# iPTF16geu: A multiply-imaged gravitationally lensed Type Ia supernova


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**We report the discovery of a multiply-imaged gravitationally lensed Type Ia supernova, iPTF16geu, at redshift $z = 0.409$. This phenomenon could be identified because the light from the stellar explosion was magnified more than fifty times by the curvature of space around matter in an intervening galaxy.**

**We used high spatial resolution observations to resolve four images of the lensed supernova, approximately $0.3''$ from the center of the foreground galaxy. The observations probe a physical scale of ∼1 kiloparsec, smaller than what is typical in other studies of extragalactic gravitational lensing. The large magnification and symmetric image configuration implies close alignment between the line-of-sight to the supernova and the lens. The relative magnifications of the four images provide evidence for sub-structures in the lensing galaxy.**

One of the foundations of Einstein's theory of General Relativity is that matter curves the surrounding space-time. For the rare cases of nearly perfect alignment between an astronomical source, an intervening massive object and the observer, multiple images of a single source can be detected, a phenomenon known as strong gravitational lensing.

Although many strongly lensed galaxies and quasars have been detected to date, it has proved extremely difficult to find multiply-imaged lensed supernova (SN) explosions. Type Ia supernovae (SNe Ia) are particularly interesting sources due to their "standard candle" nature. These explosions have nearly identical peak luminosity which makes them excellent distance indicators in cosmology (*1*). For lensed SNe Ia, the standard candle property allows the flux magnification to be estimated directly, independent of any model related to the lensing galaxy (*2, 3*). This removes important degeneracies in gravitational lensing measurements, the mass-sheet degeneracy (*4*) and the source-plane degeneracy (*5*).

A lensed SN Ia at redshift $z = 1.388$ with a large amplification ($\mu \sim 30$) , PS1-10afx, where multiple images could have been expected, has been reported earlier (*6*). A foreground lens was later identified at $z = 1.117$ (*7*). However, at the time of the discovery several interpretations were discussed, including a super-luminous supernova (*8*). Since the lensed SN Ia hypothesis was only accepted long after the explosion had faded, no high spatial resolution imaging could be carried out in that case to verify the strong lensing nature of the system. Multiple-images of another supernova, SN Refsdal (*9*), were discovered in a Hubble Space Telescope (HST) survey of the massive galaxy cluster MACS J1149.6+2223. As the source was identified as a core-collapse supernova it could not be used to measure the lensing magnification directly.

Thanks to the well-known characteristics of their time-dependent brightness in optical and near-infrared filters (the SN lightcurves), multiply-imaged SNe Ia are also ideally suited to measure time-delays in the arrival of the images. This provides a direct probe of the Hubble constant, the cosmological parameter measuring the expansion rate of the universe (*10*), as well as leverage for studies of dark energy (*11, 12*), the cosmic constituent responsible for the accelerated expansion of the universe.

The intermediate Palomar Transient Factory (iPTF) searches the sky for new transient phenomena at optical wavelengths. It uses image differencing between repeated observations (*13*) with a large field-of-view camera (7.3 sq.deg) at the 48-inch telescope (P48) at the Palomar Observatory (*14*). The first detection of iPTF16geu, with a statistical significance of five standard deviations ($5\sigma$), is from 2016 September 5. The new source was first recognized by a human scanner on September 11 (*15*). iPTF16geu (also known as SN 2016geu) was found near the center of the galaxy SDSS J$210415.89$-$062024.7$, at right ascension $21^h4^m15.86^s$ and declination $-6°20'24.5''$ (J2000).

