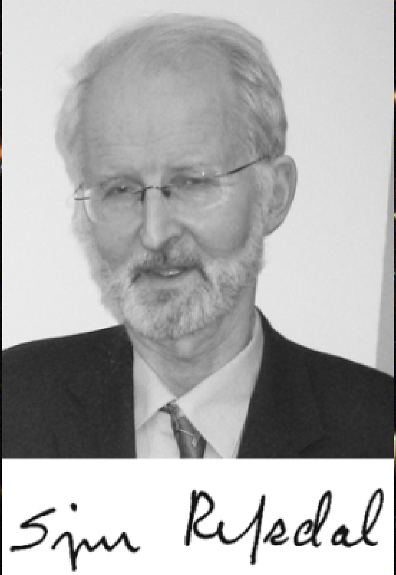
A Massive Progenitor of Strongly Lensed Supernova Refsdal

Petr Baklanov, Sergey Blinnikov, Ken'ichi Nomoto

Kavli IPMU

October 27, 2016



Sjur Refsdal
(Dec 30 1935 – Jan 29 2009)

Sjur Refsdal was a Norwegian astrophysicist.

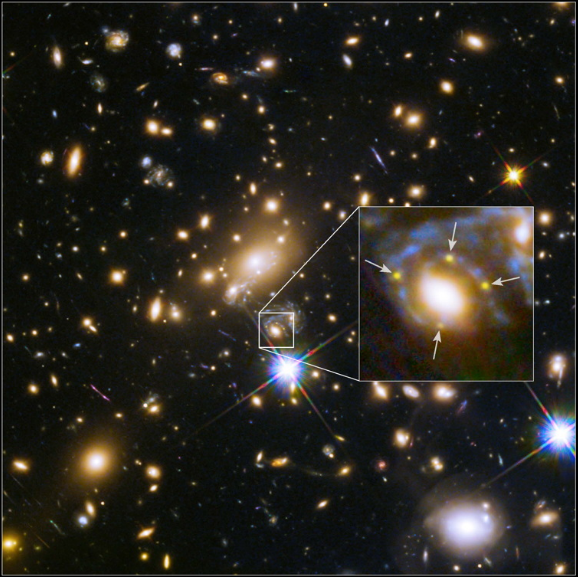
In 1964 he first proposed using time-delayed images from a lensed supernova to study the expansion of the universe.
Refsdal, S. (1964). On the Possibility of Determining Hubble's Parameter and the Masses of Galaxies from the Gravitational Lens Effect. Monthly Notices of the Royal Astronomical Society, 128(4), 307–310.

In 2014 the first detected strongly lensed supernova was nicknamed "SN Refsdal" in his honor.

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

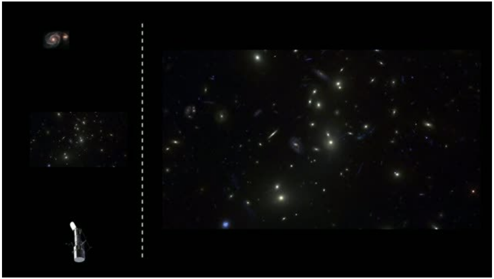


Supernova Refsdal ▪ Galaxy Cluster MACS J1149.5+2223
Hubble Space Telescope ▪ ACS/WFC ▪ WFC3/IR

NASA and ESA STScI-PRC15-08a

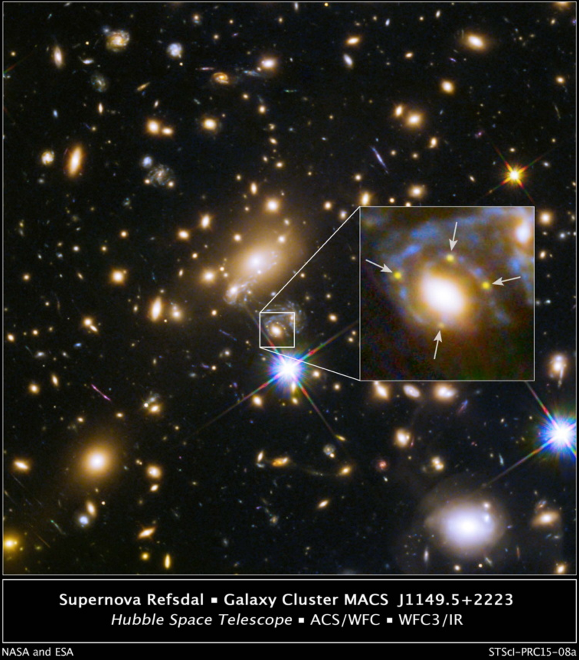
Simulation of Cosmic Lens

The Whirlpool Galaxy Seen Through a Cosmic Lens



What if we could take a well-known galaxy and put it behind one of our Frontier Fields galaxy clusters? What would that look like?

Thanks to Dr. Rachael Livermore of the University of Texas at Austin and Dr. Frank Summers of the Space Telescope Science Institute.

