Hydrodynamical model for strongly lensed SN Refsdal and time-delay measurements between its multiple images

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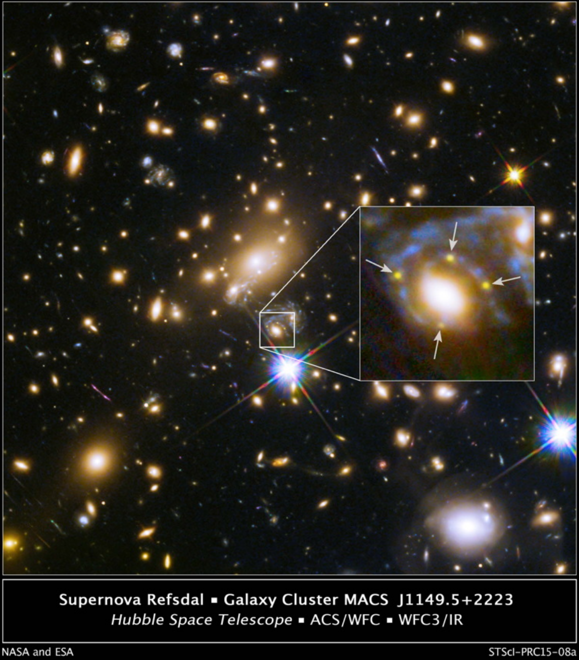
Kavli IPMU

February 04, 2020

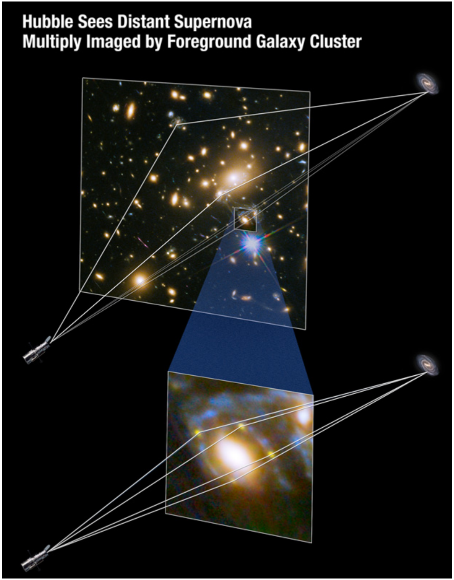
SN Refsdal: discovery



A strongly lensed supernova was found in the MACS J1149.6+2223 galaxy cluster field on 11 November 2014

Kelly et al. arxiv:1411.6009

Cluster MACS J1149.5+2223 and SN Refsdal



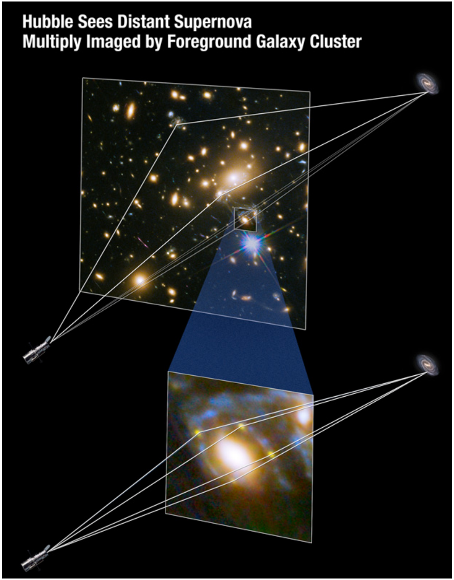
by NASA, ESA

MACS J1149.5+2223

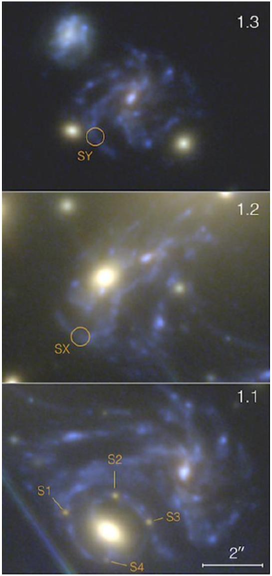
Members (Treu, 2015):
$0.520 < z < 0.570$
$D_L = 3.14$ Gpc
$D_a = 1.32$ Gpc
The light travel time is 5.235 Gyr.

SN Refsdal is located at the outer spiral arm ($R_c \sim 7$ kpc)
$z = 1.49$
$D_L = 11$ Gpc
$D_a = 1.771$ Gpc
The light travel time is 9.380 Gyr.

Cluster MACS J1149.5+2223 and SN Refsdal



by NASA, ESA



by T.Treu (2016)

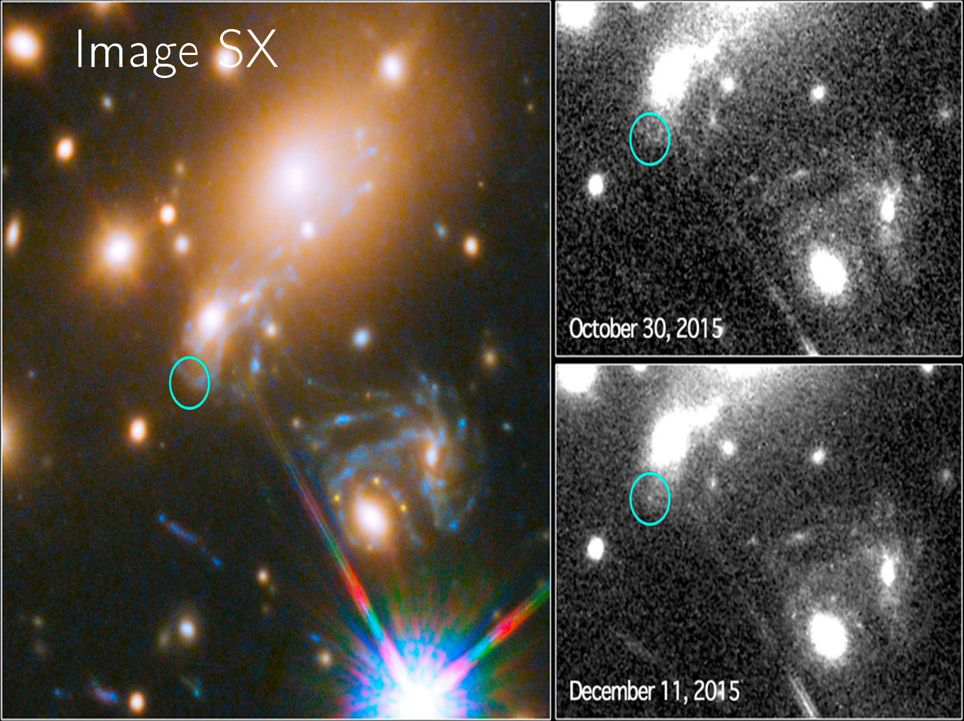
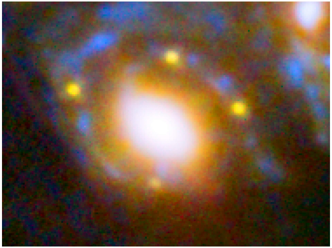
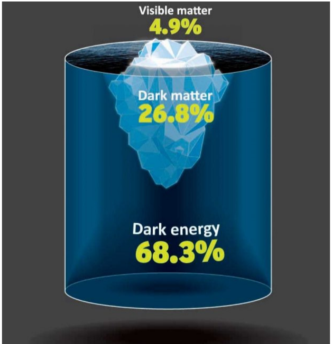