Spectroscopic identification was carried out with the Spectral Energy Distribution (SED) Machine (*16*) at the Palomar 60-inch telescope (P60) on 2016 October 2 and iPTF16geu was found to be spectroscopically consistent with a normal SN Ia at $z \approx 0.4$ (see Fig. 1). Further spectroscopic observations from the Palomar 200-inch telescope (P200) and the 2.5-meter Nordic Optical Telescope (NOT) were used to confirm the SN Ia identification and to establish the redshift of the host galaxy from narrow sodium (Na I D) absorption lines, as $z = 0.409$. The P200 and NOT spectra also show absorption features from the foreground lensing galaxy at $z = 0.216$. To estimate the velocity dispersion of the lensing galaxy, we fit two Gaussian functions with a common width to the H$\alpha$ and [N II] emission lines in the P200 spectrum in Fig 1D. After taking the instrumental resolution into account, we measure $\sigma = 3.6^{+0.9}_{-0.6}$ Å, corresponding to a velocity dispersion of $\sigma_v = 163^{+41}_{-27}$ km s$^{-1}$.

Photometric observations of iPTF16geu collected at P48 and with the SED Machine Rainbow Camera (RC) at P60, between 2016 September 5 and October 13 (see Fig. 2), were used to estimate the peak flux and lightcurve properties of the SN with the SALT2 lightcurve fitting tool (*17*). The best fit lightcurve template, also shown in Fig. 2, confirms that the observed lightcurve shapes are consistent with a SN Ia at $z = 0.409$. These fits also indicate some reddening of the supernova, suggesting that iPTF16geu suffers from moderate extinction by dust. This produces dimming at optical wavelengths of 20-40%, whith the largest losses in the $g$-band observations. Thanks to the standard candle nature of SNe Ia, after correcting the peak magnitude for lightcurve properties (*18, 19*), the flux of the SN was found to be $\sim$30 standard deviations brighter than expected for the measured redshift. This suggested that iPTF16geu was gravitationally lensed and we estimated the lensing amplification to be $\mu \sim 52$. Expressed in astronomical magnitudes, $\Delta m = -4.3 \pm 0.2$ mag, where the uncertainty is dominated by the brightness dispersion of normal SNe Ia. Since the magnification is derived from comparing the observed brightness of iPTF16geu to other SNe Ia (*20*) within a narrow redshift range around

$z = 0.409$, the measurement of the lensing magnification is independent of any assumptions on cosmology, e.g., the value of the Hubble constant or other cosmological parameters. The lensing magnification is also independent of a lens model, which is the only way to determine the magnification for almost all other strong lensing systems.

The optical observations from Palomar, with a typical angular resolution (atmospheric seeing) of $2''$, were insufficient to spatially resolve any multiple images that could result from the strong lensing nature of the system (Fig. 3A). We therefore obtained $K_s$-band (2.2 $\mu$m) observations from the European Southern Observatory (ESO) with the Nasmyth Adaptive Optics System Near-Infrared Imager and Spectrograph (NACO) at the Very Large Telescope (VLT). An angular resolution of $\sim 0.3''$ (full-width half-max, FWHM) was obtained at the location of the target. Adaptive optics (AO) corrections of the seeing were performed using a natural bright star, $\sim 30''$ south-east of the SN location, indicated in Fig. 3 along with the SDSS pre-explosion image of the field (*21*).

The near-IR image from VLT indicated the structure expected in a strongly lensed system, with higher flux in the northeastern and southwestern regions of the system, compared to the center (Fig. 3B). Multiple images of the system were first resolved with observations from the Keck observatory at near-infrared wavelengths, using the Laser Guide Star aided Adaptive Optics (LGSAO) with the OH-Suppressing Infra-Red Imaging Spectrograph (OSIRIS) instrument, yielding an image quality of $0.07''$ FWHM in the $H$-band centered at 1.6 $\mu$m (Fig. 3C).

LGSAO observations of iPTF16geu using the Near-InfraRed Camera 2 (NIRC2) at the Keck telescope on 2016 October 22 and November 5, in $K_s$-band and $J$-band (1.1$\mu$m) respectively, and optical images obtained with the Hubble Space Telescope (HST) on 2016 October 25, are shown in Fig. 4. The HST observations were carried out through the $F475W$, $F625W$ and $F814W$ filters, where the names correspond to the approximate location of the central wavelength in nanometers.