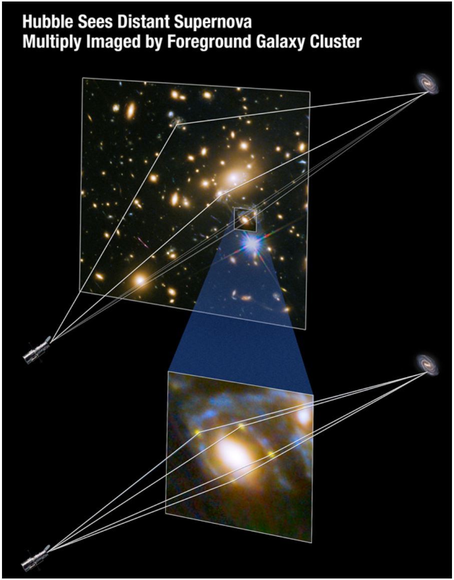


SN Refsdal: discovery

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+2233 and SN Refsdal



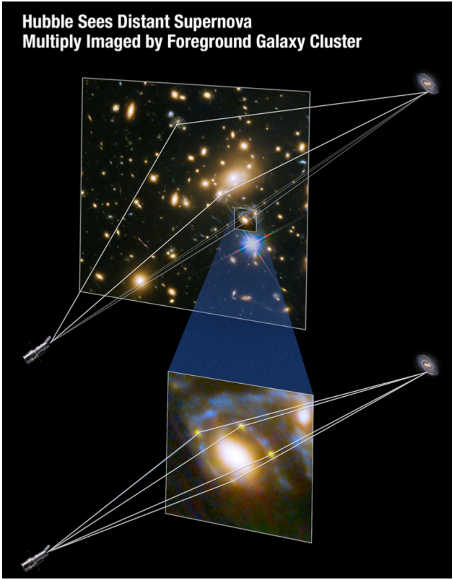
by NASA, ESA

MACS J1149.5+2233

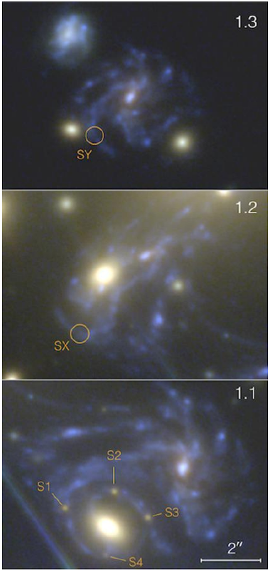
$z = 0.54$ (Grillo, 2015)
$D_L = 3.14$ Gpc
$D_a = 1.32$ Gpc
Members (Treu, 2015):
$0.520 < z < 0.570$

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

Cluster MACS J1149.5+2233 and SN Refsdal

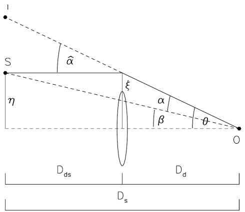


by NASA, ESA



by T.Treu (2016)

The lens equation



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

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

$$\psi(\theta) = \frac{4GD_l D_{ls}}{c^2 D_s} \int d^2\theta' \Sigma(\theta') ln(\theta - \theta')$$

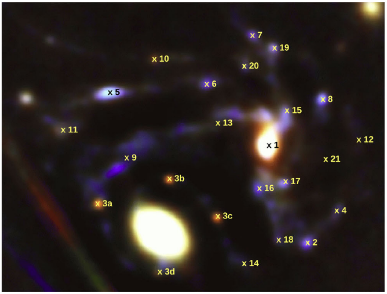
$$t(\theta) = \frac{1+z_l}{c} \frac{D_l D_s}{D_{ls}} \left[\underbrace{\frac{1}{2}(\theta - \beta)^2}_{geom} - \underbrace{\psi(\theta)}_{grav}\right], \ \mu = \frac{\theta}{\beta} \frac{d\theta}{d\beta}$$

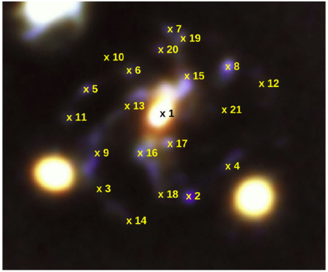
θ is the observed position of the source, α is the deflection angle, $\Sigma(\theta)$ is the surface mass density of the cluster at the position θ, β is the position of the background source, D_l, D_s and D_{ls} are the angular diameter distances to the lens, the source and from the lens to the source.

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

Models of Lens (Diego, 2016)



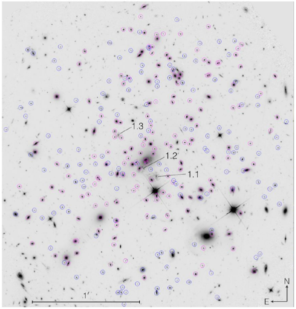


$$\beta = \theta - \alpha(\theta, \Sigma)$$

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).

Models of Lens (Diego, 2016)

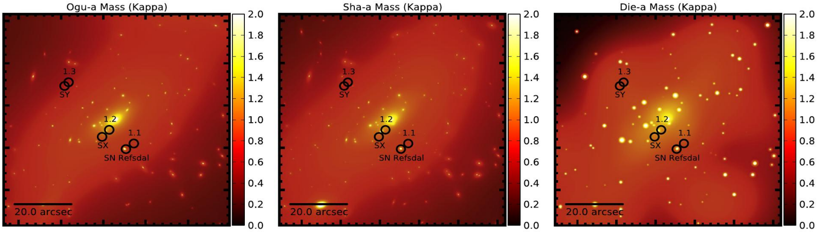


$$\beta = \theta - \alpha(\theta, \Sigma)$$

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).

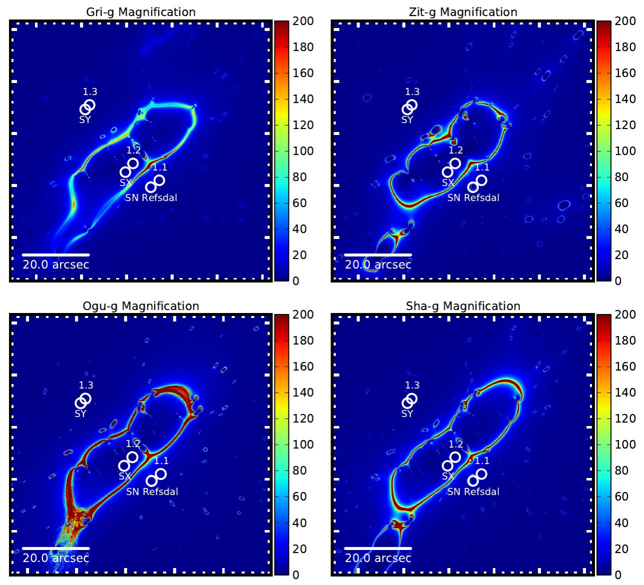
Lens mass



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

Magnification maps



The circles identify the positions of the observed and predicted images of SN Refsdal and those of the multiple images of its host galaxy.

by Treu+ arxiv:1510.05750

Magnification & Time delay

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

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}

Magnification & Time delay

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

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}

What Is a SN Refsdal?

