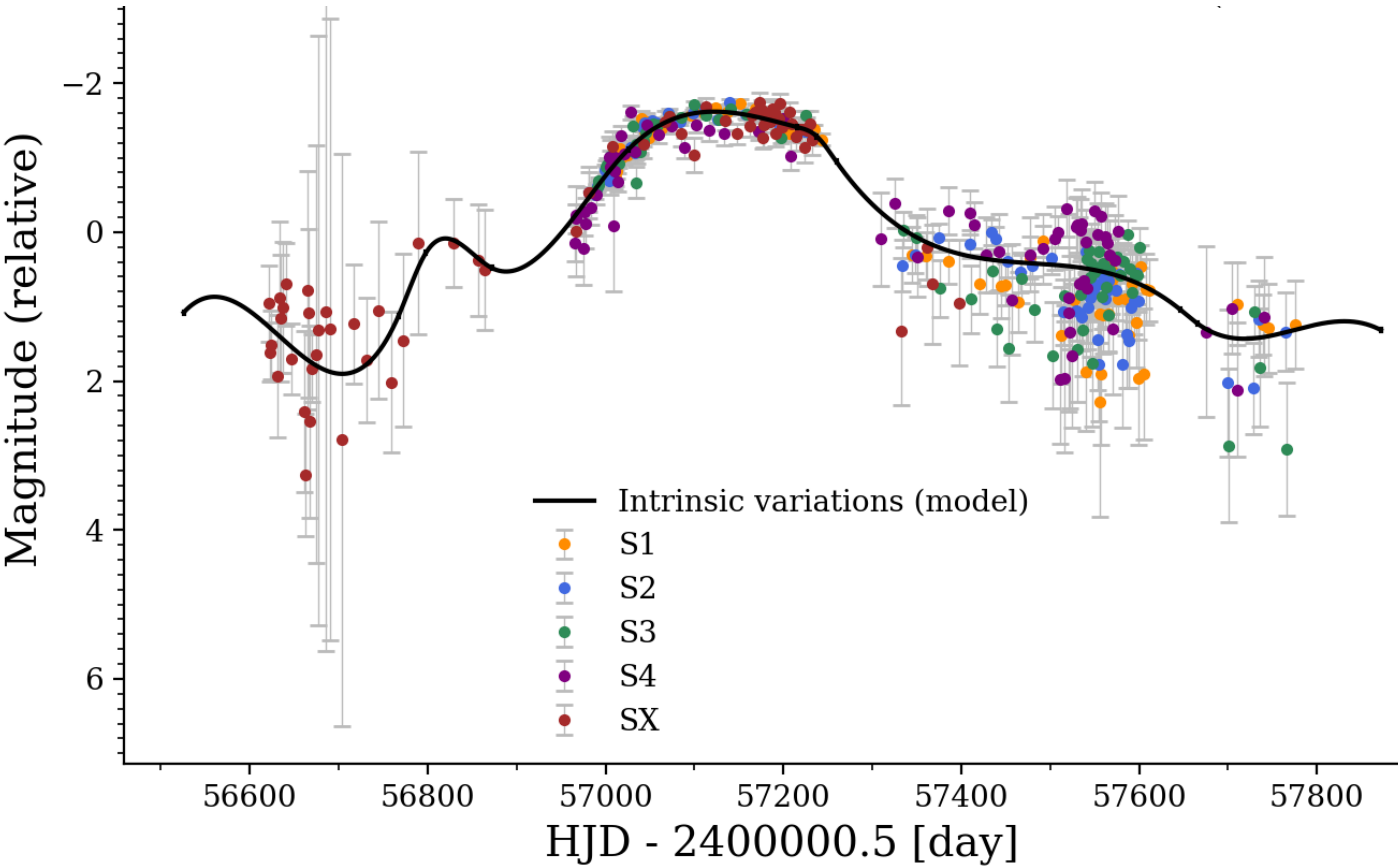
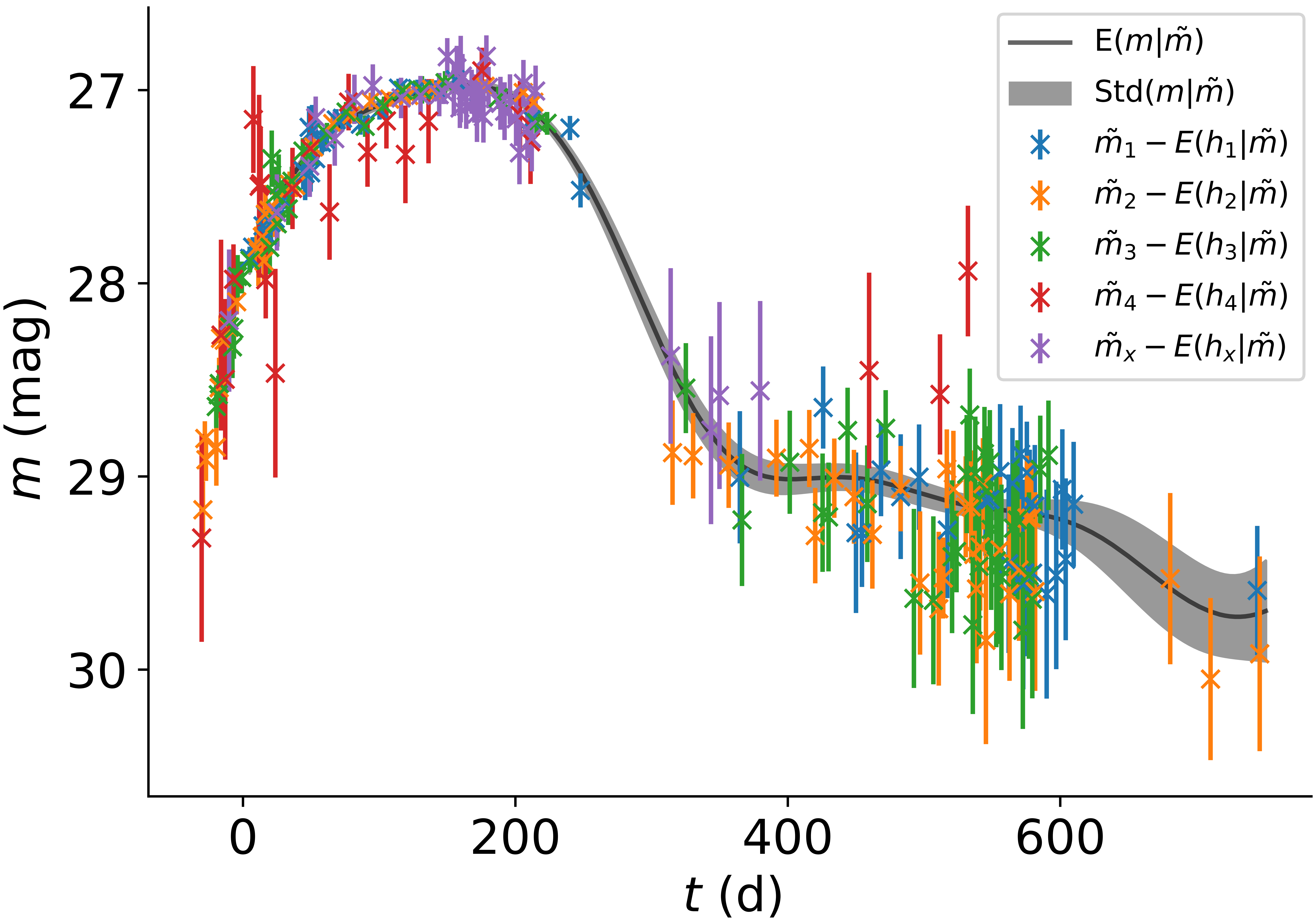


Method 3:
GPR
S. Thorp
K. Mandel



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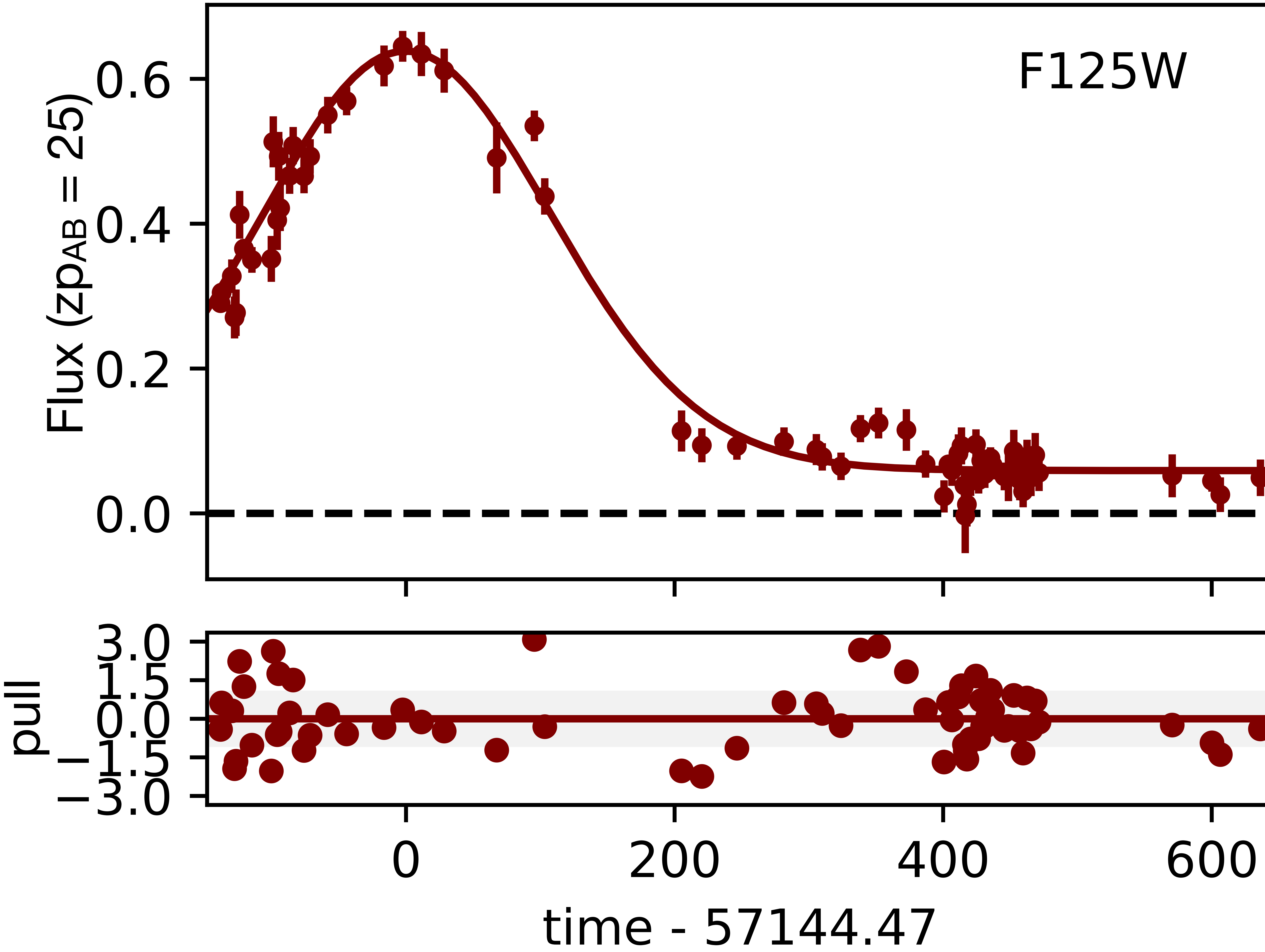
Method 4: SNTD (parameterized)