Image SX
October 30, 2015
December 11, 2015

Motivation

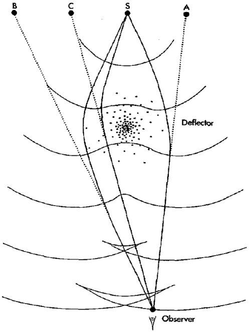
- It is very exciting to study the most distant supernovae type IIP at $z = 1.49$
  To learn the properties of the peculiar core-collapse supernova explosion at high redshifts.
- Try to get the time delays and the magnification ratios between multiple images of the supernova.
  Constraints for the structure of dark matter halos in galaxies?
  Measuring the Hubble constant?





Facts about SN Refsdal

- **Fact 1:** This is the first SN to get its own name since the Late Renaissance.
- **Fact 2:** This is the first SN with multiple images due to strong gravitational lensing.
- **Fact 3:** This is the first SN for which the place and time of its appearance was predicted.



Refsdal, S. (1964). On the Possibility of Determining Hubble's Parameter and the Masses of Galaxies from the Gravitational Lens Effect. Monthly Notices of the Royal Astronomical Society, 128(4), 307–310.

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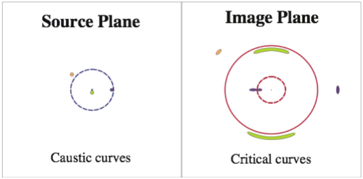

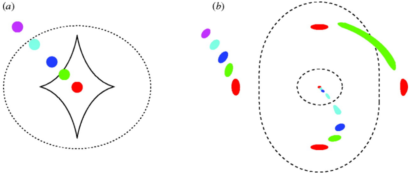

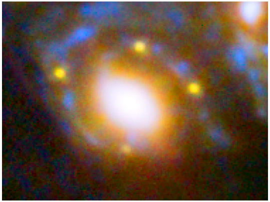

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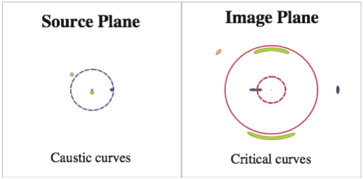
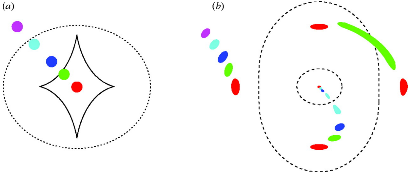
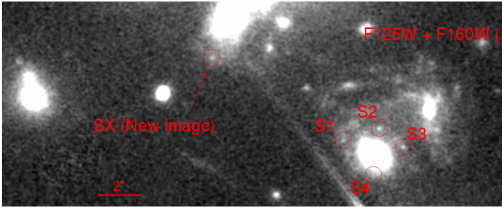


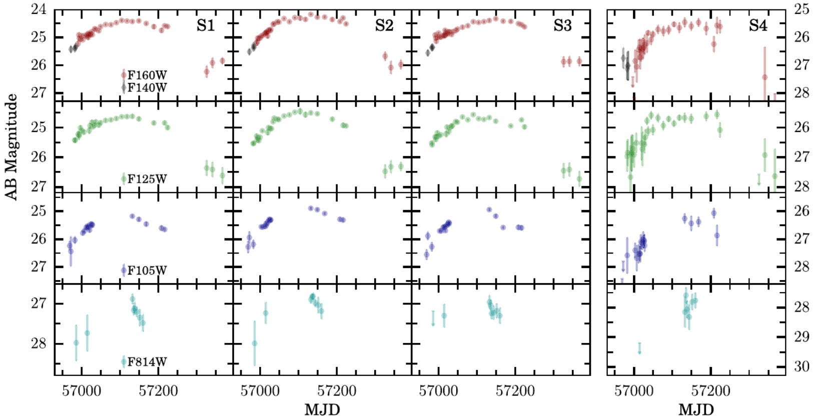




Observations: LC of SN Refsdal

The multi-color photometric data were obtained for 400 days following the discovery.

There is a slow rise to maximum light (over $\sim$ 150 days).

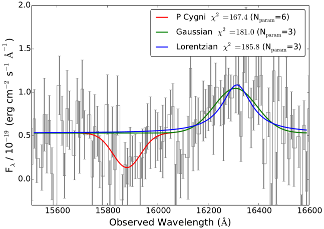


by Rodney et.al.(2015) arxiv:1512.05734

Observations: the spectra of SN Refsdal

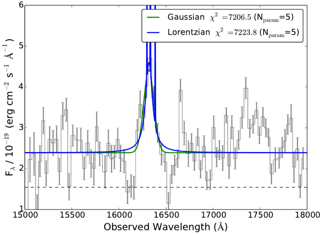
Spectrum of H_α taken -47^d

by HST WFC3 Grism

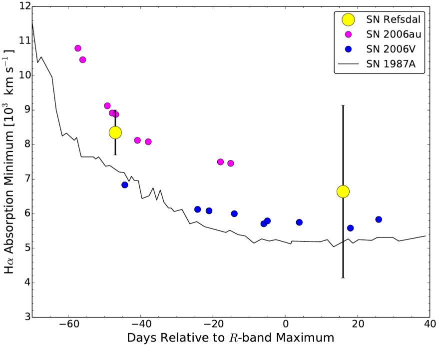


Spectrum of H_α taken 16^d

by the VLT



H_α P-Cygni expansion velocity



by Kelly+2015, arxiv:1512.09093

The analysis of observations

These are the conclusions of Rodney+2016, arxiv:1512.05734

- The hydrogen lines are shown in SN Refsdal's spectra so it should be SN II.
- SN Refsdal's slow rise to maximum light (over ~ 150 days) is clearly inconsistent with the rise times for the most common SN types (e.g., Ia, Ib/c, II-P, and II-L).
- SN Refsdal observations have been compared with these normal SN classes, using a library of 42 templates drawn from the Supernova Analysis software suite — unsuccessfully
- Rodney et.al. have concluded that the peculiar SN 1987A-like sub-class provides the best matches to the observed shape of the SN Refsdal light curve.