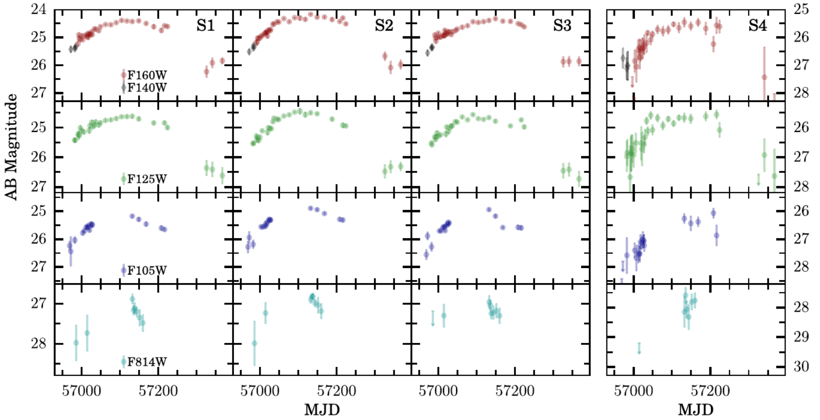
Q: What was before the supernova explosion? Can we derive the parameters for the supernova progenitor?

Q: Can we reproduce a supernova in our simulations?

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).

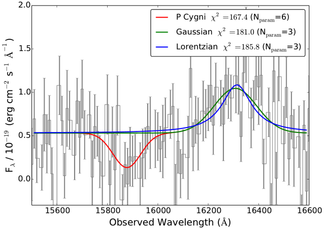


by Rodney et.al.(2015) arxiv:1512.05734

Observations: the spectra of SN Refsdal

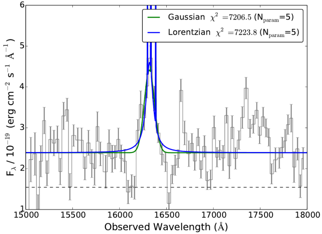
Spectrum of H_α taken -47^d

by HST WFC3 Grism

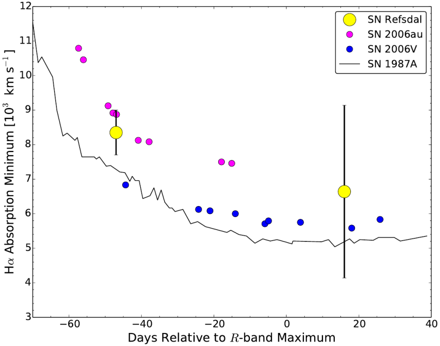


Spectrum of H_α taken 16^d

by the VLT



H_α P-Cygni expansion velocity



The analysis of observations

Rodney S.A. et.al. 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).
- Rodney have compared the SN Refsdal observations with these normal SN classes, using a library of 42 templates drawn from the Supernova Analysis software suite — unsuccessfully
- Rodney concludes that the peculiar SN 1987A-like sub-class provides the best matches to the observed shape of the SN Refsdal light curve.

There is a need for research to be targeted at this supernova.

We have used a progenitor model calculated by Nomoto & Hashimoto (Nomoto, Hashimoto 1988, Phys. Rep., 163, 13)

Model assumptions and implementation

Hydrodynamics, spherical symmetry, self-gravity, Saha-Boltzmann ion populations (with some NLTE control), no blackbody assumptions on radiation field, artificial thermal bomb explosion.

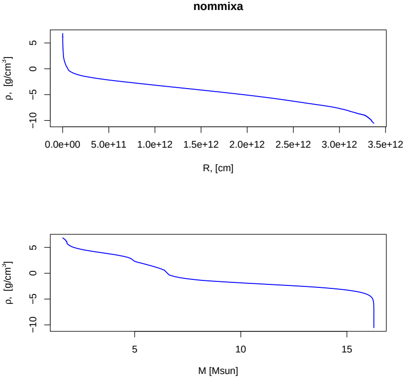
Using STELLA code, developed for supernova light curve simulations, (*Blinnikov et al., 1998, 2006*)

- Multigroup time dependent radiation hydrodynamics
- Non-relativistic ($\boldsymbol{O(v/c)}$), spherically symmetric
- Lagrangean coordinates, staggered mesh
- Full implicit time-dependent predictor-corrector solver for stiff ODE systems, modified Gear method, flexible dynamic step and error control

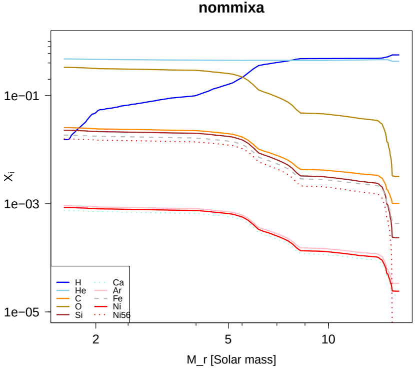
The progenitor model: chemical composition

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

Density as a function of the interior mass and radius



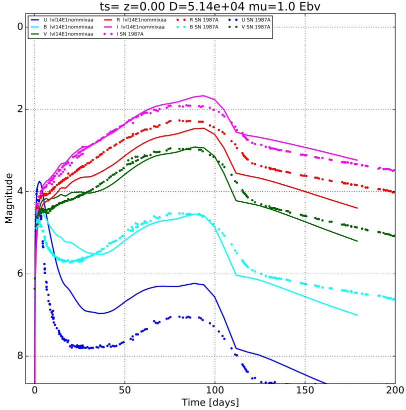
Abundance distribution as a function of enclosed mass for the ejecta