J. Pierel

S. Rodney



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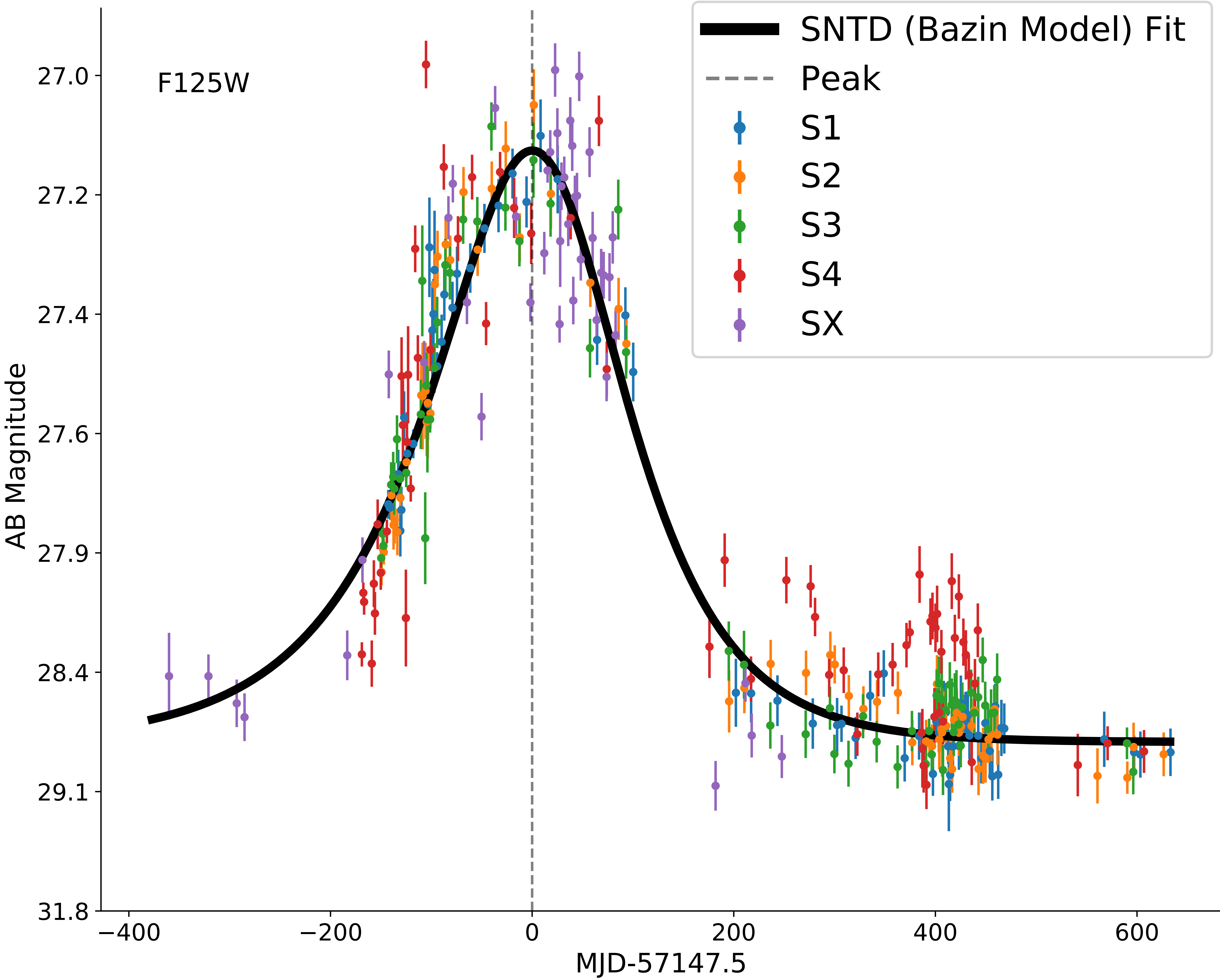
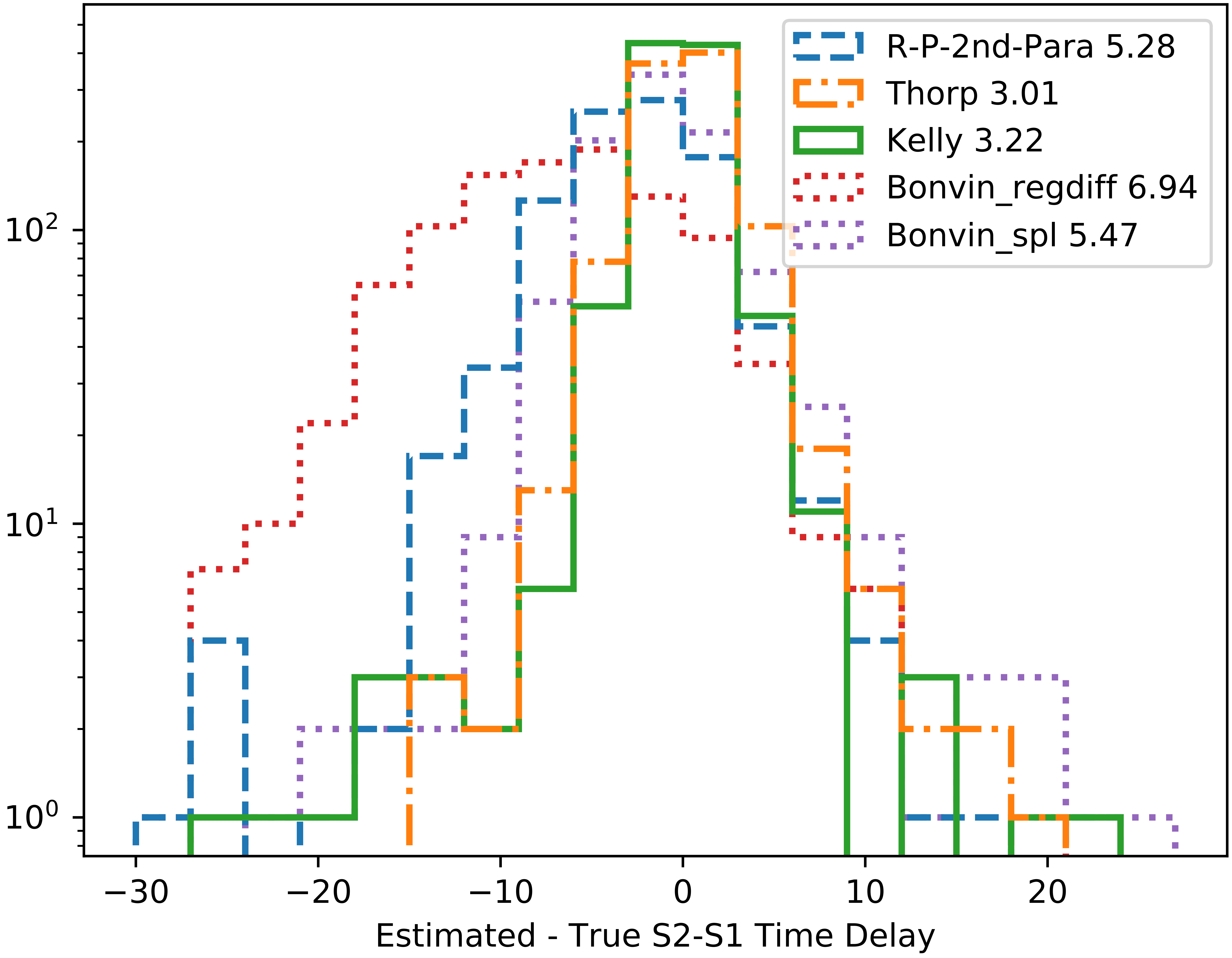


We define weights for each method by comparing performance on simulated light curves (with blind Δt and μ offsets)

Accuracy in fitting simulated light curves: S2-S1



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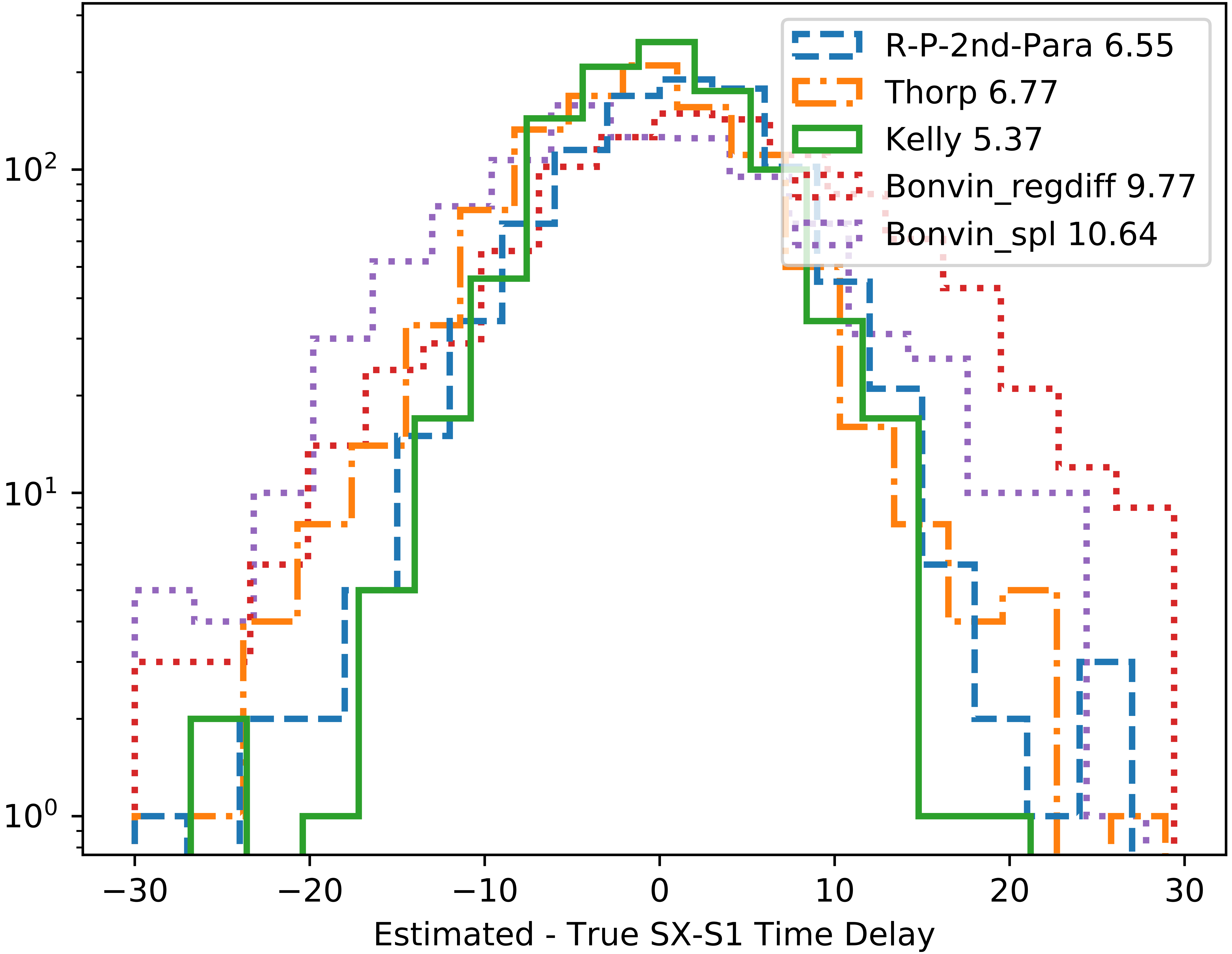
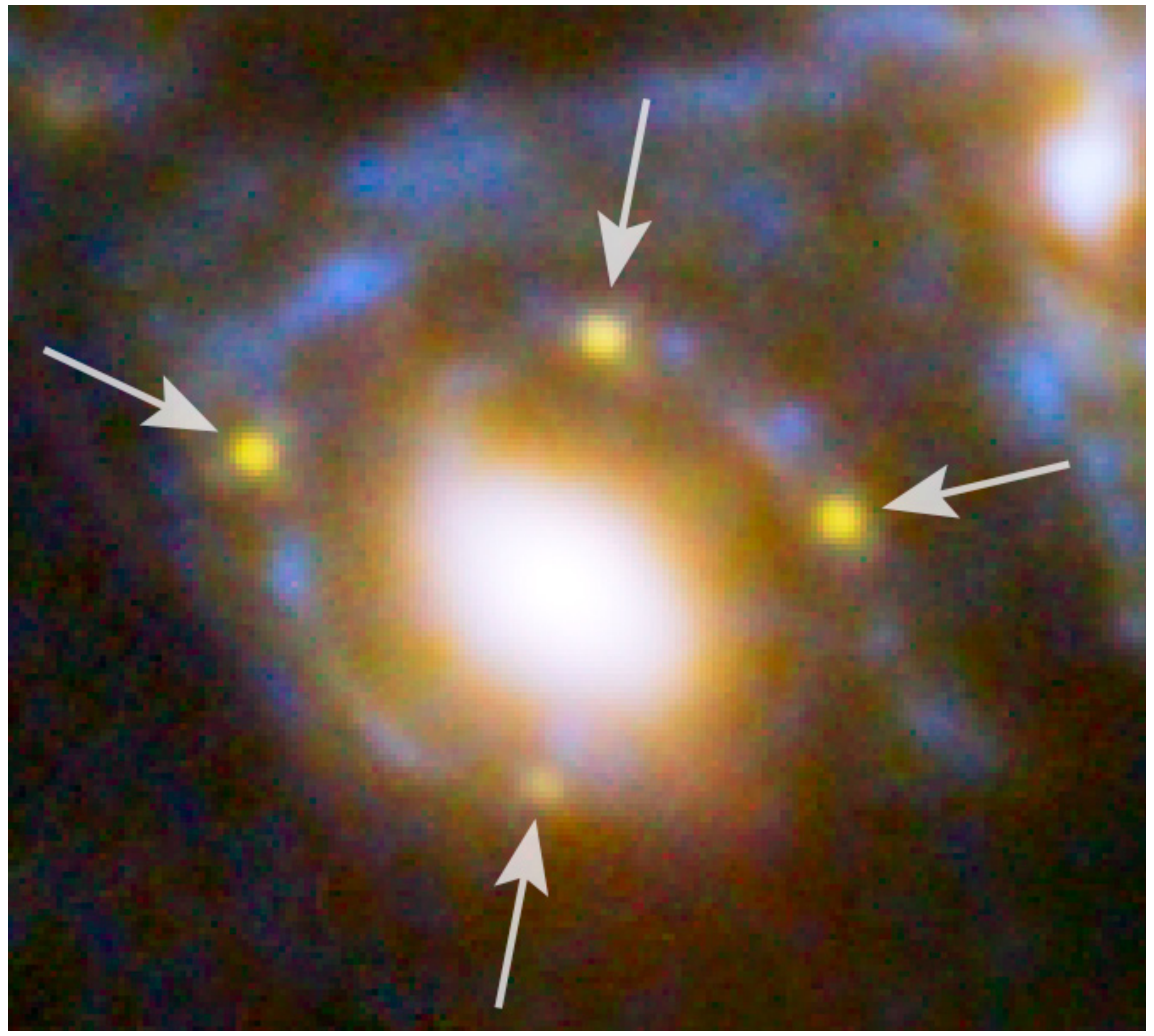
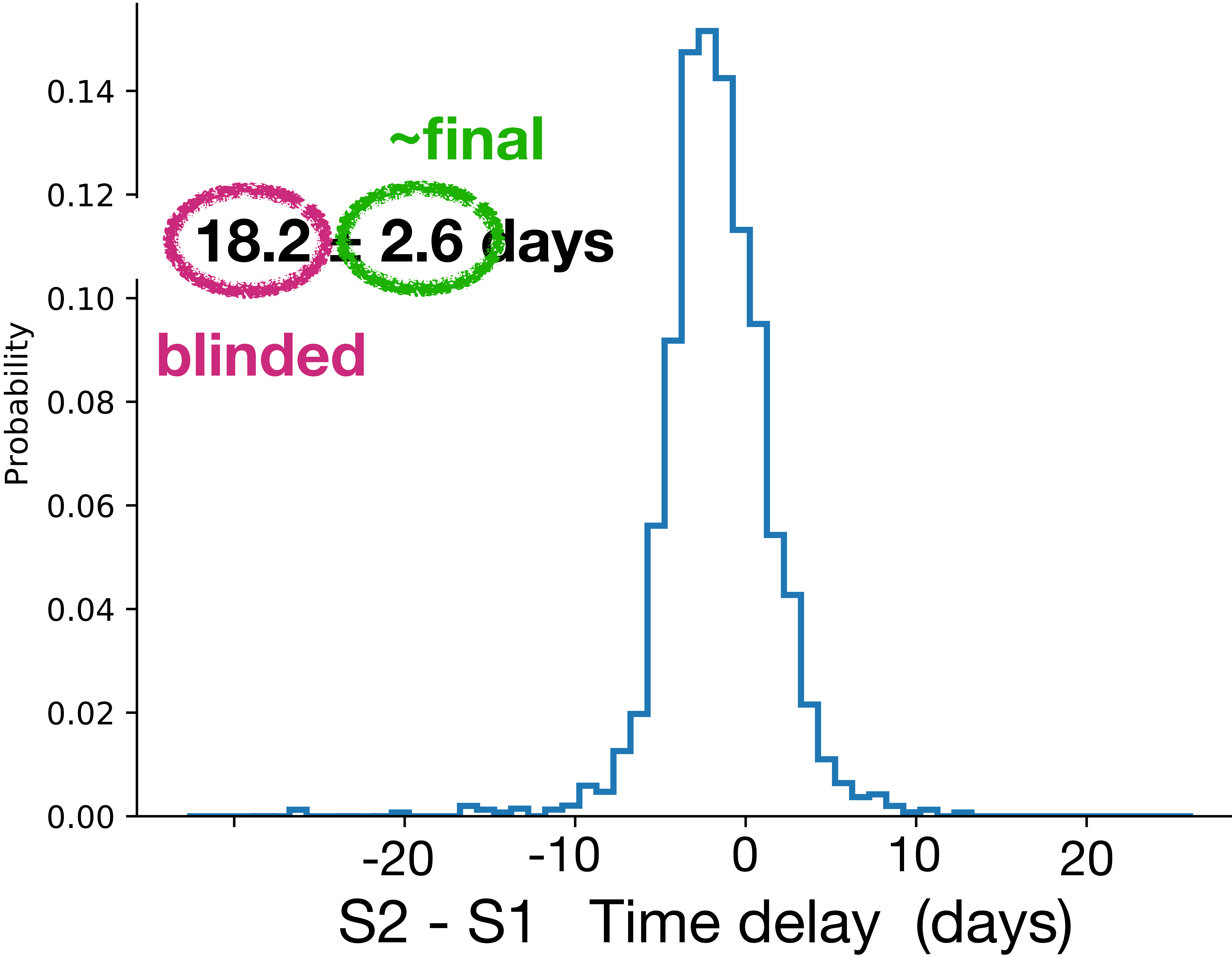
Accuracy in fitting simulated light curves: SX-S1