The observations exhibit four images of iPTF16geu, $0.26''$–$0.31''$ from the center of the lensing galaxy, with nearly 90° azimuthal separations. The extended host galaxy, warped by the lens to form a partial Einstein ring, is brighter in the near-IR compared to the observations through optical filters. Thus, the fainter individual SN images are poorly resolved for the observations with the longest wavelengths in Fig. 4. Furthermore, the SN Ia spectral energy distribution (redshifted to $z = 0.4$) peaks within the $F625W$ and $F814W$ filters, see e.g. (*22*). Dimming by interstellar dust in the line of sight is roughly inversely proportional to wavelength in the optical and near-IR (*23*). The biggest impact from extinction by dust is therefore expected for the shortest wavelength, in $F475W$ filter observations, where the two faintest SN images cannot be detected above the background light. The low spatial resolution lightcurves in Fig. 2 are dominated by the two brightest SN images, labelled 1 and 2 in Fig. 4D. The $F625W$-$F814W$ magnitude difference (color) of the resolved images measured with HST indicate small differences in relative extinction between the SN images, except for image 4, which appears to have about two magnitudes of additional dimming in $F814W$.

Unaccounted dimming of light by scattering on dust grains in the line of sight would lead to an underestimation of the lensing amplification. Including corrections for differential extinction in the intervening lensing galaxy between the SN images suggest a wider range for the lensing magnification of iPTF16geu, between $-4.1$ and $-4.8$ mag (*24*).

The SN multiple-image positions in Fig 4 were used to construct a lensing model, with an isothermal ellipsoid galaxy lens (*25, 26*) with ellipticity $\epsilon_e = 0.15 \pm 0.07$ and mass $M = (1.70 \pm 0.06) \cdot 10^{10}\, M_\odot$ inside an ellipse with major axis 1.13 kpc and minor axis 0.97 kpc. Details of the lensing model are presented in the Supplementary Material (*24*). The lens model can be independently verified through comparisons between the model-predicted and observed velocity dispersion of the lensing galaxy. From the model we derive an estimate, $\sigma_v^{\mathrm{mod}} = 156 \pm 4$ km s$^{-1}$, in good agreement with the measured value of the velocity dispersion (Fig. 1D).

However, the adopted smooth isothermal ellipsoid lens model predicts brightness differences between the multiple SN images that are in disagreement with the observations. Including corrections for extinction in the resolved SN images in the $F814W$ filter, we find large discrepancies between the model and measured magnitude differences for the multiple images of iPTF16geu: $\Delta m_{1j}^{obs} - \Delta m_{1j}^{mod}$ = $(-0.3, -1.6, -1.5)$ mag for $j = 2, 3$ and $4$, where the indices follow the numbering scheme adopted in Fig. 4. The observed discrepancy between the smooth model predictions for the SN images 1 and 2 compared to 3 and 4 (brighter by a factor 4 and 3, respectively), cannot be accounted for by time-delays between the images, as they are predicted to be $< 35$ hours (*24*). Graininess of the stellar distribution and dark matter sub-halos in the lens galaxy, in addition to the smooth mass profile, can cause variations to magnification without altering image locations. These milli- and micro-lensing effects (*27, 28*), small enough not to cause additional resolved image separations, offer a plausible explanation for the deviation from the smooth lens model.

Available forecasts for wide-field surveys (*29*) suggest that about one strongly lensed SN Ia could be expected in our survey, irrespectively of redshift and magnification, with approximately a 30% chance to be in a quad configuration. For an average ellipticity of the lenses $e = 0.3$ (*29*), only about 1% of the lensed SNe are expected to have $\mu \gtrsim 50$ (*30*). We have performed an independent rate estimate, with a somewhat simplified lensing simulation but including survey specific parameters, and confirm that the probability to detect and classify a highly magnified SN Ia like iPTF16geu does not exceed the few percent level (*24*).

iPTF16geu appears to be a rather unlikely event, unless the actual rate of very magnified SNe is higher than anticipated, e.g., if the contribution from lensing by any kind of sub-structures in galaxies is underestimated, or if we are otherwise lacking an adequate description of gravitational lensing at the $\sim$ 1 kpc scale. The physical scale probed by the resolved images of iPTF16geu is comparable to the smallest of the 299 multiply-imaged lensed systems in the

Master Lens Database (*31*). Using the standard candle nature of SNe Ia we can more easily detect strongly lensed systems with sub-arcsecond angular separations, allowing exploration of the bending of light at scales $\lesssim 1$ kpc, an otherwise challengingly small distance in studies of gravitational lensing (*32*). As demonstrated with iPTF16geu, discovered while still brightening with a modest size telescope and sub-optimal atmospheric conditions, the locations of these rare systems can be identified in advance of extensive follow-up imaging at high spatial resolution.