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

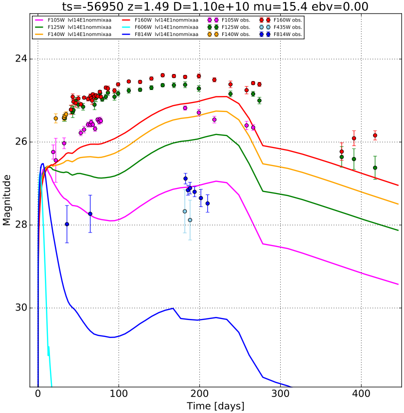
Modeling Light curves of the supernovae:

with SN 1987A



Good fit!

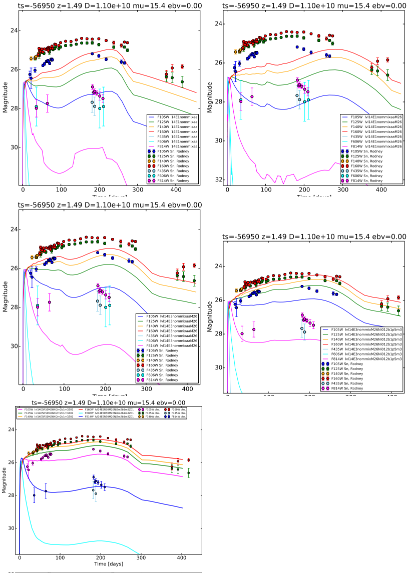
with SN Refsdal



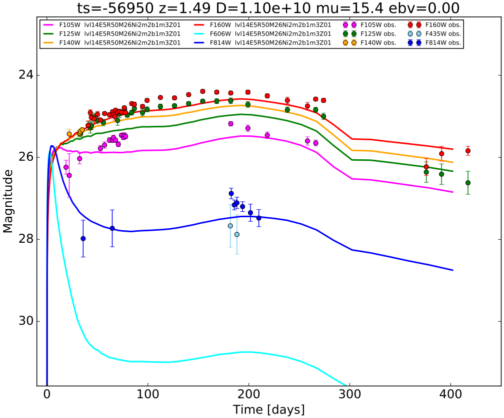
A bad agreement with the observations

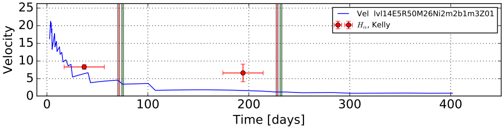
The path to the best model

- We have increased the ejected mass $M = 16.6 \rightarrow 26.6\ \mathrm{M}_\odot$
- We have increased the explosion energy $E = 1.7 \rightarrow 5 \times 10^{51}$ ergs
- We have increased the mass of ^{56}Ni: $M_{^{56}Ni} = 0.078 \rightarrow 0.116\ \mathrm{M}_\odot$
- We've increased the degree of ^{56}Ni mixing
- But we've decreased the metallicity $Z \rightarrow Z(SN\ 1987A)/10$



Best model: lvl14E5R50M26Ni2m2b1m3Z01





The SN model:

$$R_0 = 49\ R_\odot$$

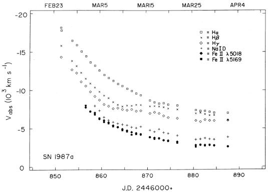
$$M_{tot} = 26\ M_\odot$$

$$M_{^{56}Ni} = 0.13\ M_\odot (\textit{mixed})$$

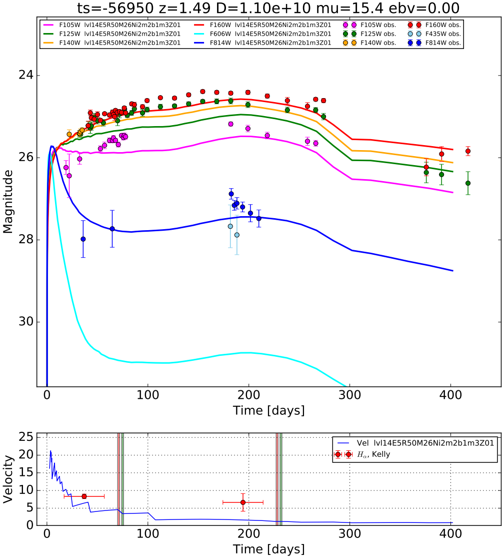
$$Z = 0.1\ Z(\textit{SN 1987A})$$

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

SN 1987A velocities



Best model: lvl14E5R50M26Ni2m2b1m3Z01



The SN model:

$R_0 = 49\ R_\odot$

$M_{tot} = 26\ M_\odot$

$M_{^{56}Ni} = 0.13\ M_\odot$(*mixed*)

$Z = 0.1\ Z$(*SN 1987A*)

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

Is this something unusual?