Composite time delays: S2 - S1





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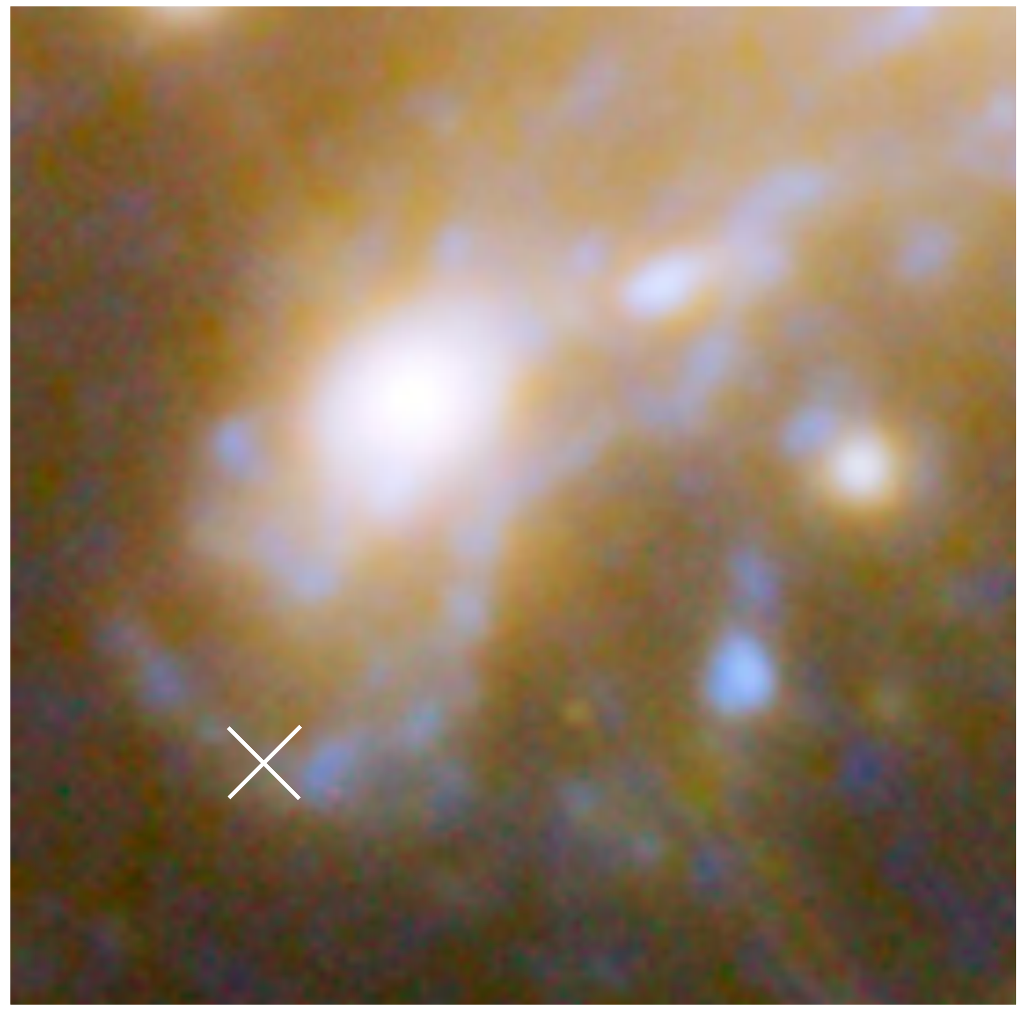
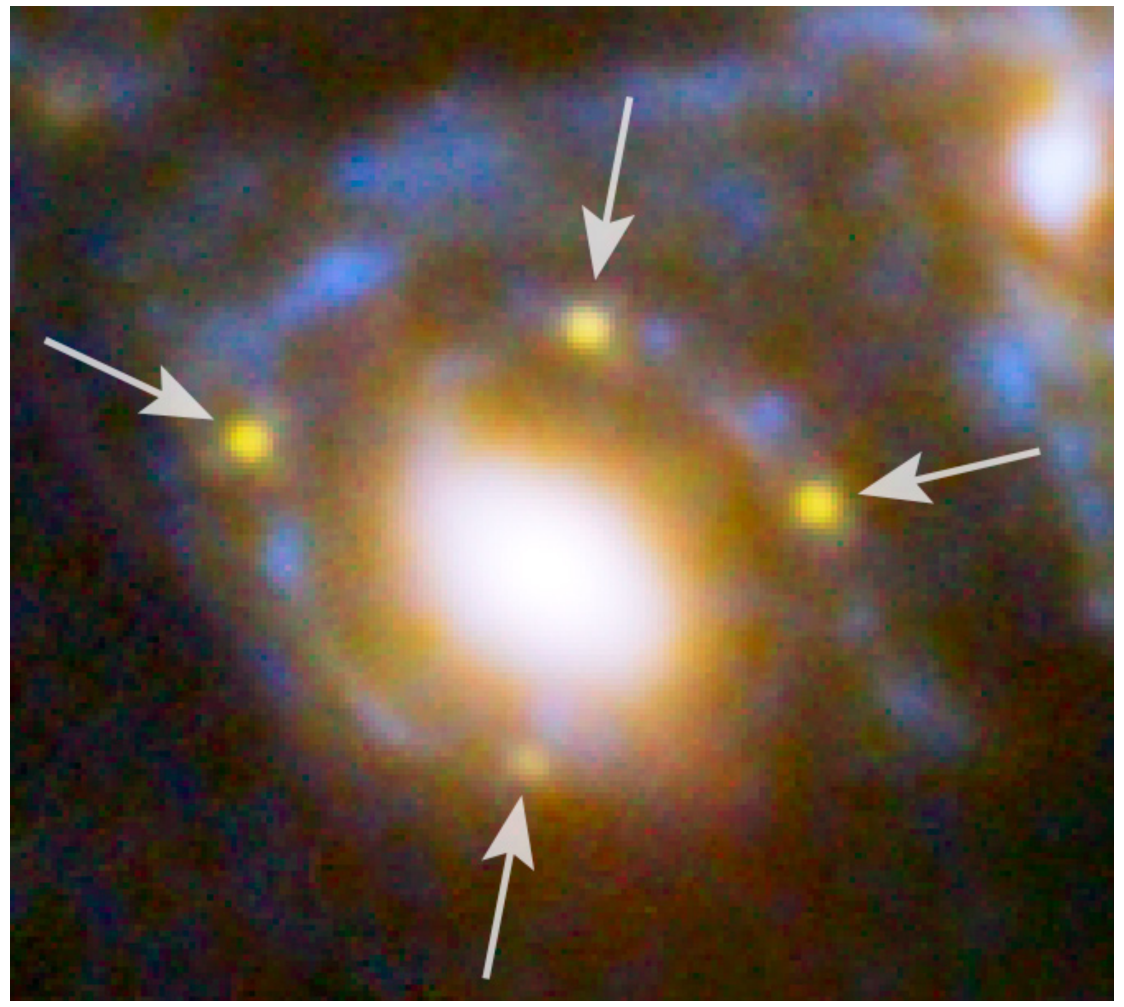
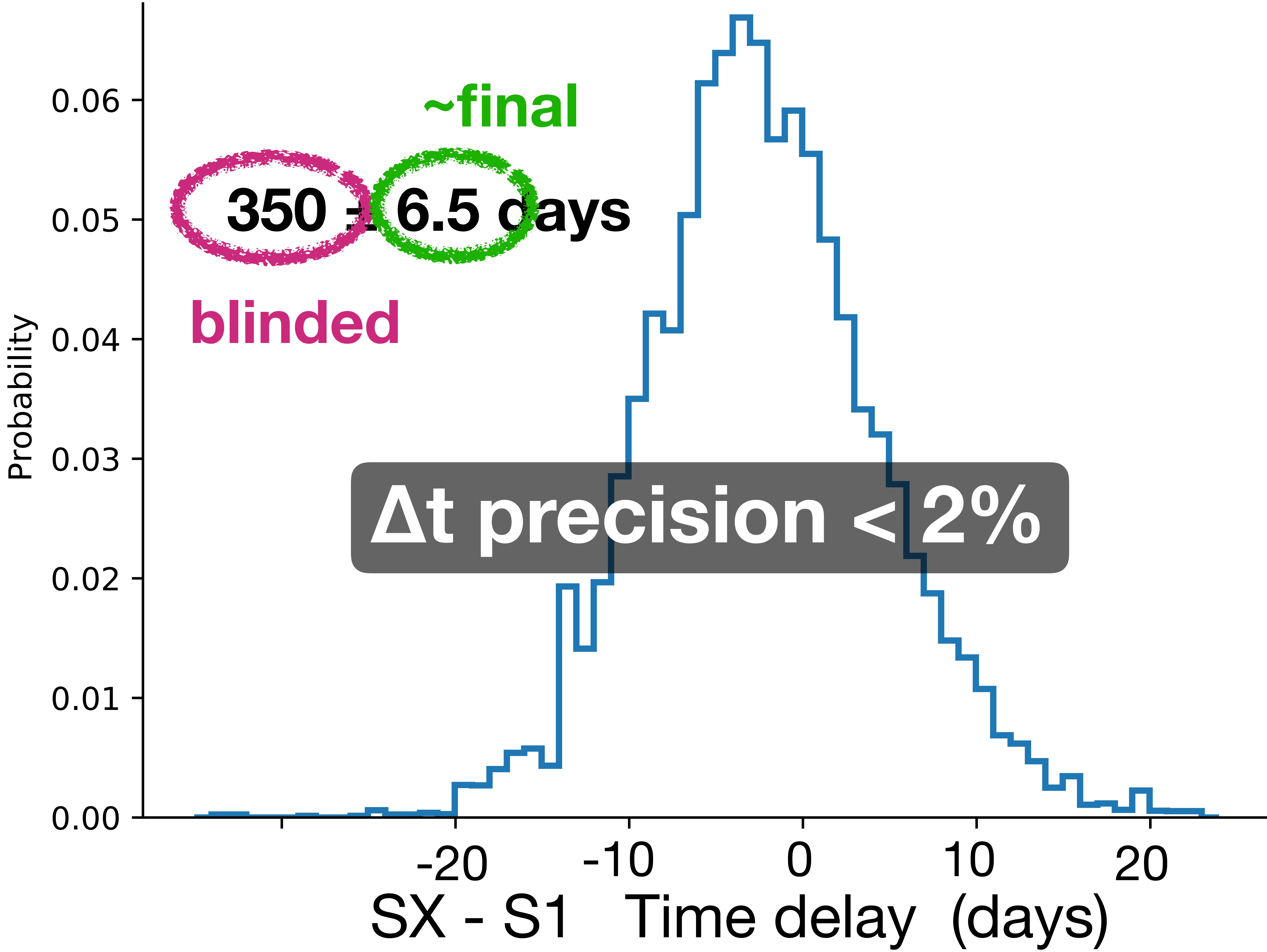
Composite Time Delays : SX-S1