Theoretical light curves: code STELLA

The optical light curves of SN Refsdal are analyzed with the multienergy group radiation hydrodynamics code STELLA developed at ITEP (S. Blinnikov, E. Sorokina, P. Baklanov).

Model assumptions

- The equations were written in one-dimensional spherical geometry.
- The levels and ions populations are computed under LTE.
- Our total opacity included contributions from photoionization, bremsstrahlung, lines, and electron scattering.
- The line opacity with expansion effect in lines was computed using atomic data from the Kurucz's list with approximately 150,000 lines.
- Multigroup radiative transfer coupled with hydrodynamics enables to derive the spectral energy distributions (SEDs) self-consistently.

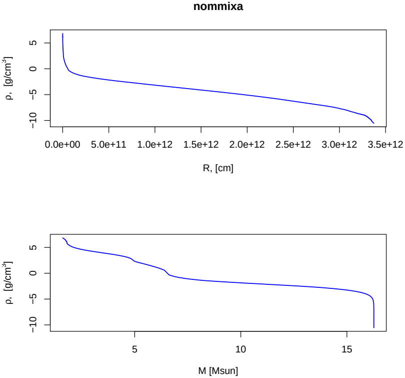
STELLA solves the time-dependent equations implicitly for the angular moments of intensity averaged over fixed frequency bands.

No assumption of radiative equilibrium

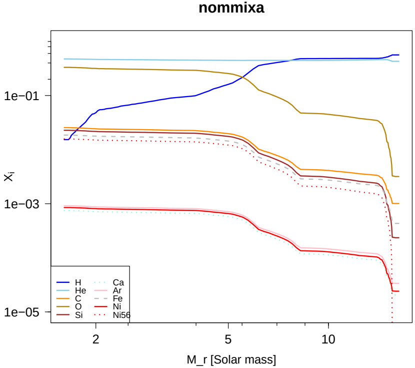
The progenitor model: chemical composition

We have used as initial model the evolutionary model of Nomoto & Hashimoto (1988)

Density as a function of the interior mass and radius



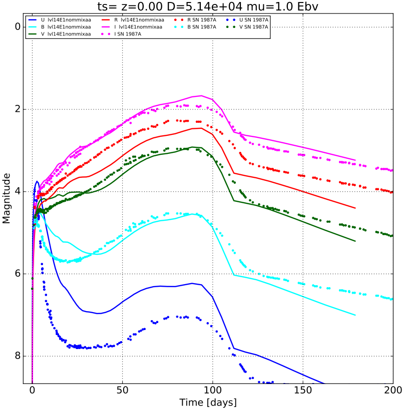
Abundance distribution as a function of enclosed mass for the ejecta



SN 1987A: $E = 1.7 \times 10^{51}$ ergs, $M = 16.6\ \mathrm{M}_\odot$, $M_{^{56}Ni} = 0.078\ \mathrm{M}_\odot$

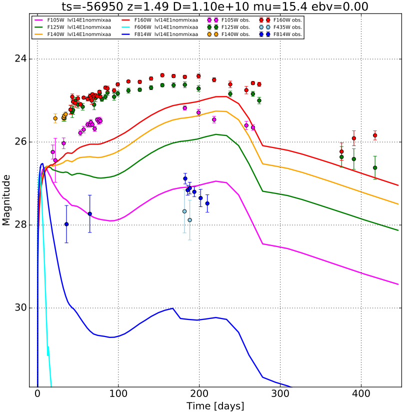
Modeling Light curves of the supernovae:

with SN 1987A



Good fit!

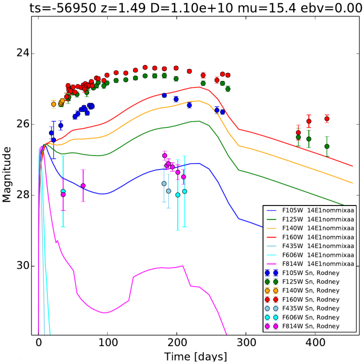
with SN Refsdal

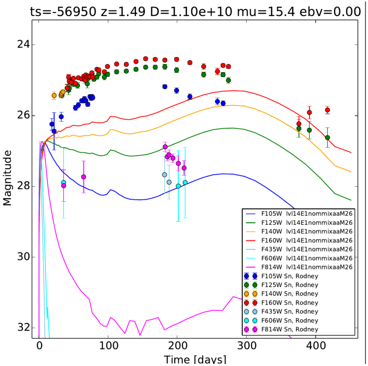


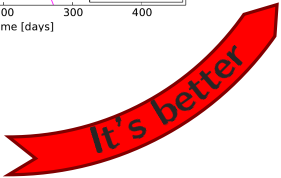
A bad agreement with the observations

The path to the best model

We have increased the ejected mass to make the cupola longer.

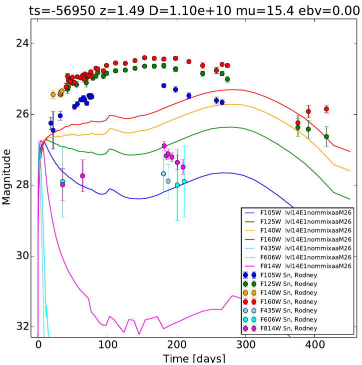


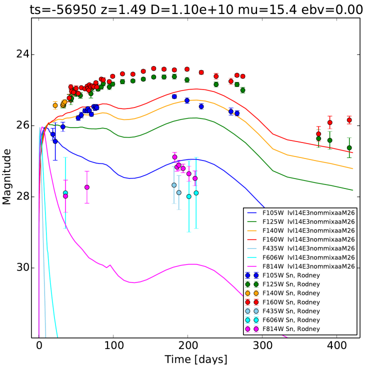


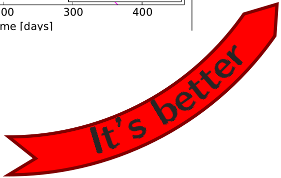


The path to the best model

We have increased the explosion energy to make the photospheric velocities higher.