SN Refsdal is not unusual

A&A 532, A100 (2011)
DOI: 10.1051/0004-6361/201117137

Supernova 2000cb: high-energy version of SN 1987A

V. P. Utrobin[1,2] and N. N. Chugai[3]

[1] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85741 Garching, Germany
e-mail: utrobin@itep.ru
[2] Institute of Theoretical and Experimental Physics, B. Cheremushkinskaya St. 25, 117218 Moscow, Russia
[3] Institute of Astronomy of Russian Academy of Sciences, Pyatnitskaya St. 48, 119017 Moscow, Russia

Received 26 April 2011 / Accepted 6 July 2011

ABSTRACT

Context. Among type IIP supernovae there are a few events that resemble the well-studied supernova 1987A produced by the blue supergiant in the Large Magellanic Cloud.
Aims. We study a peculiar supernova 2000cb and compare it with the supernova 1987A.
Methods. We carried out hydrodynamic simulations of the supernova in an extended parameter space to describe its light curve and spectroscopic data. The hydrogen Hα and Hβ lines are modeled using a time-dependent approach.
Results. We constructed the hydrodynamic model by fitting the photometric and spectroscopic observations. We infer a presupernova radius of $35 \pm 14\ R_{\odot}$, an ejecta mass of $22.3 \pm 1\ M_{\odot}$, an explosion energy of $(4.4 \pm 0.3) \times 10^{51}$ erg, and a radioactive ^{56}Ni mass of $0.083 \pm 0.039\ M_{\odot}$. The estimated progenitor mass on the main sequence lies in the range of 24–28 $M_{\odot}$. The early Hα profile on Day 7 is consistent with the density distribution found from hydrodynamic modeling, while the Hα line on Day 40 indicates an extended ^{56}Ni mixing up to a velocity of 8400 km s^{-1}. We emphasize that the dome-like light curves of both supernova 2000cb and supernova 1987A are entirely powered by radioactive decay. This is unlike normal type IIP supernovae, the plateau of which is dominated by the internal energy deposited after the shock wave propagation through the presupernova. We find signatures of the explosion asymmetry in the photospheric and nebular spectra.
Conclusions. The explosion energy of supernova 2000cb is higher by a factor of three compared to supernova 1987A, which poses a

SN Refsdal is not unusual

A&A 532, A100 (2011)
DOI: 10.1051/0004-6361/201117137

Astronomy & Astrophysics

Supernova 2000cb: high-energy version of SN 1987A

V. P. Utrobin[1,2] and N. N. Chugai[3]

[1] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85741 Garching, Germany
e-mail: utrobin@itep.ru
[2] Institute of Theoretical and Experimental Physics, B. Cheremushkinskaya St. 25, 117218 Moscow, Russia
[3] Institute of Astronomy of Russian Academy of Sciences, Pyatnitskaya St. 48, 119017 Moscow, Russia

Received 26 April 2011 / Accepted 6 July 2011

ABSTRACT

Context. Among type IIP supernovae there are a few events that resemble the well-studied supernova 1987A produced by the blue supergiant in the Large Magellanic Cloud.
Aims. We study a peculiar supernova 2000cb and compare it with the supernova 1987A.
Methods. We carried out hydrodynamic simulations of the supernova in an extended parameter space to describe its light curve and spectroscopic data. The hydrogen Hα and Hβ lines are modeled using a time-dependent approach.
Results. We constructed the hydrodynamic model by fitting the photometric and spectroscopic observations. We infer a p
radius of $35 \pm 14\ R_\odot$, an ejecta mass of $22.3 \pm 1\ M_\odot$, an explosion energy of $(4.4 \pm 0.3) \times 10^{51}$ erg, and a radioactive
$0.083 \pm 0.039\ M_\odot$. The estimated progenitor mass on the main sequence lies in the range of 24–28 $M_\odot$. The early Hα pro
are entirely powered by radioactive decay. This is unlike normal type IIP supernovae, the plateau of which is dominated by the internal energy deposited after the shock wave propagation through the presupernova. We find signatures of the explosion asymmetry in the photospheric and nebular spectra.
Conclusions. The explosion energy of supernova 2000cb is higher by a factor of three compared to supernova 1987A, which poses a

The lens models: Magnification & Time delay

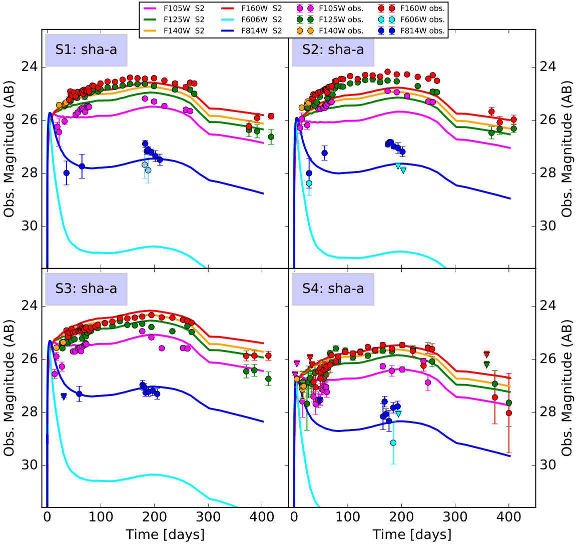
Magnification

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

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}

SN Refsdal and lens models: Sharon et al., 2015



Lens model **sha-g**

Magnification:

$$\mu_{S2}/\mu_{S1} = 0.84^{+0.18}_{-0.06}$$

$$\mu_{S3}/\mu_{S1} = 1.68^{+0.55}_{-0.21}$$

$$\mu_{S4}/\mu_{S1} = 0.57^{+0.11}_{-0.04}$$

Time delay:

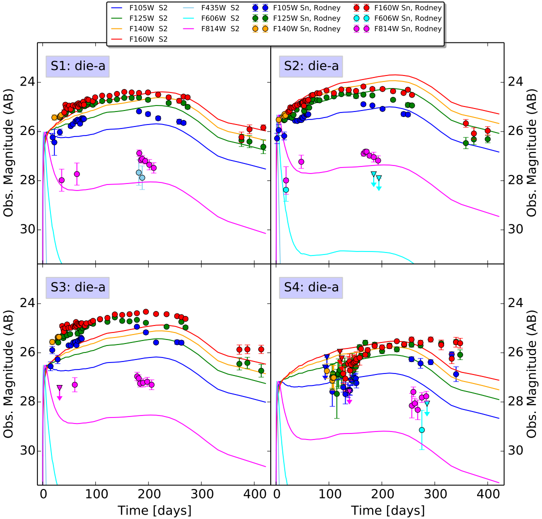
$$\Delta t_{S2-S1} = 6^{6}_{-5}$$

$$\Delta t_{S3-S1} = -1^{7}_{-5}$$

$$\Delta t_{S4-S1} = 17^{6}_{-5}$$

via Tommaso Treu
(arxiv:1510.05750)