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anticipated Error Budget for H_0 from SN Refsdal

	Best Case
Time Delay Measurement	2%
Primary lens model	3%
Line of sight	2%
Cluster Multi-plane Effects	0%
fΛCDM parameters	3%

in fΛCDM with uniform priors $H_0 \in [20, 120]$ km s^{-1} Mpc^{-1} and $\Omega_m \in [0, 1]$

see Grillo...SR et al. 2018

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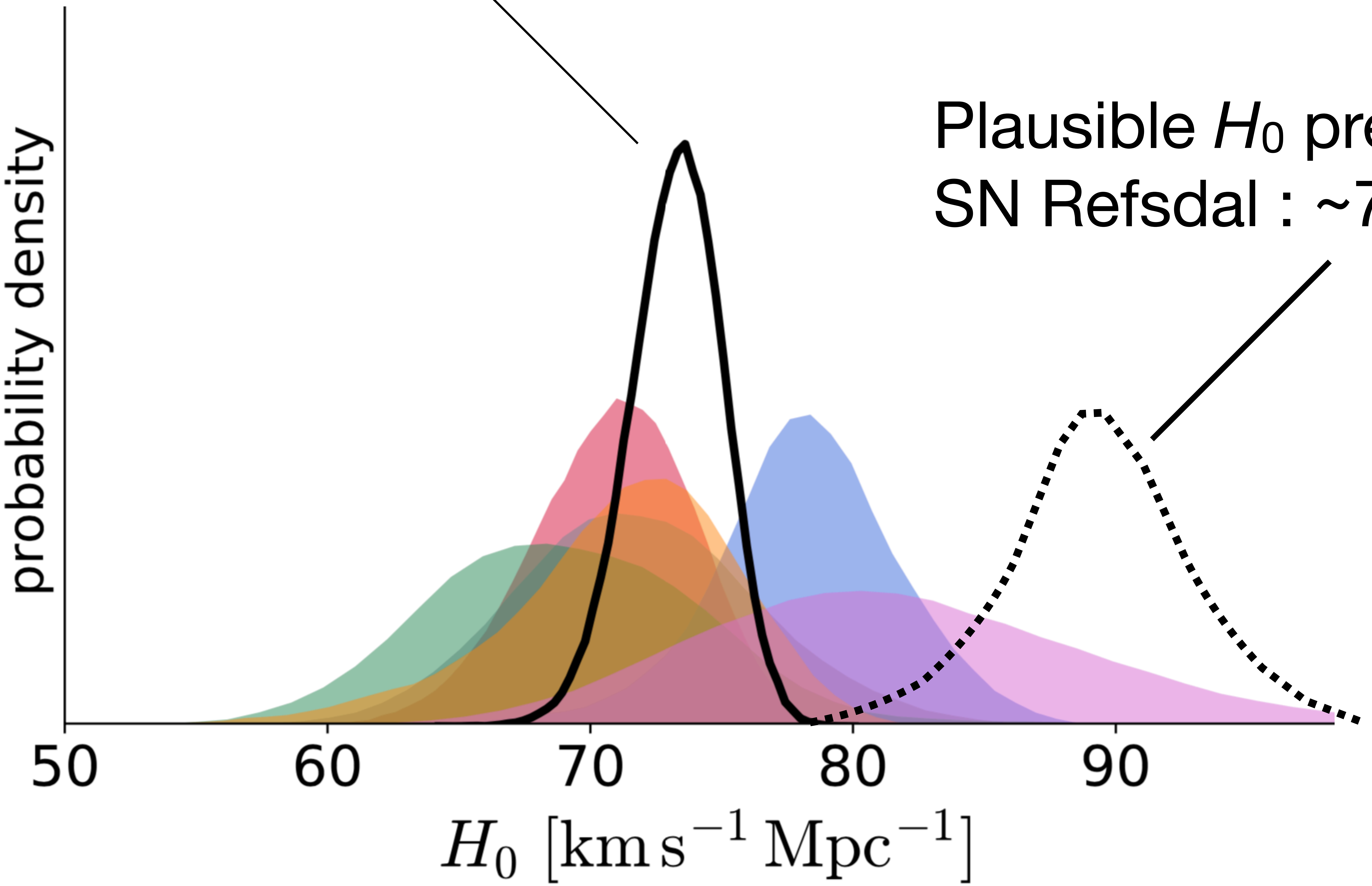
Take-home message:

We have measured the time delay for SN Refsdal with a precision of ~2%

This will deliver the first GLSN measurement of H0, with a precision of ~7%

H_0 measured to 2.4%, combining 6 lensed QSOs from H0LiCOW, each with ~6-10% precision.

Wong+ 2019



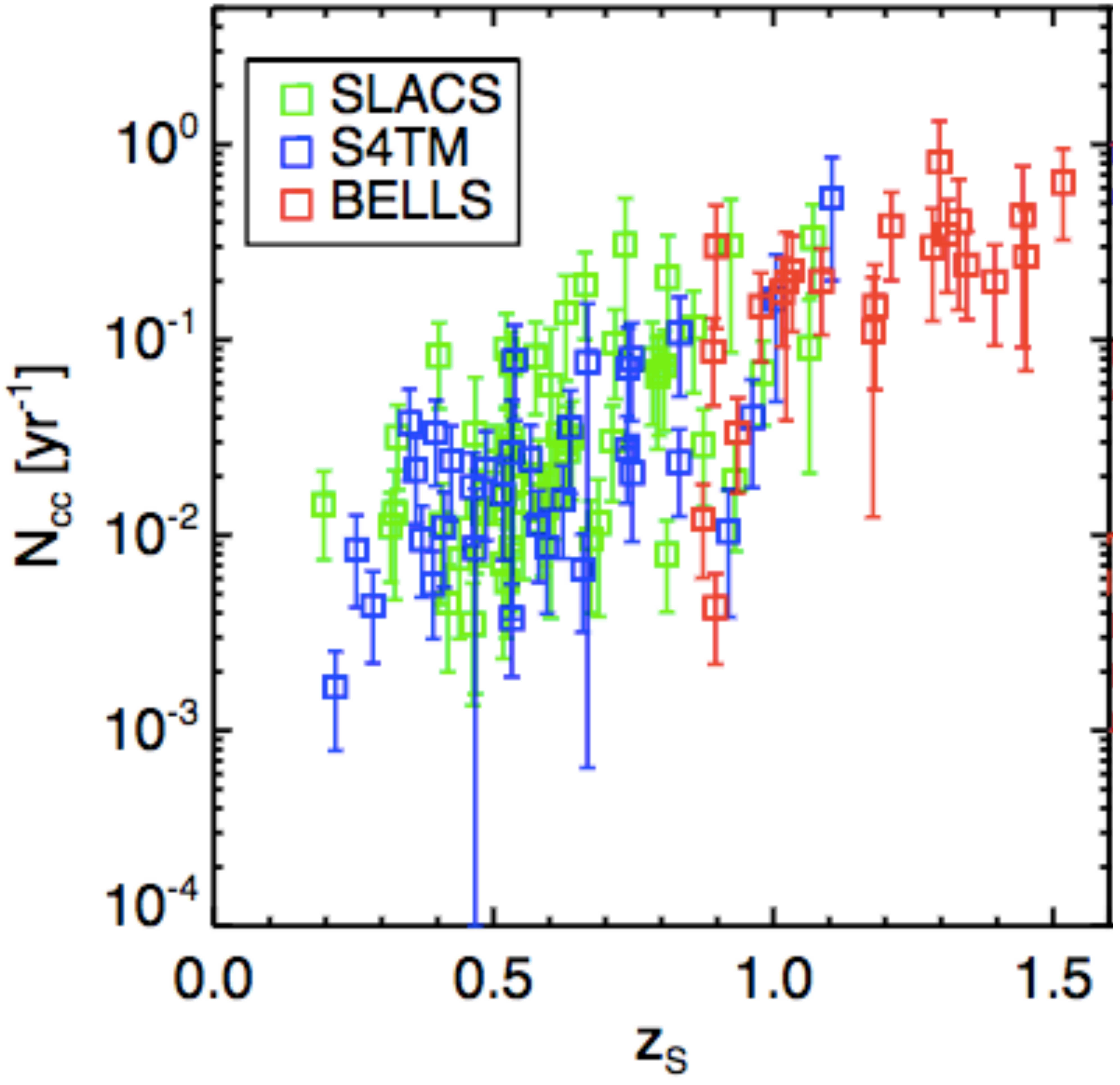
Plausible H_0 precision from SN Refsdal : ~7%