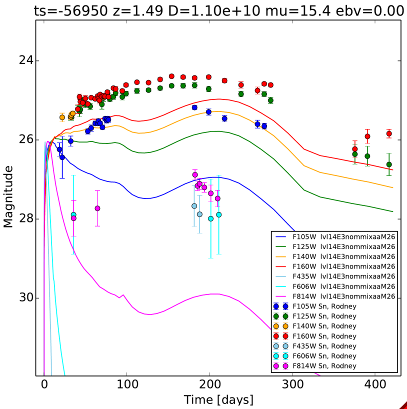


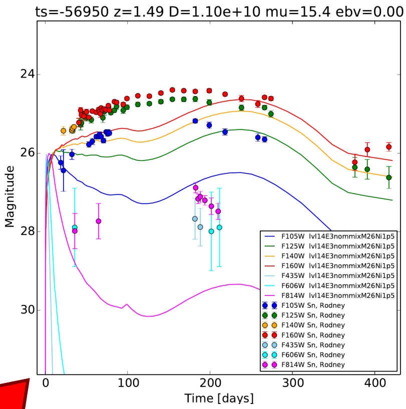


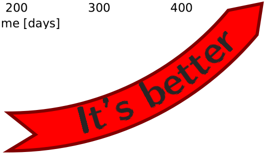


The path to the best model

We have increased the mass of ^{56}Ni: $M_{^{56}Ni} = 0.078 \rightarrow 0.116$ $M_\odot$

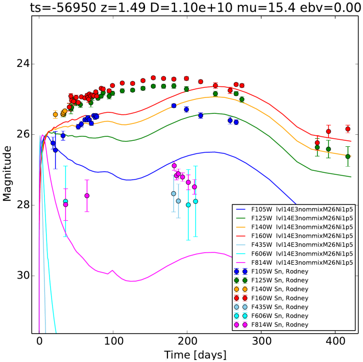


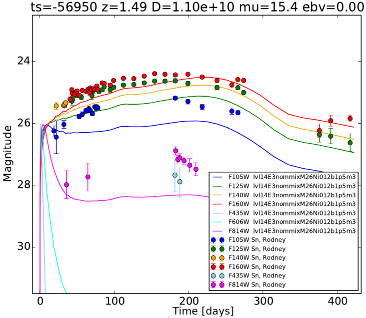


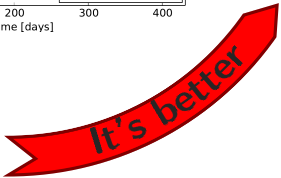


The path to the best model

We've increased the degree of ^{56}Ni mixing

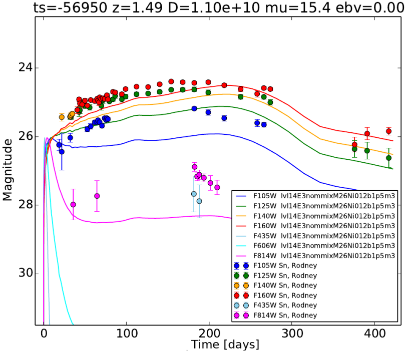


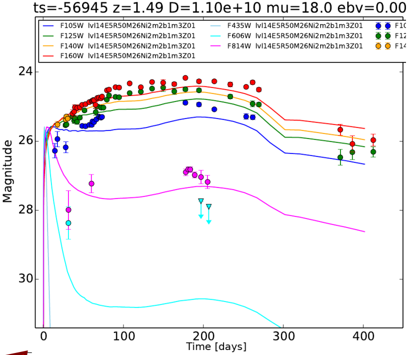




The path to the best model

We've decreased the metallicity $Z \rightarrow Z(SN\ 1987A)/10$





The path to the best model

To evaluate the best-fit model which simultaneously reproduces multi-band SN Refsdal light curves, we computed the set of the radiation-hydrodynamical supernova models.

The parameter space of our 181 SN models

	R [$R_\odot$]	M [$M_\odot$]	Ni56 [$M_\odot$]	E [Foe]	Z [$Z_\odot$]
min	30	16	0.077	1	1
	⋮	⋮	⋮	⋮	⋮
max	100	27	0.42	7	0.1

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	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
max	100	27	0.42	7	0.1

Q: How to choose the best model?

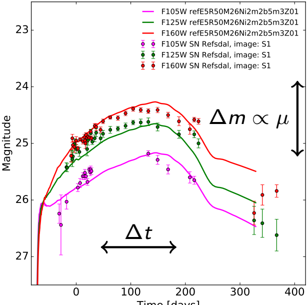
Model fitting and selection

The likelihood function is a Gaussian where summation was performed for time and the broad-band filters of HST (F105W, F125W, F160W):

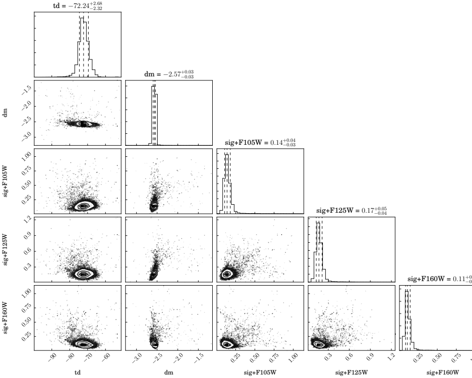
$$\log p = -\frac{1}{2}\sum_{t,F}\left[\frac{\left(m^{o}_{l,F} - m^{m}_{l,F}(t_l + \Delta t_l) - \Delta m_l\right)^2}{\sigma_o^2 + \sigma_{m,F}^2} + \log(\sigma_o^2 + \sigma_{m,F}^2) + \log(2\pi)\right]$$

,

where σ_o – the observational uncertainties,
$\sigma_{m,S}$ – the model uncertainties,
dt, dm – time delay, magnification



MCMC (emcee, arxiv: 1202.3665)



The models

There are the 8 best-fit models selected by criteria $BayesianEvidence > 0.001$.