SN Refsdal and lens models: Diego et al., 2015



Lens model **die-a**:

Magnification:

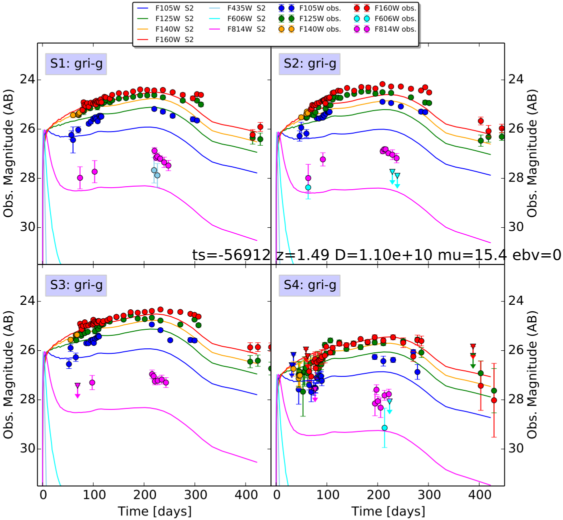
$$\mu_{\rm S2}/\mu_{\rm S1} = 1.89 \pm 0.79$$
$$\mu_{\rm S3}/\mu_{\rm S1} = 0.64 \pm 0.19$$
$$\mu_{\rm S4}/\mu_{\rm S1} = 0.35 \pm 0.11$$
$$\mu_{\rm SX}/\mu_{\rm S1} = 0.31 \pm 0.1$$

Time delay:

$$\Delta t_{\rm S2-S1} = -17 \pm 19$$
$$\Delta t_{\rm S3-S1} = -4 \pm 27$$
$$\Delta t_{\rm S4-S1} = 74 \pm 43$$
$$\Delta t_{\rm SX-S1} = 262 \pm 55$$

via Tommaso Treu (arxiv:1510.05750)

SN Refsdal and lens models: Grillo et al., 2015



Lens model **gri-g**:

Magnification:

$$\mu_{\rm S2}/\mu_{\rm S1} = 0.92^{+0.43}_{-0.52}$$

$$\mu_{\rm S3}/\mu_{\rm S1} = 0.99^{+0.52}_{-0.33}$$

$$\mu_{\rm S4}/\mu_{\rm S1} = 0.42^{+0.19}_{-0.20}$$

$$\mu_{\rm SX}/\mu_{\rm S1} = 0.36^{+0.11}_{-0.09}$$

Time delay:

$$\Delta t_{\rm S2-S1} = 10.6^{+6.2}_{-3.0}$$

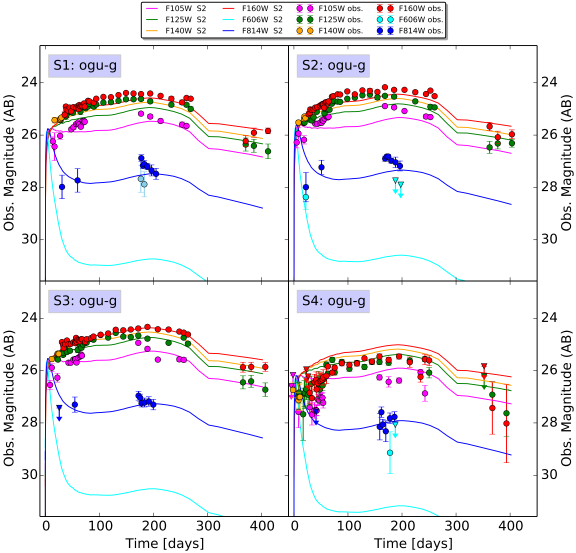
$$\Delta t_{\rm S3-S1} = 4.8^{+3.2}_{-1.8}$$

$$\Delta t_{\rm S4-S1} = 25.9^{+8.1}_{-4.3}$$

$$\Delta t_{\rm SX-S1} = 361^{+19}_{-27}$$

via Tommaso Treu (arxiv:1510.05750)

SN Refsdal and lens models: Oguri et al., 2015



Lens model **ogu-g**:

Magnification:

$$\mu_{S2}/\mu_{S1} = 1.14 \pm 0.24$$
$$\mu_{S3}/\mu_{S1} = 1.22 \pm 0.24$$
$$\mu_{S4}/\mu_{S1} = 0.67 \pm 0.17$$
$$\mu_{SX}/\mu_{S1} = 0.27 \pm 0.05$$

Time delay:

$$\Delta t_{S2-S1} = 8.7 \pm 0.7$$
$$\Delta t_{S3-S1} = 5.1 \pm 0.5$$
$$\Delta t_{S4-S1} = 18.8 \pm 1.7$$
$$\Delta t_{SX-S1} = 311 \pm 24$$

via Masamune Oguri (MNRAS, 2015)