## References and Notes


1. A. Goobar, B. Leibundgut, *Annu. Rev. Nuc. Part. Sci.* **61**, 251 (2011).

2. T. S. Kolatt, M. Bartelmann, *Mon. Not. Roy. Astron. Soc.* **296**, 763 (1998).

3. M. Oguri, Y. Kawano, *Mon. Not. Roy. Astron. Soc.* **338**, L25 (2003).

4. E. E. Falco, M. V. Gorenstein, I. I. Shapiro, *Astrophys. J.* **289**, L1 (1985).

5. P. Schneider, D. Sluse, *Astron. Astrophys.* **559**, A37 (2013).

6. R. M. Quimby, *et al.*, *Astrophys. J.* **768**, L20 (2013).

7. R. M. Quimby, *et al.*, *Science* **344**, 396 (2014).

8. R. Chornock, *et al.*, *Astrophys. J.* **767**, 162 (2013).

9. P. L. Kelly, *et al.*, *Science* **347**, 1123 (2015).

10. S. Refsdal, *Mon. Not. R. Astron. Soc.* **128**, 307 (1964).

11. A. Goobar, E. Mörtsell, R. Amanullah, P. Nugent, *Astron. Astrophys.* **393**, 25 (2002).

12. S. H. Suyu, *et al.*, *Astrophys. J.* **766**, 70 (2013).

13. Y. Cao, P. E. Nugent, M. M. Kasliwal, *Publ. Astron. Soc. Pac.* **128**, 114502 (2016).

14. N. M. Law, *et al.*, *Publ. Astron. Soc. Pac.* **121**, 1395 (2009).

15. A. Goobar, *The Astronomer's Telegram* **9603**, 1 (2016).

16. A. Ritter, C. C. Ngeow, N. Konidaris, R. Quimby, S. Ben-Ami, *Contributions of the Astronomical Observatory Skalnate Pleso* **43**, 209 (2014).

17. J. Guy, *et al.*, *Astron. Astrophys.* **466**, 11 (2007).

18. M. M. Phillips, *Astrophys. J.* **413**, L105 (1993).

19. R. Tripp, *Astron. Astrophys.* **331**, 815 (1998).

20. M. Betoule, *et al.*, *Astron. Astrophys.* **568**, A22 (2014).

21. S. Alam, *et al.*, *Astrophys. J.* **219**, 12 (2015).

22. P. A. Mazzali, *et al.*, *Mon. Not. R. Astron. Soc.* **439**, 1959 (2014).

23. J. A. Cardelli, G. C. Clayton, J. S. Mathis, *Astrophys. J.* **345**, 245 (1989).

24. Materials and methods are available as supplementary materials on Science Online.

25. A. Kassiola, I. Kovner, *Liege International Astrophysical Colloquia*, J. Surdej, D. Fraipont-Caro, E. Gosset, S. Refsdal, M. Remy, eds. (1993), vol. 31 of *Liege International Astrophysical Colloquia*, p. 571.

26. R. Kormann, P. Schneider, M. Bartelmann, *Astron. Astrophys.* **284**, 285 (1994).

27. R. Kayser, S. Refsdal, *Nature* **338**, 745 (1989).

28. H. J. Witt, S. Mao, *Astrophys. J.* **429**, 66 (1994).

29. M. Oguri, P. J. Marshall, *Mon. Not. R. Astron. Soc.* **405**, 2579 (2010).

30. K.-H. Chae, *Mon. Not. R. Astron. Soc.* **346**, 746 (2003).

31. L. A. Moustakas, *et al.*, *Bull. Am. Astron. Soc.* (2012), vol. 219, p. 146.01. The Master Lens Database is available at http://admin.masterlens.org.