1. Why use GLSN?

2. Measuring time delays: SNTD

3. Time delay cosmography
   with SN Refsdal

4. How to find the next one



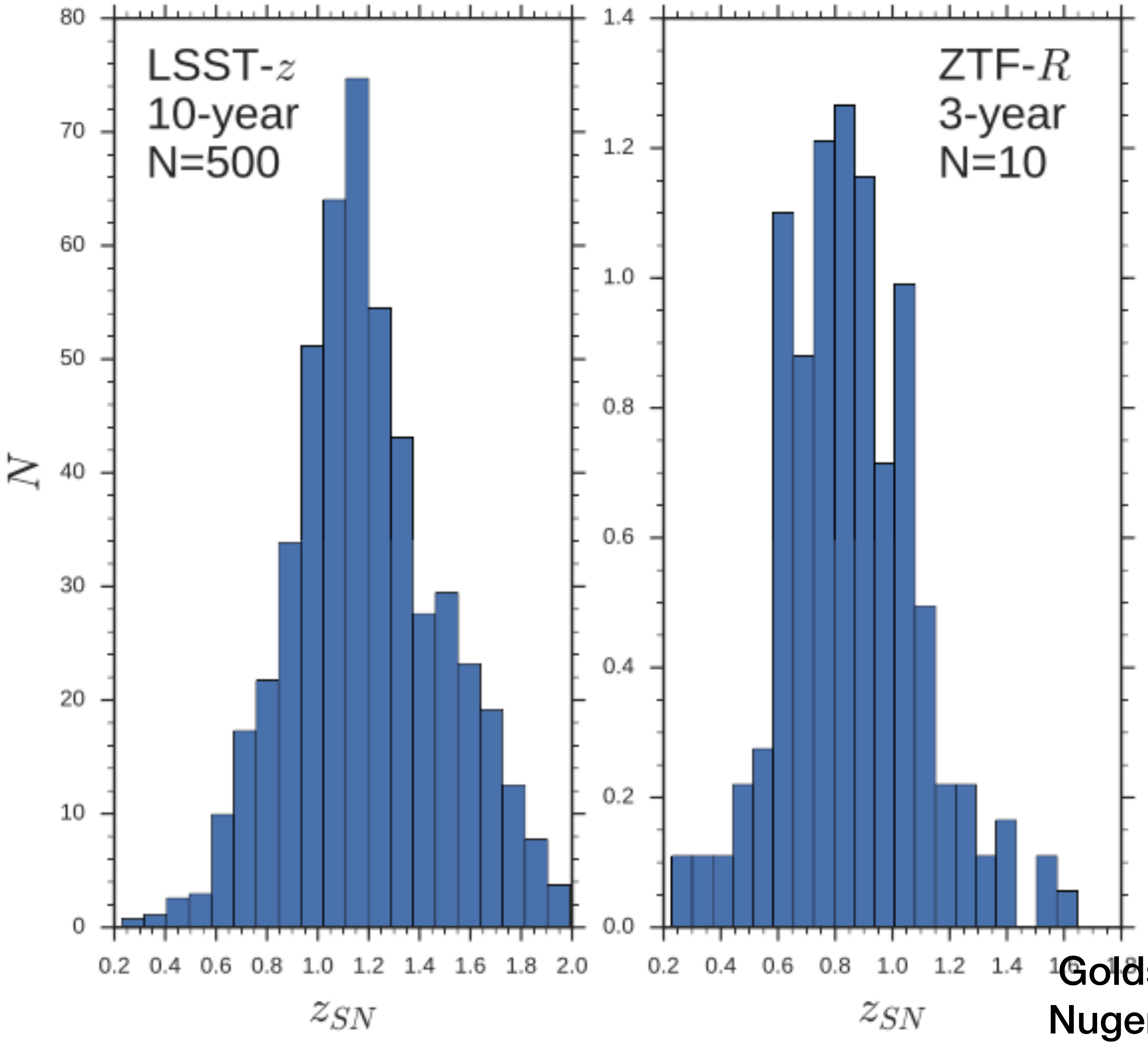
Two ways to find a rare lensed transient event

- Wide-field sky survey
- Targeted search

Rapid, wide-field sky surveys: get a bigger haystack.

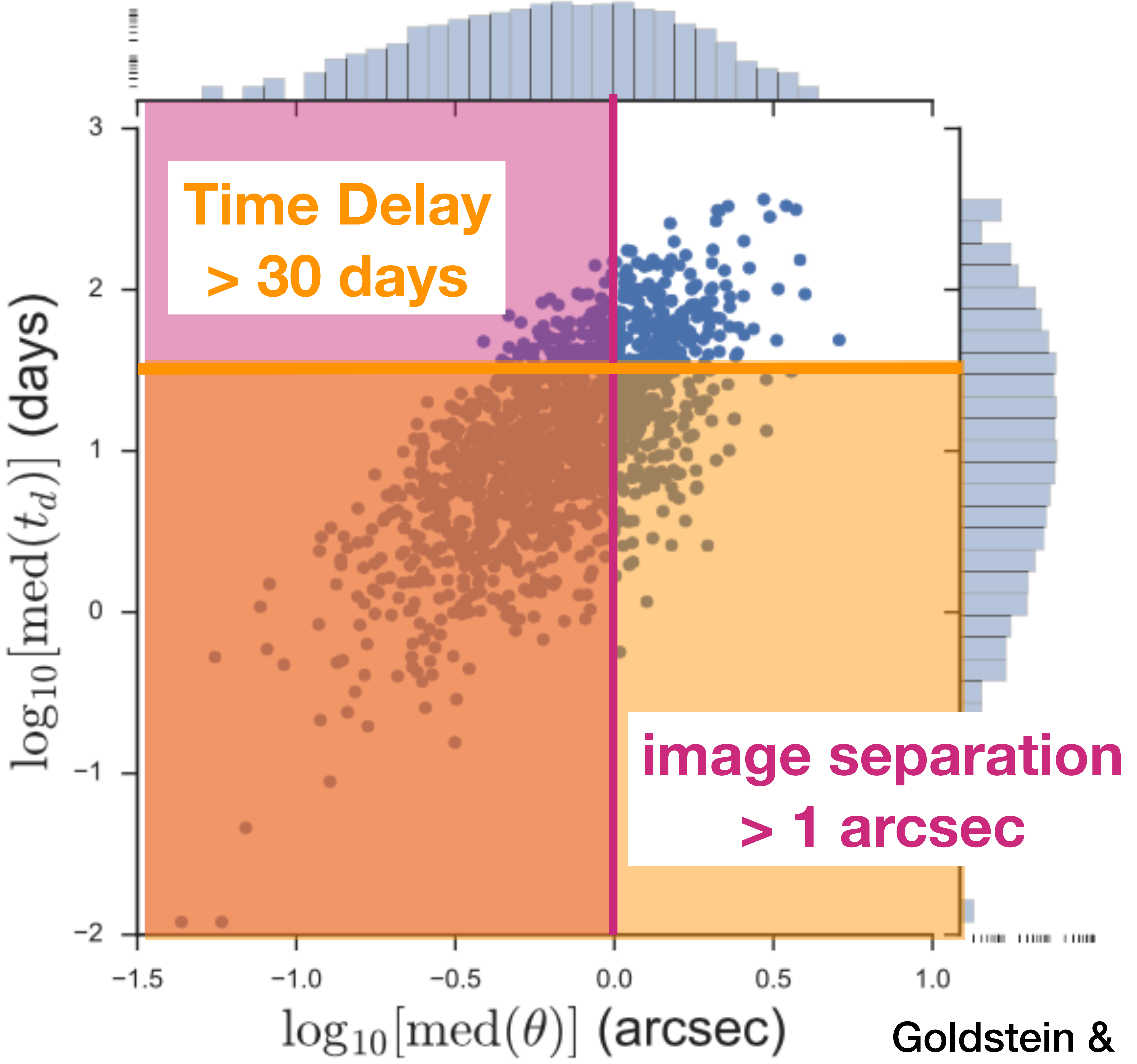
Haystacks, End of Summer - Claude Monet , 1891