The parameters of the top best-fit models

Model	$\log R$ ($R_\odot$)	M_{tot} ($M_\odot$)	$M(^{56}\mathrm{Ni})$ ($M_\odot$)	E_{burst} (E51)	Evidence
ref1	50.0	26.3	0.245193	5.0	0.7096
ref2	50.0	20.6	0.373069	3.0	0.165
ref3	50.0	26.0	0.243826	5.0	0.0891
ref4	45.0	25.0	0.118098	6.0	0.0253
ref5	50.0	26.3	0.245193	3.0	0.0048
ref6	40.0	26.0	0.119082	5.5	0.0022
ref7	50.0	26.0	0.243826	4.0	0.0021
ref8	50.0	26.0	0.243826	3.0	0.0012

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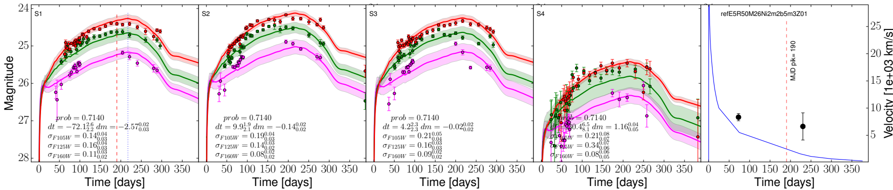
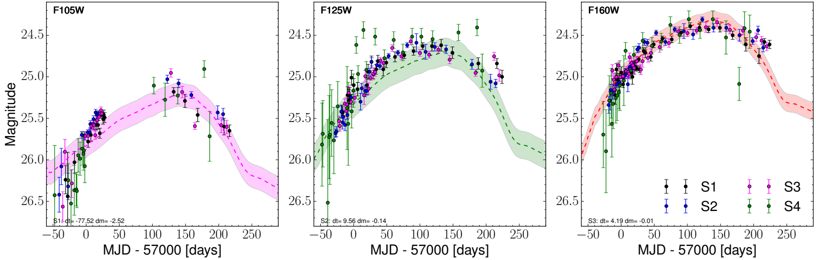
ref6	40.0	26.0	0.119082	5.5	0.0022
ref7	50.0	26.0	0.243826	4.0	0.0021
ref8	50.0	26.0	0.243826	3.0	0.0012

Best model: `refR50M26Ni2m2b5m3Z01`

The light curves for S1-S4 Images



LCs for the broadband filters with merged data for images S1-S4.



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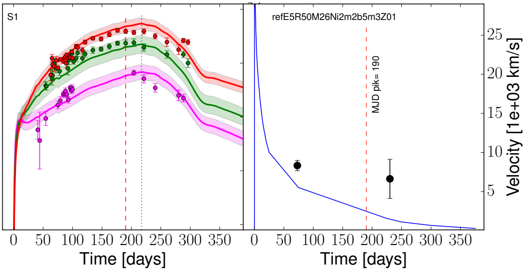


The SN model:

$\mathrm{R}_0 = 50\ \mathrm{R}_\odot$

$\mathrm{M}_{\mathrm{tot}} = 26\ \mathrm{M}_\odot$

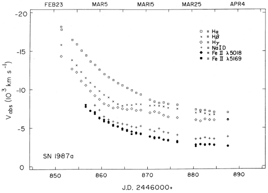
$\mathrm{M}_{^{56}\mathrm{Ni}} = 0.13\ \mathrm{M}_\odot$(*mixed*)

$\mathrm{Z} = 0.1\ \mathrm{Z}(\mathit{SN}\ 1987\mathit{A})$

$\mathrm{E} = 5 \times 10^{51}$ *ergs*

According to our modelling, the SN Refsdal is a more massive and energetic version of SN 1987A.

SN 1987A velocities



Summary of Time Delays and Magnifications

To estimate the time delays and magnifications we use the Bayesian model averaging (BMA) method, where the model parameters are averaged to the weight corresponding to this model.

Time delay and Magnification Ratio Measurements

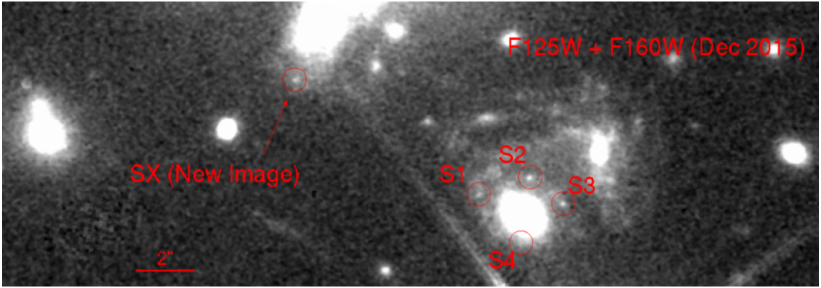
Parameter	SN fit	Template LC Fits[a]	Polynomial Curve Fits[a]
$\mathtt{MJD}_{pk}$	$57139^{2.5}_{2.3}$ d	57138 ± 10 d	57132 ± 4 d
$\Delta t_{S2:S1}$	$9.6^{2.0}_{2.2}$ d	4 ± 4 d	7 ± 2 d
$\Delta t_{S3:S1}$	$4.3^{2.3}_{2.3}$ d	2 ± 5 d	0.6 ± 3 d
$\Delta t_{S4:S1}$	$29.8^{7.1}_{7.6}$ d	24 ± 7 d	27 ± 8 d
$\mu_{S2/S1}$	$1.14^{0.02}_{0.02}$	1.15 ± 0.05	1.17 ± 0.02
$\mu_{S3/S1}$	$1.01^{0.02}_{0.02}$	1.01 ± 0.04	1.00 ± 0.01
$\mu_{S4/S1}$	$0.35^{0.02}_{0.01}$	0.34 ± 0.02	0.38 ± 0.02

Notes

[a] Values given in Rodney et al. 2016 in Table 3.

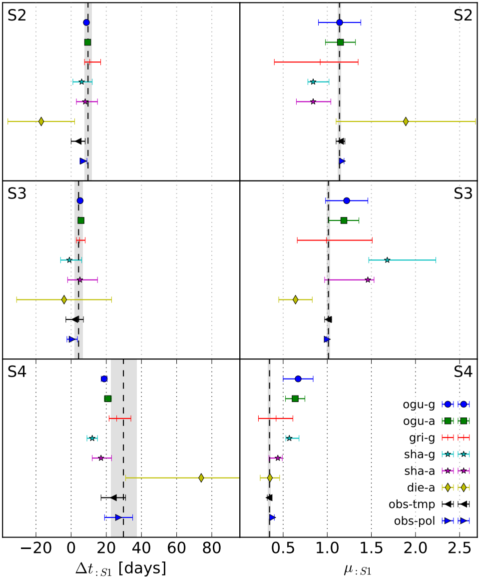
Constraints for lens models

We used our best model for measuring time delays and magnification ratios.



Q: Can we offer any constraints on the parameters of lens models?