32. D. A. Goldstein, P. E. Nugent, *Astrophys. J.* **834**, L5 (2017).

33. O. Yaron, A. Gal-Yam, *Publ. Astron. Soc. Pac.* **124**, 668 (2012).

34. More information about the iPTF survey is available at http://www.ptf.caltech.edu/iptf.

35. E. O. Ofek, *et al.*, *Publ. Astron. Soc. Pac.* **124**, 854 (2012).

36. H. Brink, J. W. Richards, D. Poznanski, J. S. Bloom, J. Rice, S. Negahban, M. Wainwright, *Mon. Not. R. Astron. Soc.* **435**, 1047 (2013).

37. U. Rebbapragada, B. Bue, P. R. Wozniak, *Bull. Am. Astron. Soc.* (2015), vol. 225, p. 434.02.

38. F. J. Masci, *et al.*, *Publ. Astron. Soc. Pac.* **129**, 014002 (2017).

39. C. Fremling, *et al.*, *Astron. Astrophys.* **593**, A68 (2016).

40. J. B. Oke, J. E. Gunn, *Publ. Astron. Soc. Pac.* **94**, 586 (1982).

41. W. Freudling, *et al.*, *Astron. Astrophys.* **559**, A96 (2013).

42. J. Larkin, *et al.*, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* (2006), vol. 6269 of *Proceedings of the Society of Photo-Optical Instrumentation Engineers Conference Series*, p. 62691A.

43. J. L. Sérsic, *Boletin de la Asociacion Argentina de Astronomia La Plata Argentina* **6**, 41 (1963).

44. R. Amanullah, *et al.*, *Mon. Not. R. Astron. Soc.* **453**, 3300 (2015).

45. P. A. R. Ade, *et al.*, *Astron. Astrophys.* **594**, A13 (2016).

46. C. R. Keeton, *ArXiv e-prints 0102340* (2001).

47. C. R. Keeton, *ArXiv e-prints 0102341* (2001).

48. P. Schneider, J. Ehlers, E. E. Falco, *Gravitational Lenses* (1992).

49. R. Pereira, *et al.*, *Astron. Astrophys.* **554**, A27 (2013).

50. A. Goobar, E. Mörtsell, R. Amanullah, M. Goliath, L. Bergström, T. Dahlén, *Astron. Astrophys.* **392**, 757 (2002).

51. J. F. Navarro, C. S. Frenk, S. D. M. White, *Astrophys. J.* **490**, 493 (1997).

52. V. Springel, *et al.*, *Mon. Not. Roy. Astron. Soc.* **391**, 1685 (2008).

53. G. Dobler, C. R. Keeton, *Astrophys. J.* **653**, 1391 (2006).

54. P. L. Schechter, D. Pooley, J. A. Blackburne, J. Wambsganss, *Astrophys. J.* **793**, 96 (2014).

55. J. Wambsganss, *Proceedings, 33rd Advanced Saas Fee Course on Gravitational Lensing: Strong, Weak, and Micro: Les Diablerets, Switzerland, April 7-12, 2003* (2006), pp. 453–540.

56. S. Ben-Ami, N. Konidaris, R. Quimby, J. T. Davis, C. C. Ngeow, A. Ritter, A. Rudy, *Ground-based and Airborne Instrumentation for Astronomy IV* (2012), vol. 8446 of *Proceedings of the Society of Photo-Optical Instrumentation Engineers Conference Series*, p. 844686.