ZTF should find a handful, LSST will find hundreds



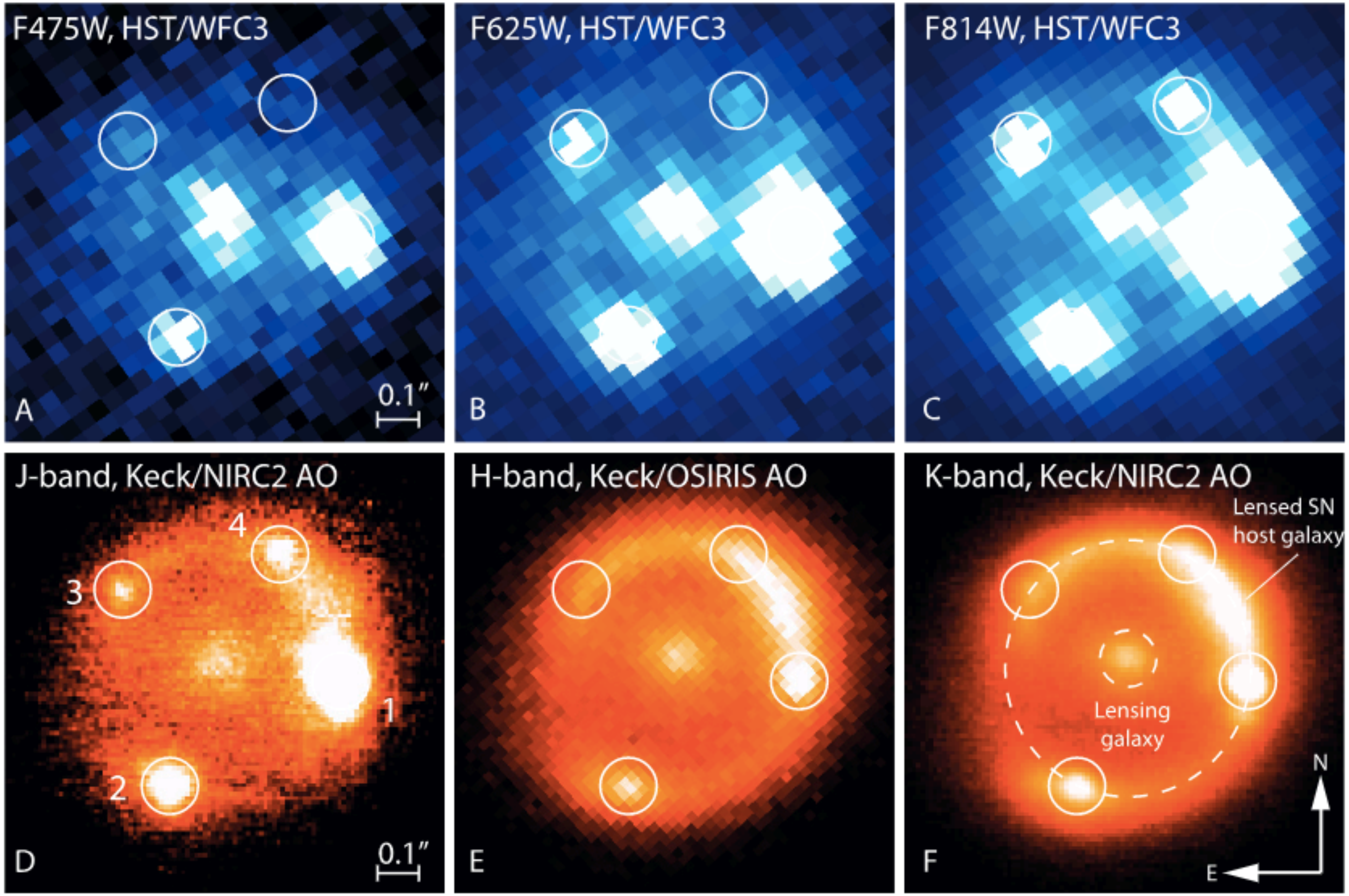
Goldstein & Nugent 2017

Only a small fraction will be suitable for time delay cosmography



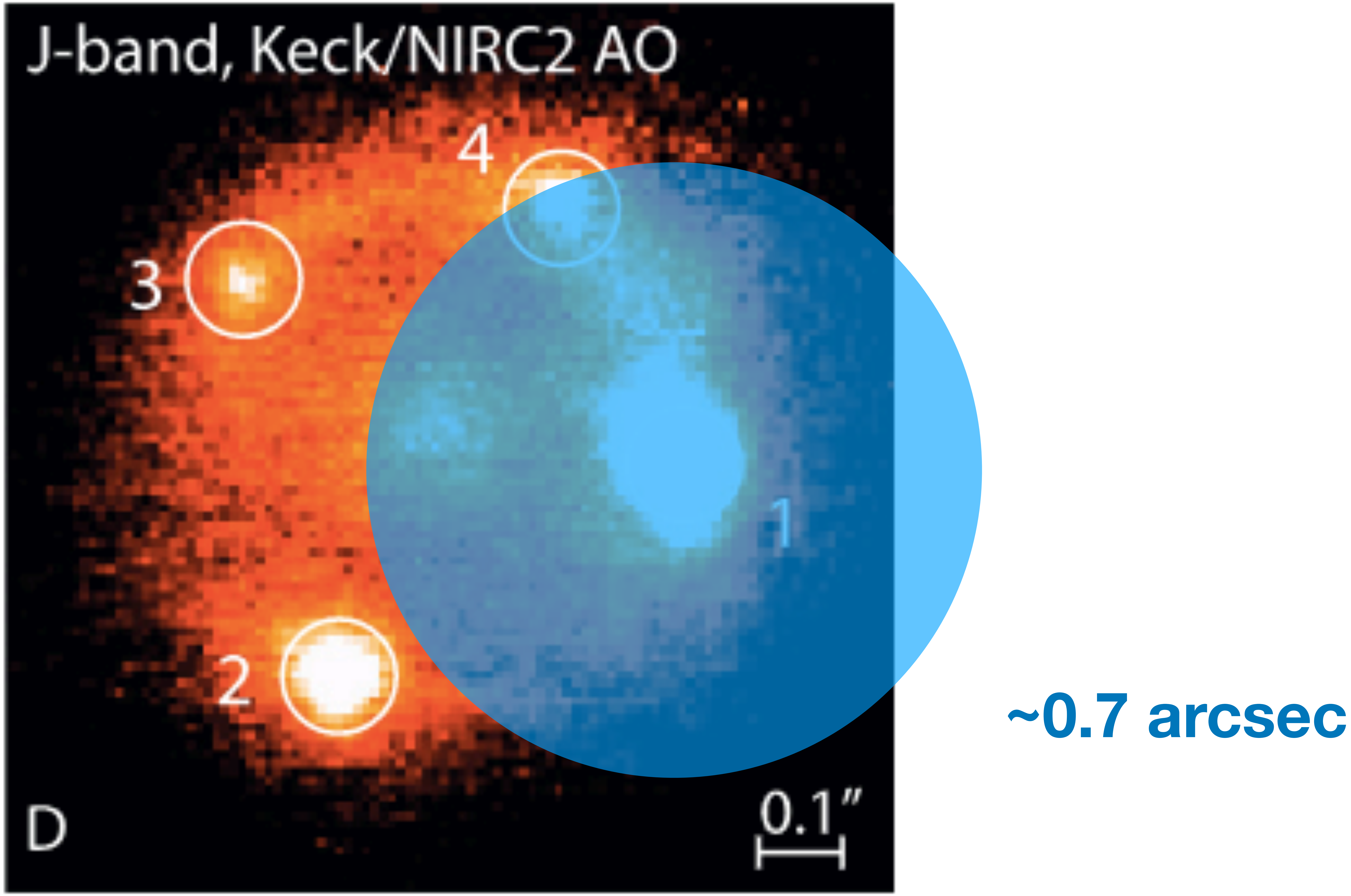
Goldstein & Nugent 2017

iPTF 16geu



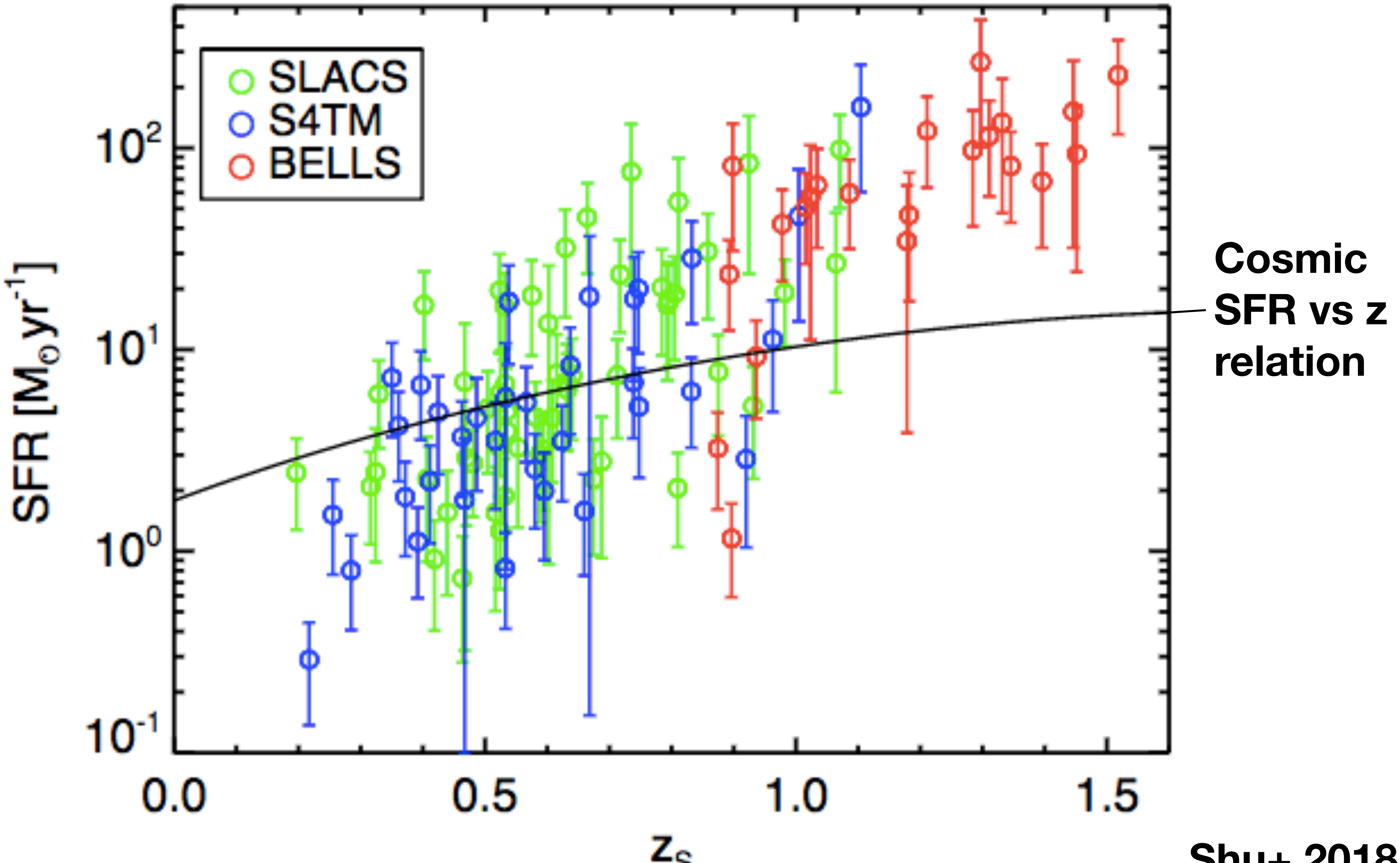
Goobar+ 2017

SN 2016geu



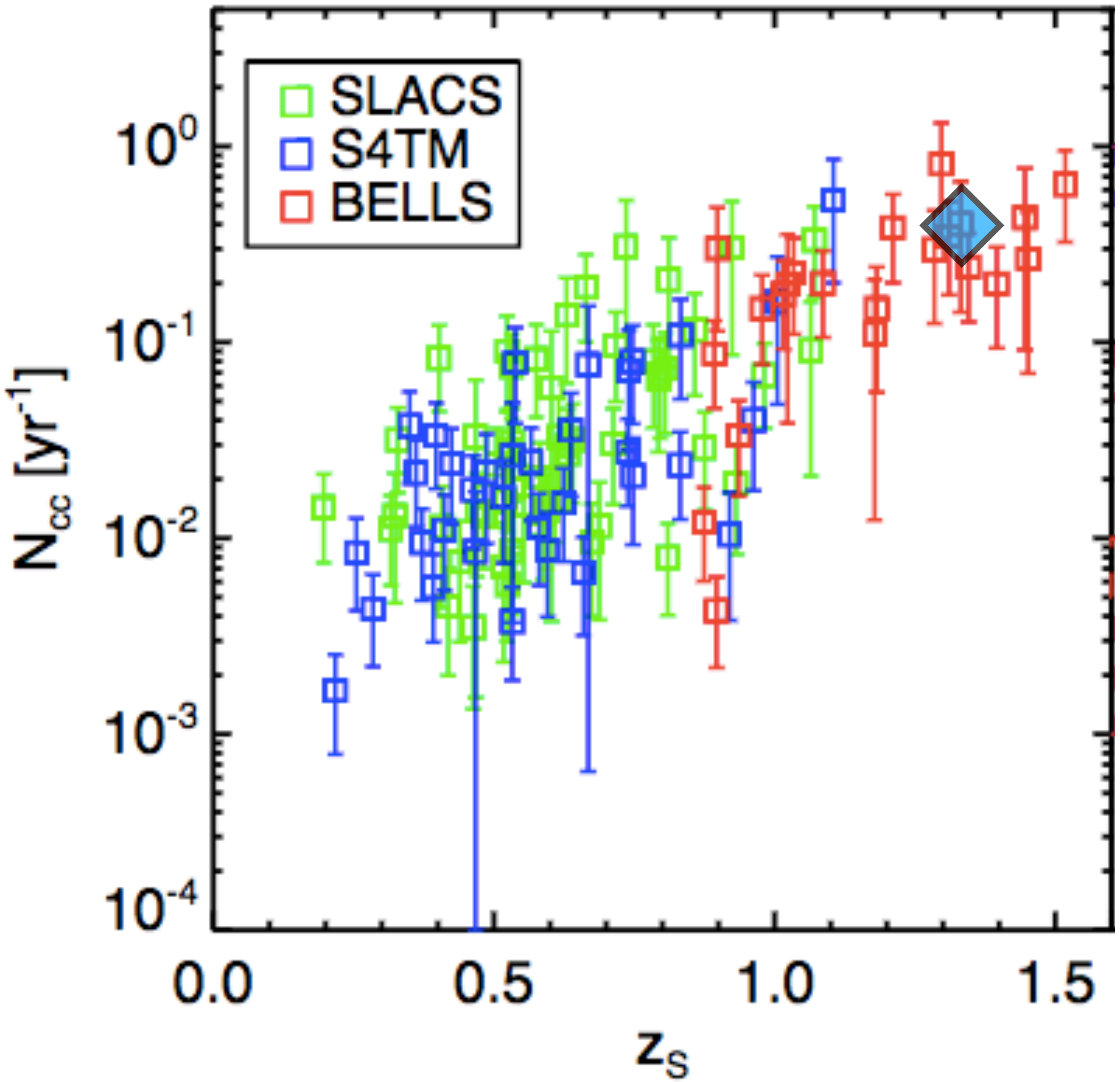
Targeted Search : to find a needle, look in the sewing kit