Lens models VS SN fit



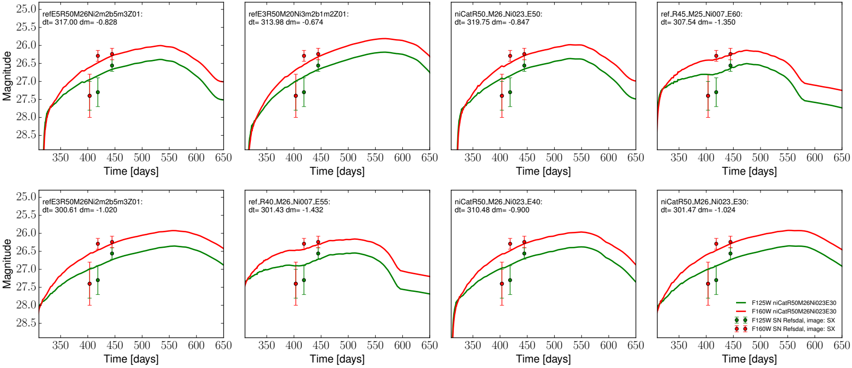
Comparison of the model fitting time delays and magnification ratios (gray color) against values predicted by lensing models and template&polinomial fitting.

Summary of Models (Treu, 2016)

Nickname	Team
Die-a	Diego et al.
Gri-g	Grillo et al.
Ogu-g	Oguri et al.
Ogu-a	Oguri et al.
Sha-g	Sharon et al.
Sha-a	Sharon et al.
obs-tmp	Rodney et al.
obs-pol	Rodney et al.

Fitting of the SX LCs

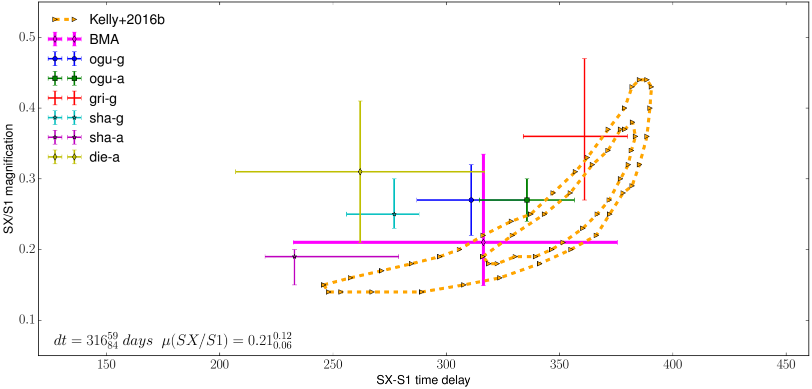
Unfortunately, we have only three observation points.
We used our 8 best models to fit LCs of SX image.



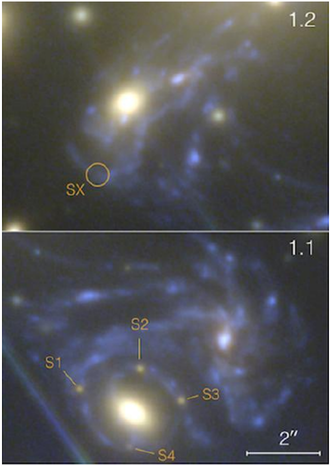
Fitting of the SX LCs

We used our best model for measuring time delays and magnification ratios.

$$\Delta t_{SN}(SX/S1) = 316^{59}_{84}\ days,\ \mu(SX/S1) = 0.21^{0.12}_{0.06}$$



The time delay of gravitational lens and H_0



$$\Delta t(\theta) = \frac{1+z_l}{c}\frac{D_l D_s}{D_{ls}}\left[\underbrace{\frac{1}{2}(\theta-\beta)^2}_{geom} - \underbrace{\psi(\theta)}_{grav}\right]$$

$$D_A = \frac{c(1+z)}{H_0}\int_0^z \frac{dz'}{E(z')}$$

$$E(z) = \sqrt{\Omega_M(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda}$$

$$\Delta t(\theta) \propto \frac{D_l D_s}{D_{ls}} \propto \frac{1}{H_0}$$

To measure the Hubble constant H_0 we need:

- The time delays
- The lens mass models

The Hubble constant

To derive H_0, we follow the approach proposed in Vega-Ferrero+2018, where the Hubble constant is obtained via rescaling the time delays predictions of the lens models to match the observed values.

$$P_{lens}(\Delta t, \mu | H_0) = P_{lens}(\frac{H_0^{base}}{H_0} \Delta t, \mu | H_0^{base}, GL)$$

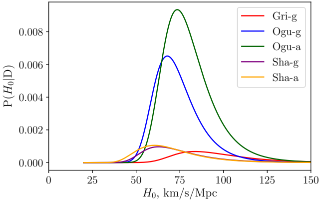
The probability of $\mathrm{P}(H_0|\mathrm{D})$ is the product of the observed probability distribution of the observed time delay and magnification times the probability distribution from the individual models.

$$\mathrm{P}(H_0|\mathrm{D}) \propto \mathrm{P}(H_0)\ \mathrm{P}(\mathrm{D}|H_0) \propto \mathrm{P}(H_0) \int d\Delta t\, d\mu \cdot p_{obs}(\Delta t, \mu) \cdot p_{lens}(\Delta t, \mu | H_0),$$

The time delay (μ) of multiple images of SN Refsdal predicted the different lens models.

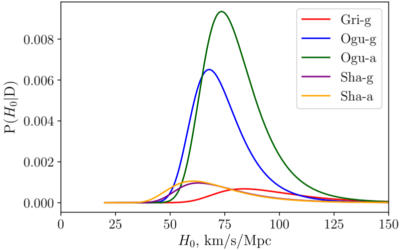
model	dt(S2)	$\mu(S2)$	dt(SX)	$\mu(SX)$
ogu-g	$8.7^{0.7}_{0.7}$	$1.1^{0.24}_{0.24}$	$311.0^{24.0}_{24.0}$	$0.3^{0.05}_{0.05}$
ogu-a	$9.4^{1.1}_{1.1}$	$1.1^{0.17}_{0.17}$	335.6^{21}_{21}	$0.3^{0.03}_{0.03}$
gri-g	$10.6^{3.0}_{6.2}$	$0.9^{0.52}_{0.43}$	361.0^{27}_{19}	$0.4^{0.09}_{0.11}$
sha-g	6.0^{5}_{6}	$0.8^{0.06}_{0.18}$	277.0^{21}_{11}	$0.2^{0.02}_{0.05}$
sha-a	8.0^{5}_{7}	$0.8^{0.19}_{0.2}$	233.0^{13}_{46}	$0.2^{0.04}_{0.01}$
die-a	-17.0^{19}_{19}	$1.9^{0.79}_{0.79}$	262.0^{55}_{55}	$0.3^{0.1}_{0.1}$

Contribution of each lens model predictions to the posterior distribution $\mathrm{P}_{+}(H_0|\mathrm{D})$.