SN Refsdal: the prediction of image SX

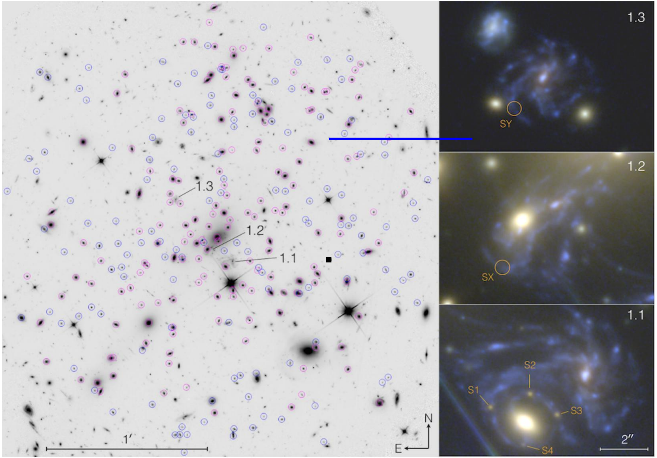
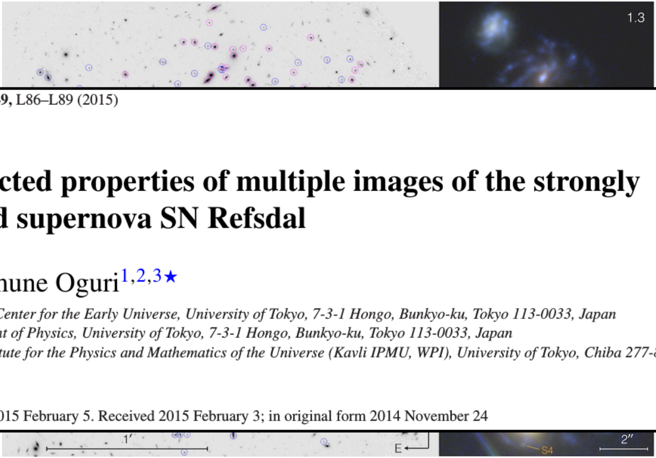


Figure 1. Multiple images of the SN Refsdal host galaxy behind MACSJ1149.5+2223. The left panel shows a wide view of the cluster, encompassing the entire footprint of the WFC3-IR camera. Spectroscopically confirmed cluster member galaxies are highlighted in magenta circles. Cyan circles indicate those associated with the cluster based on their photometric properties. The three panels on the right show in more detail the multiple images of the SN Refsdal host galaxy (labeled 1.1, 1.2, and 1.3). The positions of the known images of SN Refsdal are labeled as S1–S4, while the model-predicted locations of the future and past appearances are labeled as SX and SY, respectively.

MACS J1149.5+2233: Treu+ arxiv:1510.05750

SN Refsdal: the prediction of image SX



MNRAS **449,** L86–L89 (2015)

Predicted properties of multiple images of the strongly lensed supernova SN Refsdal

Masamune Oguri[1,2,3★]

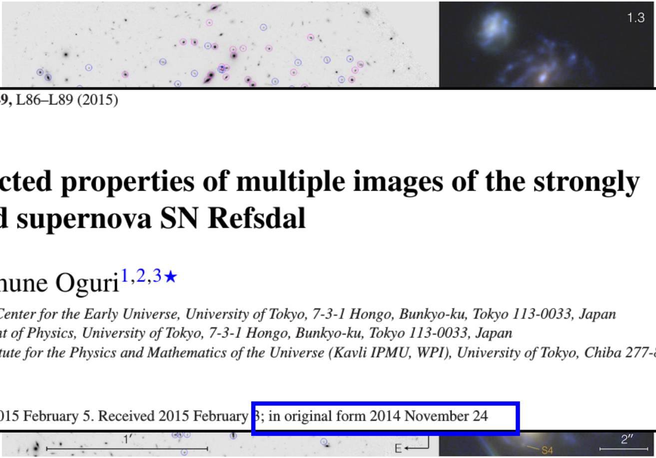
[1] *Research Center for the Early Universe, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[2] *Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[3] *Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI), University of Tokyo, Chiba 277-8583, Japan*

Accepted 2015 February 5. Received 2015 February 3; in original form 2014 November 24

Figure 1. Multiple images of the SN Refsdal host galaxy behind MACSJ1149.5+2223. The left panel shows a wide view of the cluster, encompassing the entire footprint of the WFC3-IR camera. Spectroscopically confirmed cluster member galaxies are highlighted in magenta circles. Cyan circles indicate those associated with the cluster based on their photometric properties. The three panels on the right show in more detail the multiple images of the SN Refsdal host galaxy (labeled 1.1, 1.2, and 1.3). The positions of the known images of SN Refsdal are labeled as S1–S4, while the model-predicted locations of the future and past appearances are labeled as SX and SY, respectively.

MACS J1149.5+2233: Treu+ arxiv:1510.05750

SN Refsdal: the prediction of image SX



MNRAS **449,** L86–L89 (2015)

Predicted properties of multiple images of the strongly lensed supernova SN Refsdal

Masamune Oguri[1,2,3★]

[1]*Research Center for the Early Universe, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[2]*Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[3]*Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI), University of Tokyo, Chiba 277-8583, Japan*

Accepted 2015 February 5. Received 2015 February 3; in original form 2014 November 24

Figure 1. Multiple images of the SN Refsdal host galaxy behind MACSJ1149.5+2223. The left panel shows a wide view of the cluster, encompassing the entire footprint of the WFC3-IR camera. Spectroscopically confirmed cluster member galaxies are highlighted in magenta circles. Cyan circles indicate those associated with the cluster based on their photometric properties. The three panels on the right show in more detail the multiple images of the SN Refsdal host galaxy (labeled 1.1, 1.2, and 1.3). The positions of the known images of SN Refsdal are labeled as S1–S4, while the model-predicted locations of the future and past appearances are labeled as SX and SY, respectively.