High-z Lensed Galaxies have High Star Formation Rates



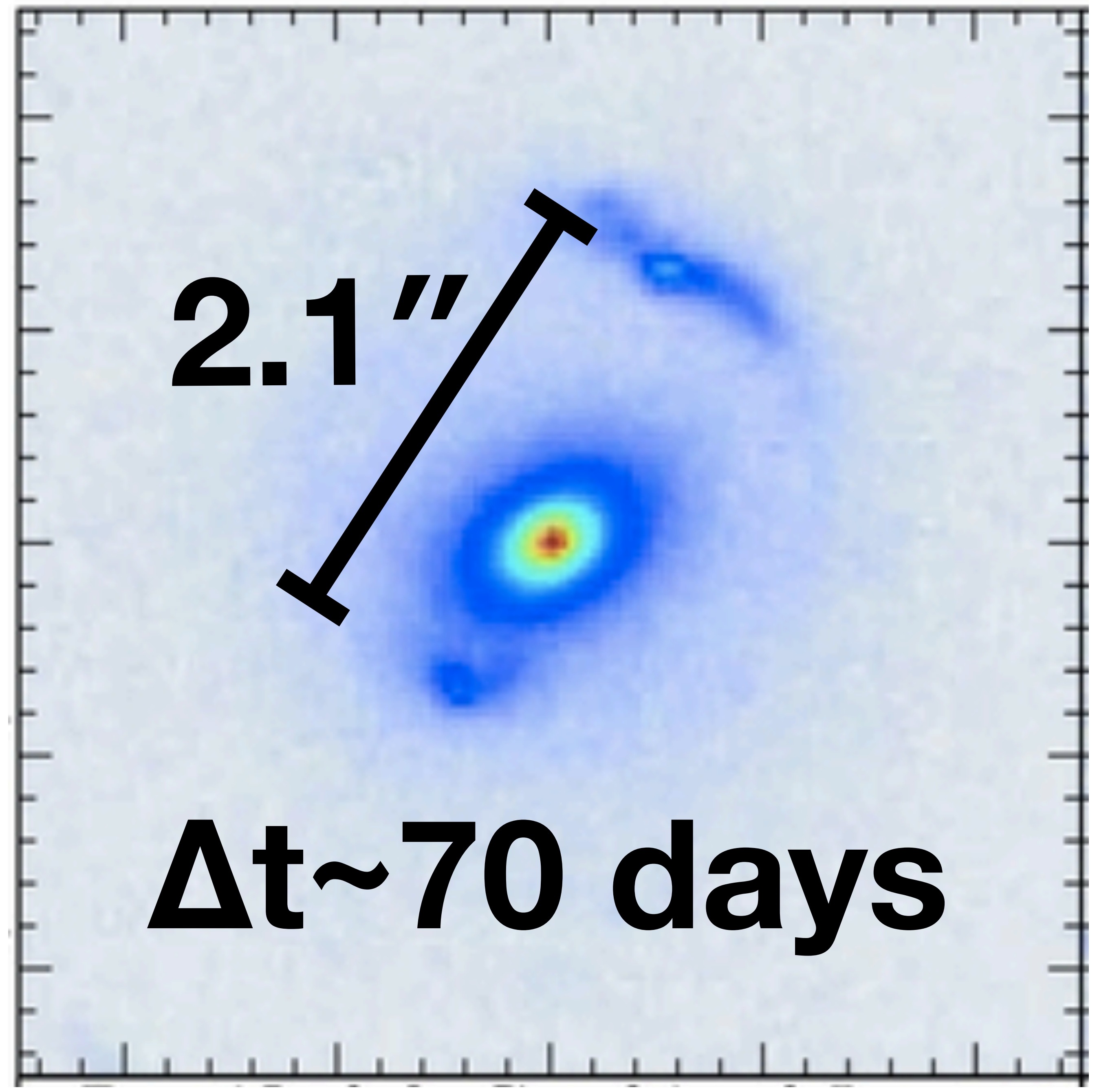
Shu+ 2018

High SFR = High SN Rate



BELLS J0830

0.4±0.3 SN yr^{-1}



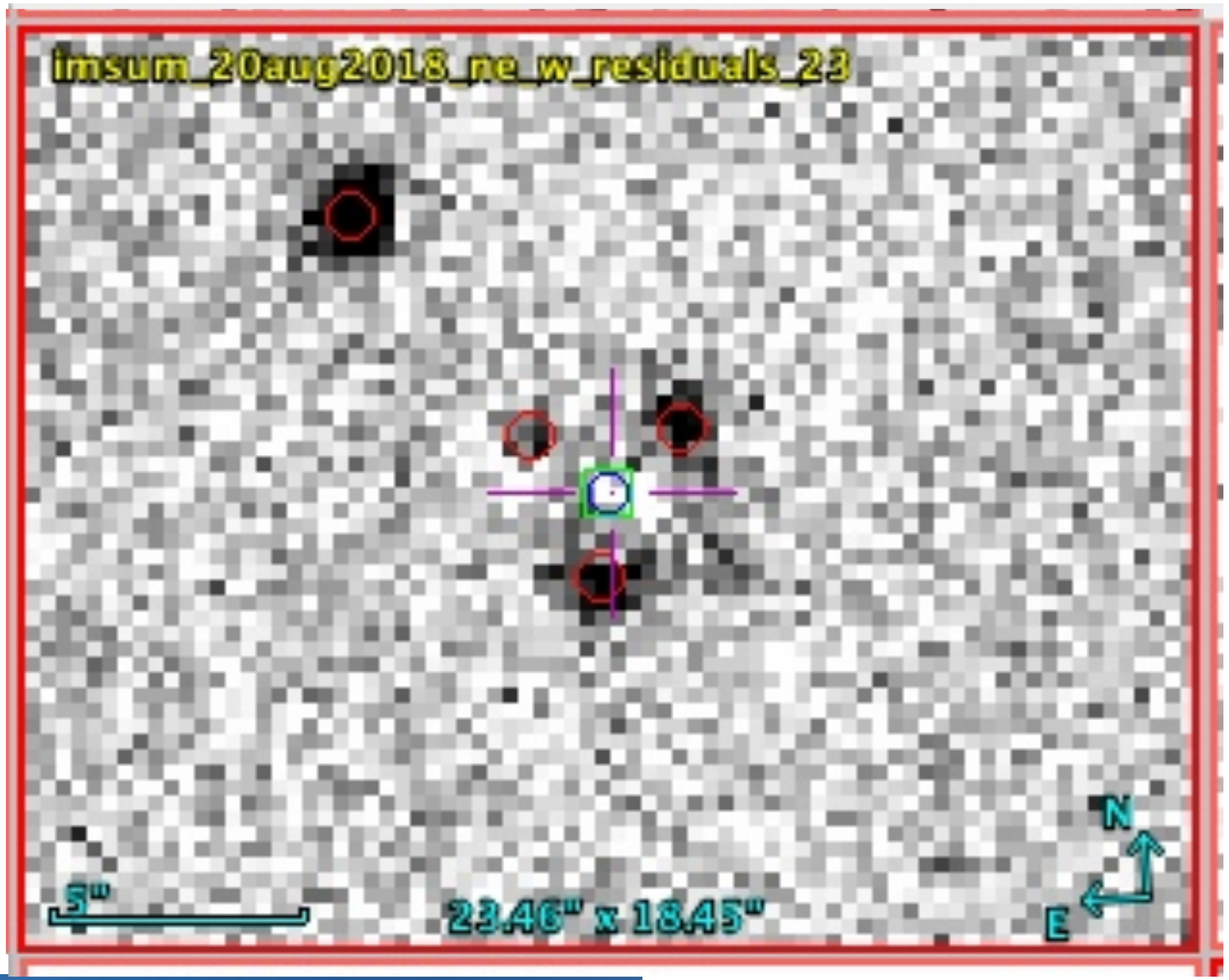
Brownstein+ 2012

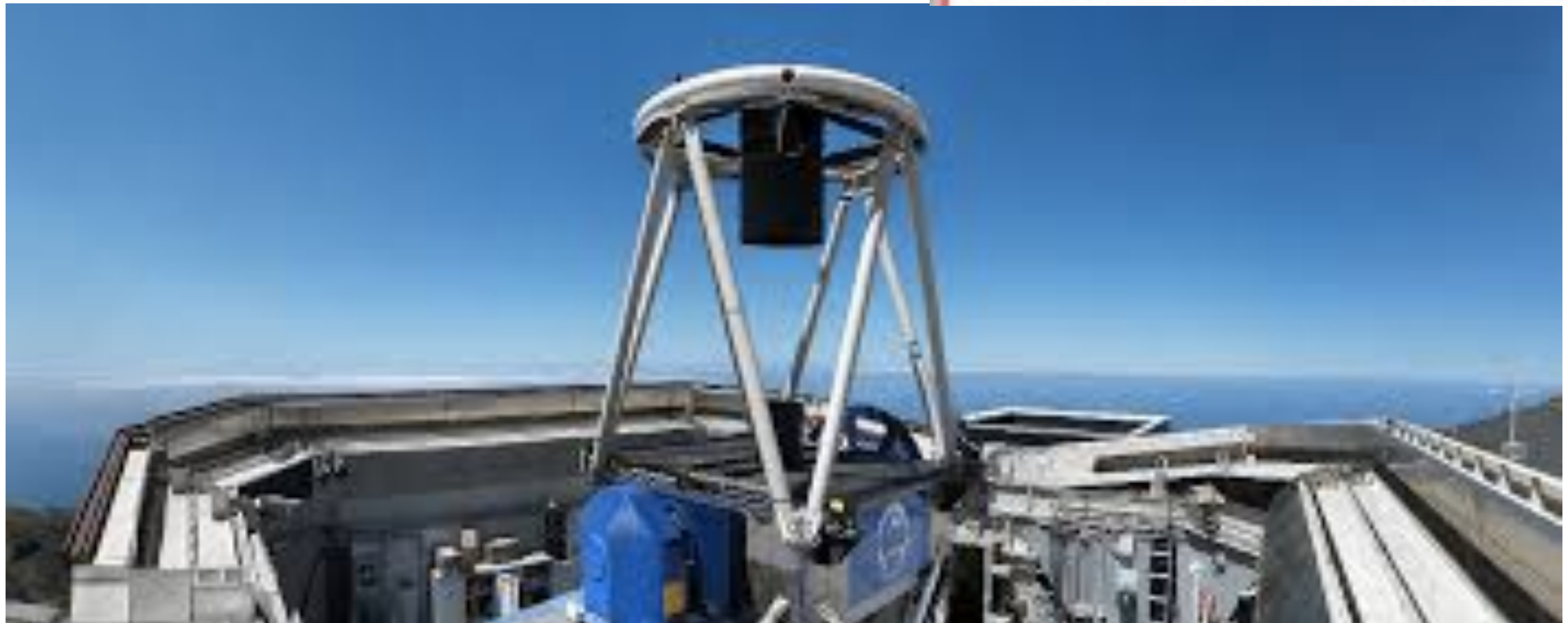
Shu+ 2018

Liverpool Telescope Strongly Lensed SN Discovery Survey

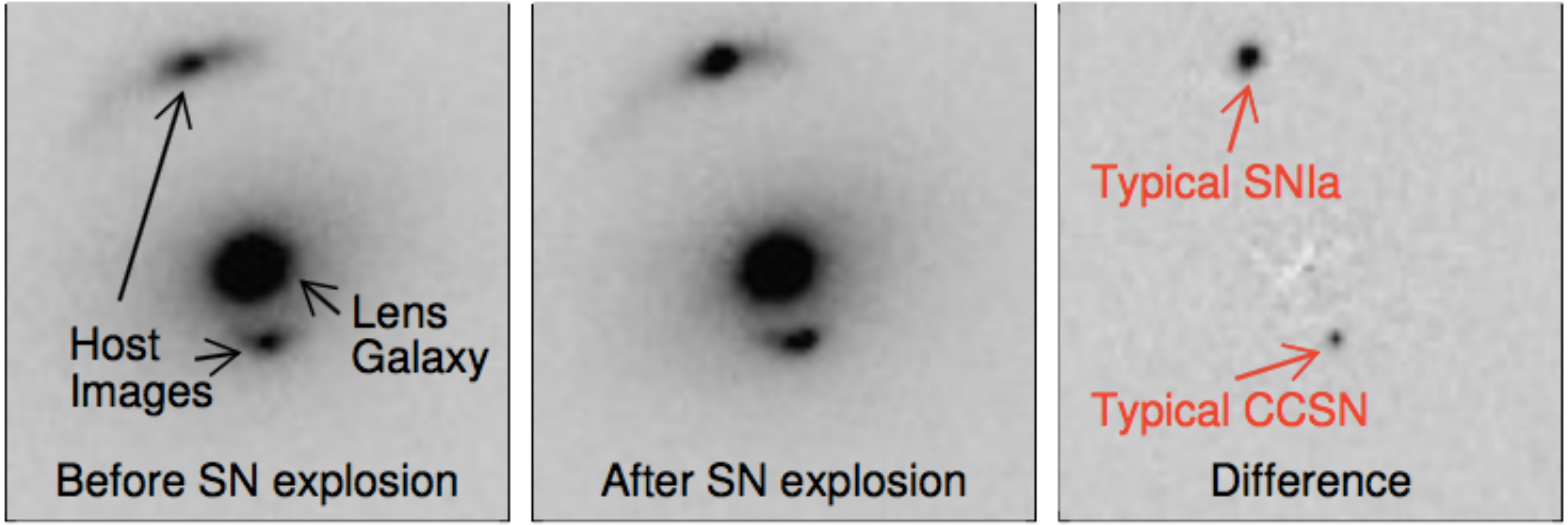
PI: Ismael Perez-Fournon

r_{lim} ~ 23.5 AB mag





with HST: $m_{10\sigma}$~26.5 AB



Probability of detecting at least one glSN in a 1-year survey:

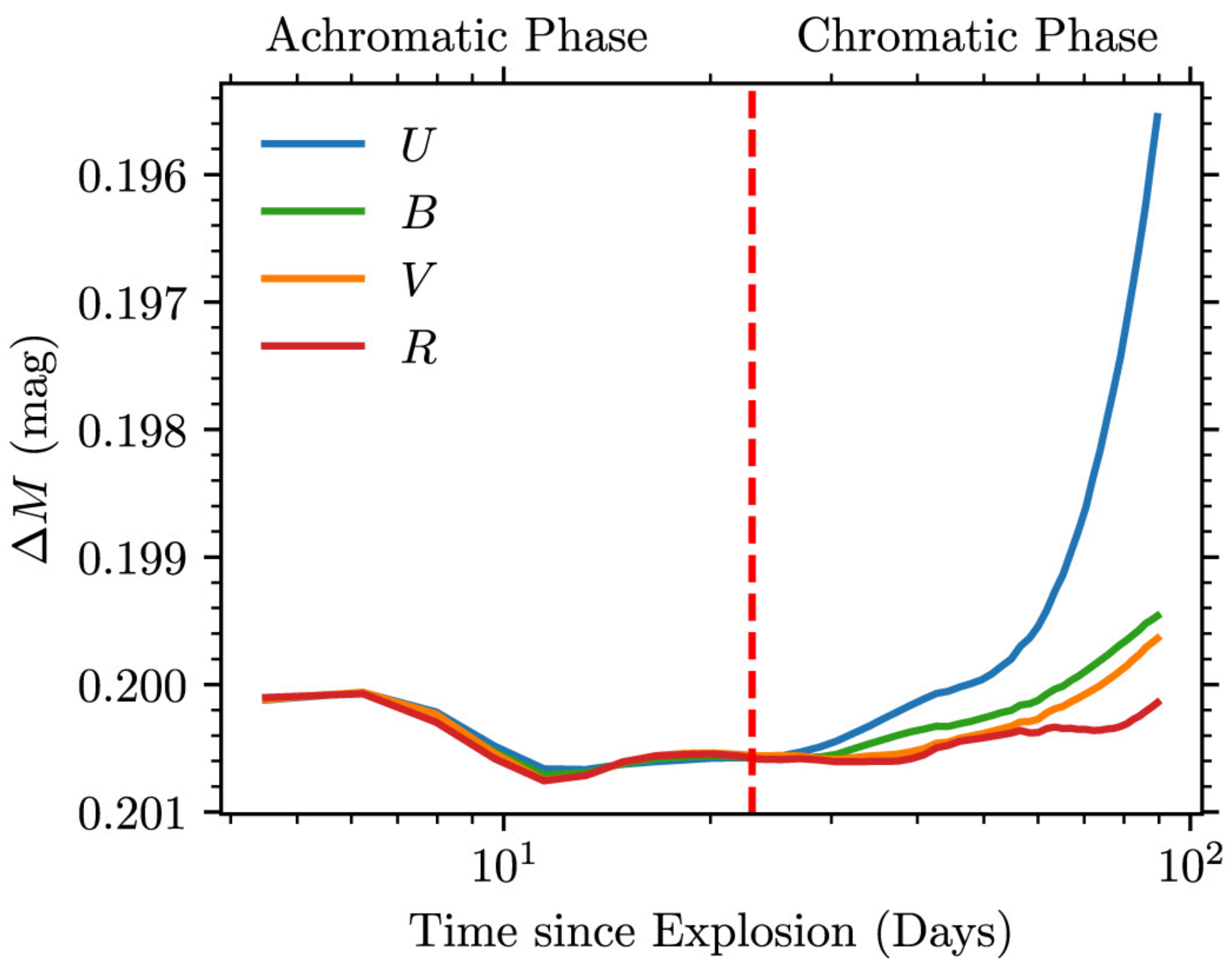
- 2m: m_{lim} ~ 23.5 p~20%
- 8m: m_{lim} ~ 24.5 p~50%
- HST: m_{lim} ~ 26.5 p~95%

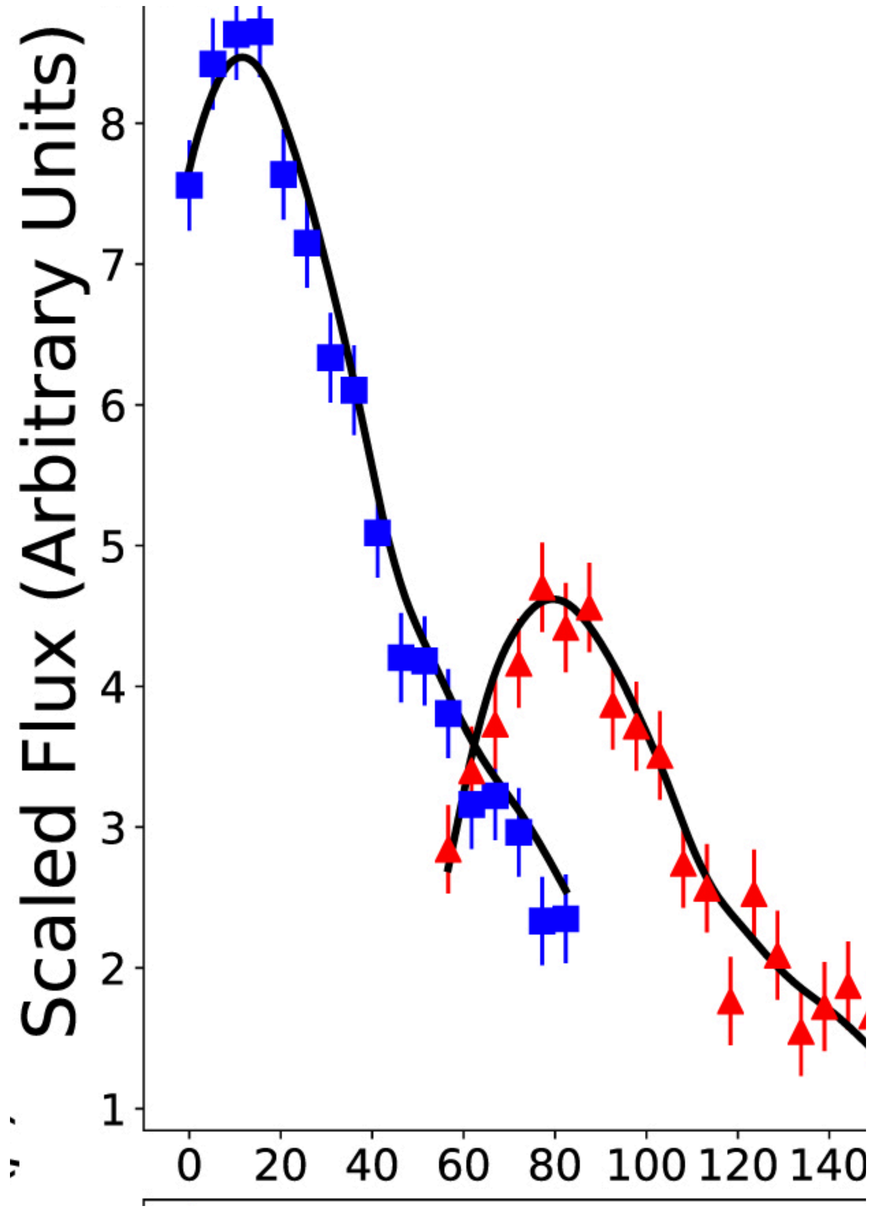
1. Why use GLSN? *They have natural strengths for time delay cosmography.*

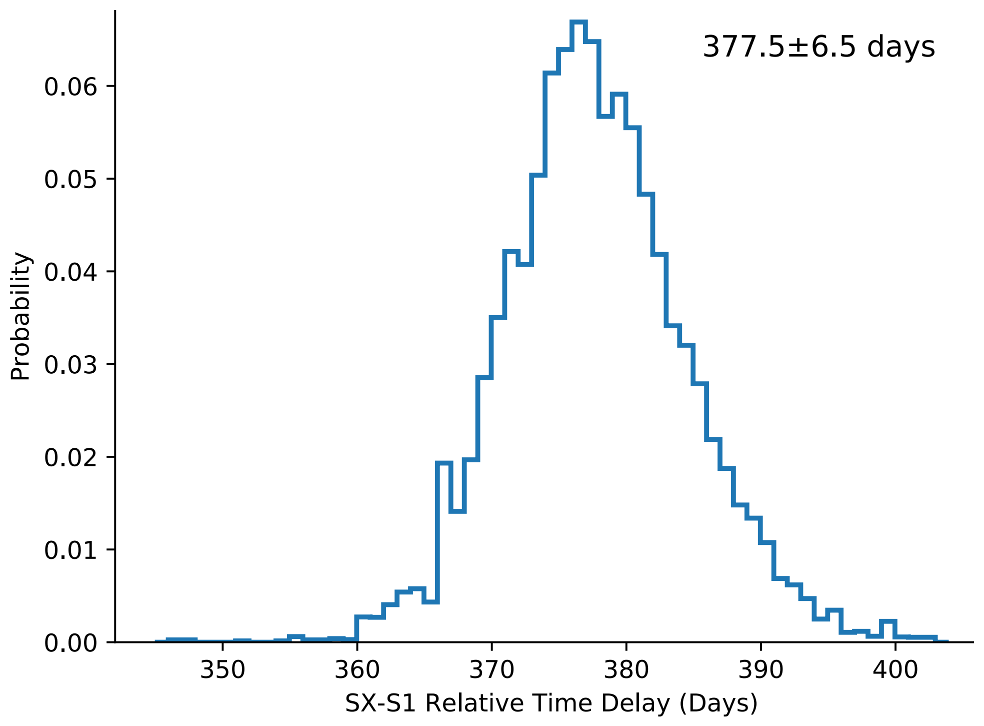
2. Measuring time delays: SNTD is designed to leverage those strengths.

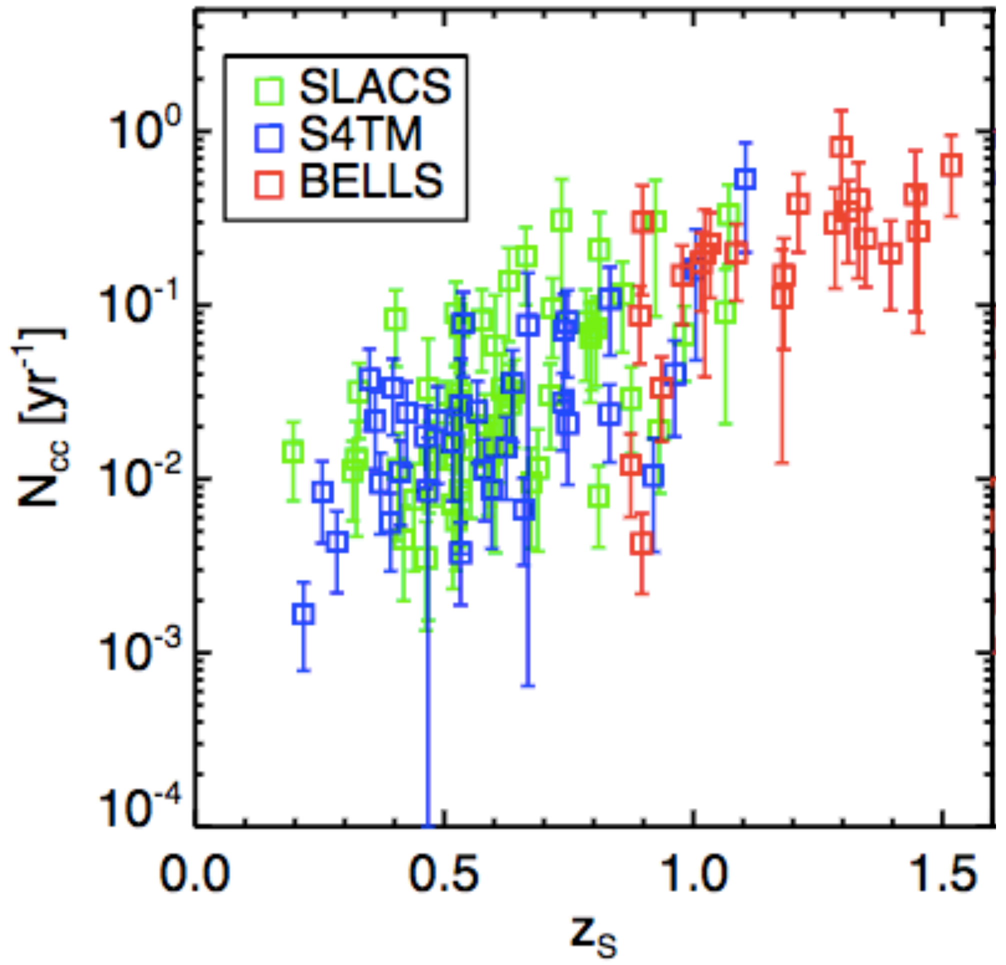
3. SN Refsdal is delivering a time delay measurement <2%, will deliver H0~7%

4. Expect a handful more by 2025, hundreds by 2030









Steve Rodney (UofSC)

Some questions to answer while you're waiting for the next GLSN...

- How can we (really) use GLSN to reduce *lens model degeneracies*?
- How precise can *spectroscopic* time delay measurements be?
- How well can we measure time delays from *unresolved* GLSNe?
- How can we mitigate microlensing uncertainties for *Core Collapse* SNe?