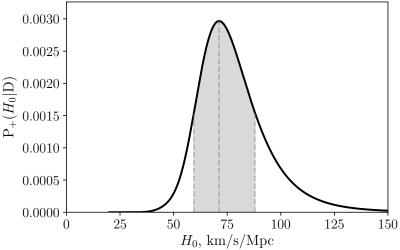
The Hubble constant

Contribution of each lens model predictions to the posterior distribution $\mathrm{P}_+(H_0|\mathrm{D})$.



We average the probabilities of the models $\mathrm{P}_+(H_0|\mathrm{D})$.

The total posterior distribution $\mathrm{P}_+(H_0|\mathrm{D})$ defined from observations of images S2 and SX. Grey area shows 68% CL.



The best value for H_0 resulting from the combined analysis of S2 and SX images is

$$H_0 = 71.2^{+16.7}_{-11.6}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}\ .$$

Conclusions

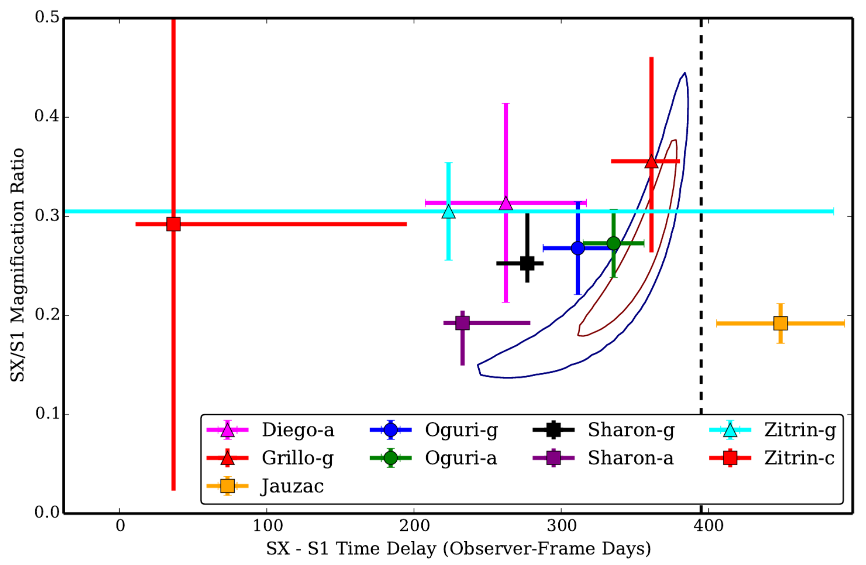
- Our major result is that SN Refsdal was the massive and high-energy version of SN 1987A.
  It is amazing that the progenitors of the closest (SN 1987A) and the most distant SN IIP are the BSG stars.
- The progenitor of SN Refsdal was the BSG with next parameters:

$$\mathrm{R}_0 = 50\ \mathrm{R}_\odot$$
$$\mathrm{M}_{\mathrm{tot}} = 26\ \mathrm{M}_\odot$$
$$\mathrm{M}_{^{56}\mathrm{Ni}} = 0.13\ \mathrm{M}_\odot (\textit{mixed})$$
$$\mathrm{Z} = 0.1\ \mathrm{Z}\ (\textit{SN 1987A})$$
$$\mathrm{E} = 5 \times 10^{51}\ \textit{ergs}$$

- We get the time delays and magnification ratios between multiple images of the supernova.
- The best value for H_0 resulting from the combined analysis of S2 and SX images is 71^{+17}_{-12} km s^{-1} Mpc^{-1} .
- Potential bias errors: reddening $E(B - V) > 0$, microlensing?
- Thank you!

Appendix

SX - S1 Time Delay (Observer-Frame Days)

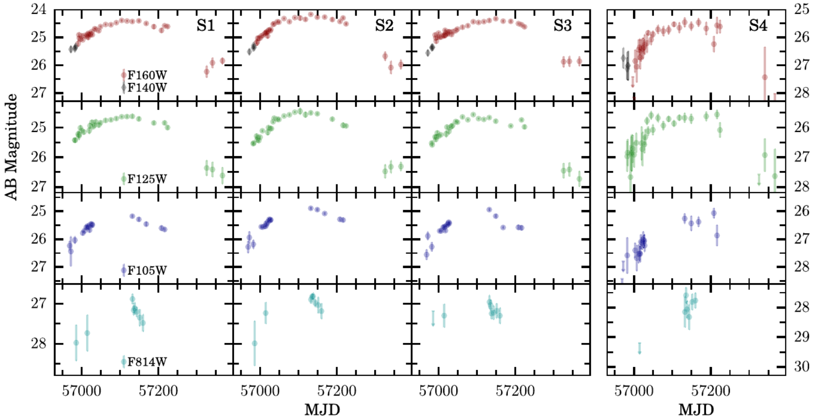


by Kelly et.al.(2015) arxiv:1512.04654

Observations: LC of SN Refsdal

The multi-color photometric data were obtained for 400 days following the discovery.

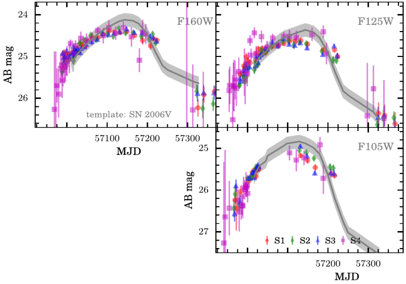
There is a slow rise to maximum light (over $\sim$ 150 days).