MACS J1149.5+2233: Treu+ arxiv:1510.05750

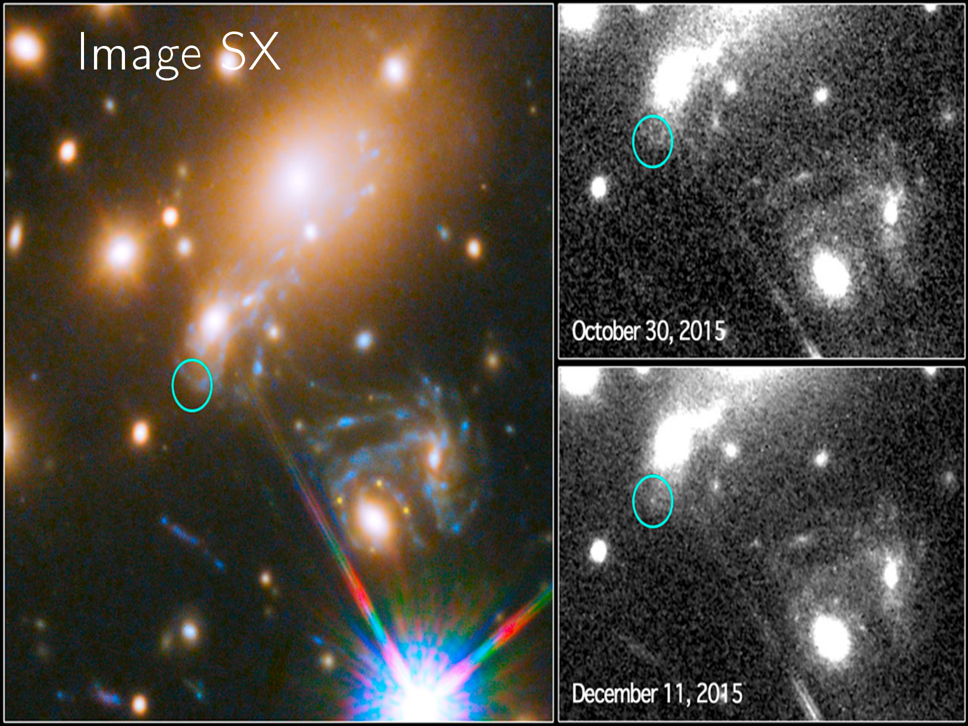
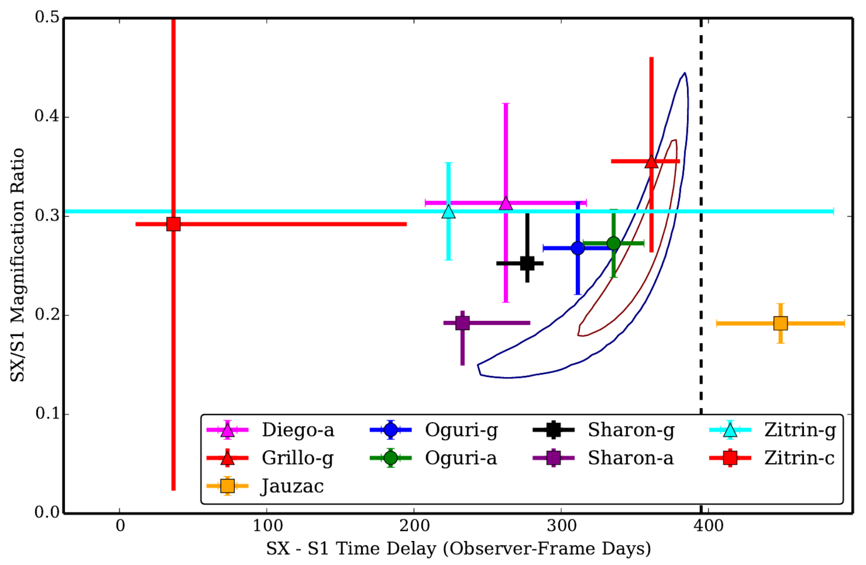


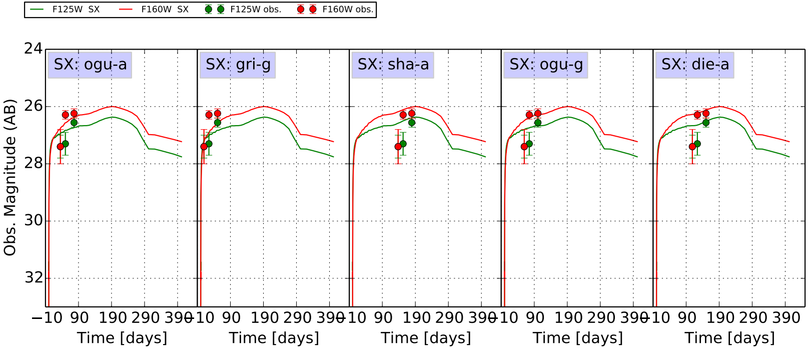
Image SX
October 30, 2015
December 11, 2015

SX - S1 Time Delay (Observer-Frame Days)



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

Light Curves of SX



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
Ogu-a	Oguri et al.	Simply param	0.31	all
Sha-g	Sharon et al.	Simply param	0.16	gold

Conclusions

- Our major result is that SN Refsdal was the massive and high-energy version of SN 1987A.
- The progenitor of SN Refsdal was the BSG with next parameters:

$$\mathrm{R}_0 = 49\ \mathsf{R}_\odot$$
$$\mathrm{M}_{\mathrm{tot}} = 26\ \mathsf{M}_\odot$$
$$\mathrm{M}_{^{56}\mathrm{Ni}} = 0.13\ \mathsf{M}_\odot (\mathit{mixed})$$
$$\mathrm{Z} = 0.1\ \mathrm{Z}(\mathit{SN}\ 1987\mathit{A})$$
$$\mathrm{E} = 5 \times 10^{51}\ \mathit{ergs}$$

- To make a prediction for magnifications & time delays of gravitational lens models, to make constraints for the structure of dark matter halos in galaxies
- To make a prediction of the maximum of SX image
- It is amazing that the progenitors of the closest and the most distant SN IIP are the BSG stars.