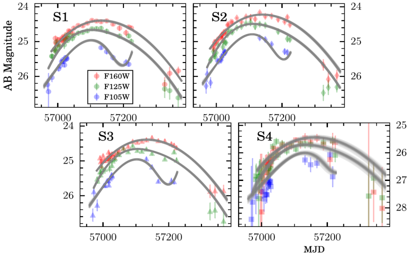
by Rodney et.al.(2015) arxiv:1512.05734

SN Refsdal: fitting the observations

Rodney S. et.al. “SN Refsdal: photometry and time delay measurements of the first einstein cross supernova”, arxiv:1512.05734



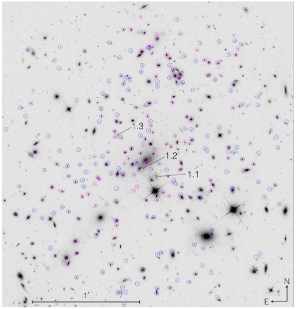
Results of the template fits to the SN Refsdal light curves using the best-matching template, which is the SN 1987A-like Type II SN 2006 V.



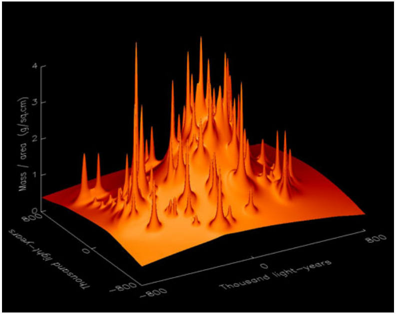
Results of fitting the SN Refsdal light curves using a cubic spline

Models of Lenses

Diego, 2016



Credit: NASA, Colley, Turner, and Tyson

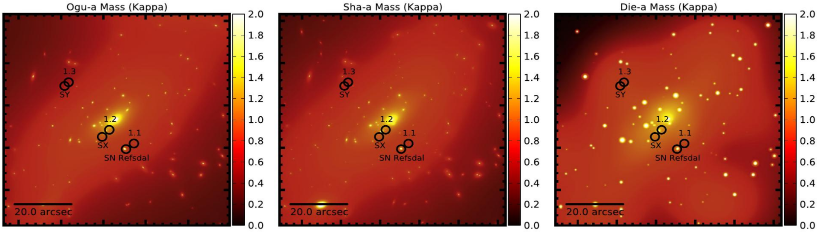


$$\beta = \theta - \alpha(\theta, \Sigma)$$

θ is the observed position of the source, α is the deflection angle, Σ is the surface mass density of the cluster at the position θ and β is the position of the background source

The surface mass density is described by the combination of two components:
(i) A soft (or diffuse) component that is parametrized as a super- position of Gaussians on a grid of constant width (regular grid) or varying width (adaptive grid).
(ii) A compact component that accounts for the mass associated with the individual haloes (galaxies) in the cluster. This component is modelled either as Navarro Frenk and White profiles with a mass proportional to the light of each galaxy or adopting directly the light profile (in one of the IR bands).

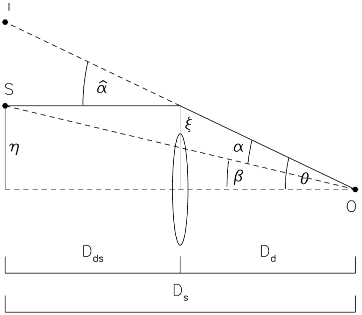
Lens mass



Summary of Models (Table 5)

Short name	Team	Type	rms	Images
Die-a	Diego et al.	Free-form	0.78	gold+sil
Gri-g	Grillo et al.	Simply param	0.26	gold
Ogu-g	Oguri et al.	Simply param	0.43	gold
Sha-g	Sharon et al.	Simply param	0.16	gold
Zit-g	Zitrin et al.	Light-tr-mass	1.3	gold

The lens equation



$$\beta = \theta - \alpha, \quad \Sigma(\theta) = \int \rho(\theta, z) dz$$

$$\alpha(\theta, \Sigma) = \nabla_\theta \psi(\theta, \Sigma), \left[\sim \frac{4GM}{c^2 p} = 2\frac{R_{sc}}{p}\right]$$

$$\Delta t(\theta) = \frac{1+z_l}{c} \frac{D_l D_s}{D_{ls}} \left[\underbrace{\frac{1}{2}(\theta - \beta)^2}_{geom} - \underbrace{\psi(\theta)}_{grav} \right]$$

$$\mu = \frac{\theta}{\beta} \frac{d\theta}{d\beta}$$

θ is the observed position of the source, α is the deflection angle,$\Sigma(\theta)$ is the surface mass density of the cluster at the position θ, β is the position of the background source, D_l, D_s and D_{ls} are the angular diameter distances to the lens, the source and from the lens to the source.

geom: time delay due to the extra path length of the deflected light ray relative to an unperturbed null geodesic

grav: time delay due to general relativistic time dilation, Shapiro time delay

Magnification & Time delay (Treu+2016)

Magnification: $\mu = \frac{\theta}{\beta} \frac{d\theta}{d\beta}$

Source	$\mu(S1)$	$\mu(S2)$	$\mu(S3)$	$\mu(S4)$	$\mu(SX)$
Diego+(2015)	$\mu(S_i)/\mu(S1)$	1.89 ± 0.79	0.64 ± 0.19	0.35 ± 0.11	0.31 ± 0.1
Sharon+(2015)	$18.5^{+6.4}_{-4.5}$	$14.4^{7.5}_{-5.5}$	$20.5^{+19.1}_{-3.9}$	$11.0^{+6.9}_{-4.2}$	
Oguri+(2015)	15.4 ± 1.6	17.7 ± 1.9	18.3 ± 1.9	9.8 ± 1.4	4.2 ± 0.3
Grillo+(2016)	$13.5^{+17.4}_{-10.3}$	$12.4^{7.9}_{-18.8}$	$13.4^{+19.2}_{10.3}$	$5.7^{+3.7}_{-8.1}$	$4.8^{+4.5}_{-5.3}$

Time delay: $\Delta t(\theta) = \frac{1+z_d}{c} \frac{D_d D_s}{D_{ds}} \left[\frac{1}{2}(\theta - \beta)^2 - \psi(\theta)\right]$

Source	$\Delta t(S2 - S1)$	$\Delta t(S3 - S1)$	$\Delta t(S4 - S1)$	$\Delta t(SX - S1)$
Diego+(2015)	17 ± 19	-4.3 ± 27	73 ± 43	262 ± 55
Sharon+(2015)	2.0^{+10}_{-6}	-5.0^{13}_{-7}	7.0^{+16}_{-3}	237^{+37}_{-50}
Oguri+(2015)	9.4 ± 1.1	5.6 ± 0.5	20.9 ± 2.0	335.6 ± 20.7
Grillo+(2016)	$10.6^{+7.6}_{-16.8}$	$4.8^{3.0}_{-8.0}$	$25.9^{+34}_{-21.6}$	361^{+334}_{-381}