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**SUPPLEMENTARY MATERIALS**

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Materials and Methods

Figs. S1, S2, S3

Tables S1, S2, S3, S4, S5, S6

References (34-56)

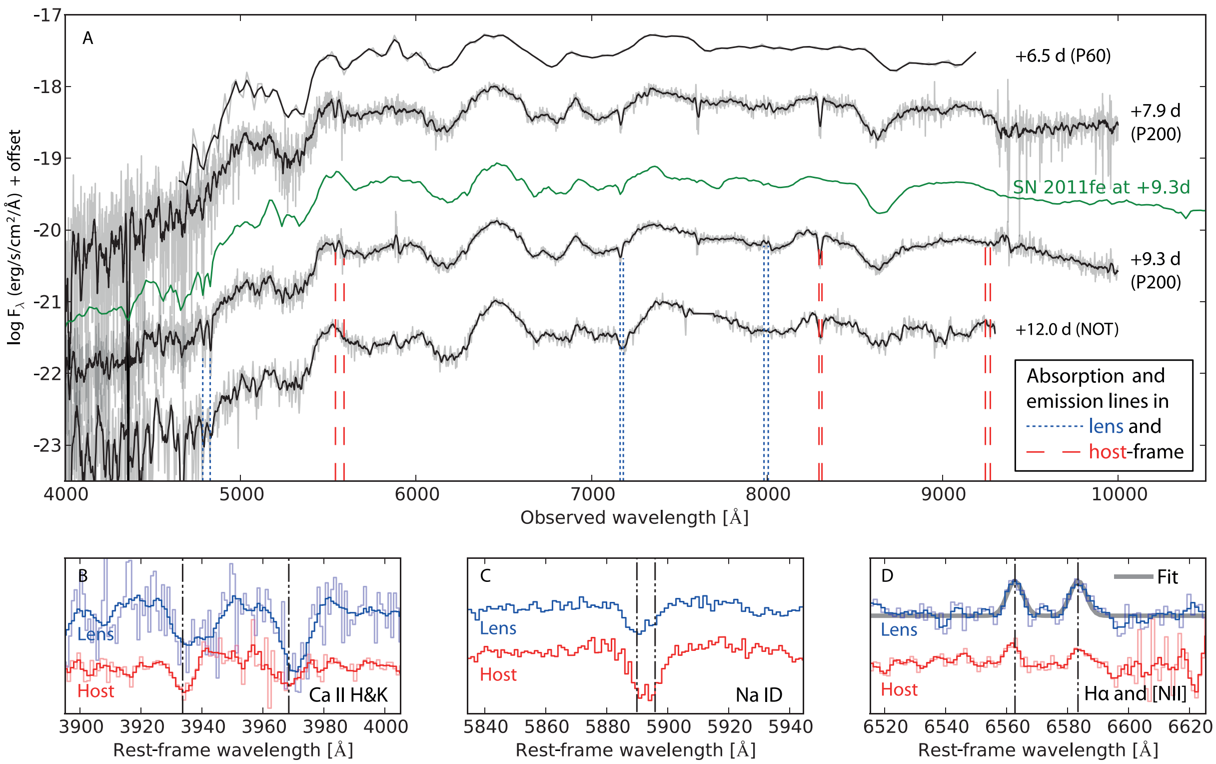


Figure 1: **Spectroscopic identification of iPTF16geu as a Type Ia supernova and measurements of the redshifts of the SN host galaxy and the intervening lensing galaxy.** Measurements of the SN spectral energy distribution, $F_\lambda$, obtained with the P60, P200 and NOT telescopes are best fitted by a normal SN Ia spectral template. Panel A shows a comparison with the near-by SN Ia, SN 2011fe, redshifted to $z = 0.409$ (green line, (*22*)) at a similar rest-frame phase, expressed in units of days with respect the time of optical lightcurve maximum. The spectra also reveal narrow absorption and emission lines, marked by the dashed vertical lines, from which the redshifts of the lens ($z = 0.216$, blue lines) and SN host galaxy ($z = 0.409$, red lines) were determined. Zoomed in view in rest-frame wavelengths of the Ca II H & K and Na I D absorption features are shown in panels B, and C, respectively, together with the H$\alpha$ and [N II] emission lines (panel D). The H$\alpha$ and [N II] emission lines at $z = 0.216$ were used to fit the velocity dispersion of matter in the lensing galaxy, $\sigma_v = 163^{+41}_{-27}$ km s$^{-1}$.

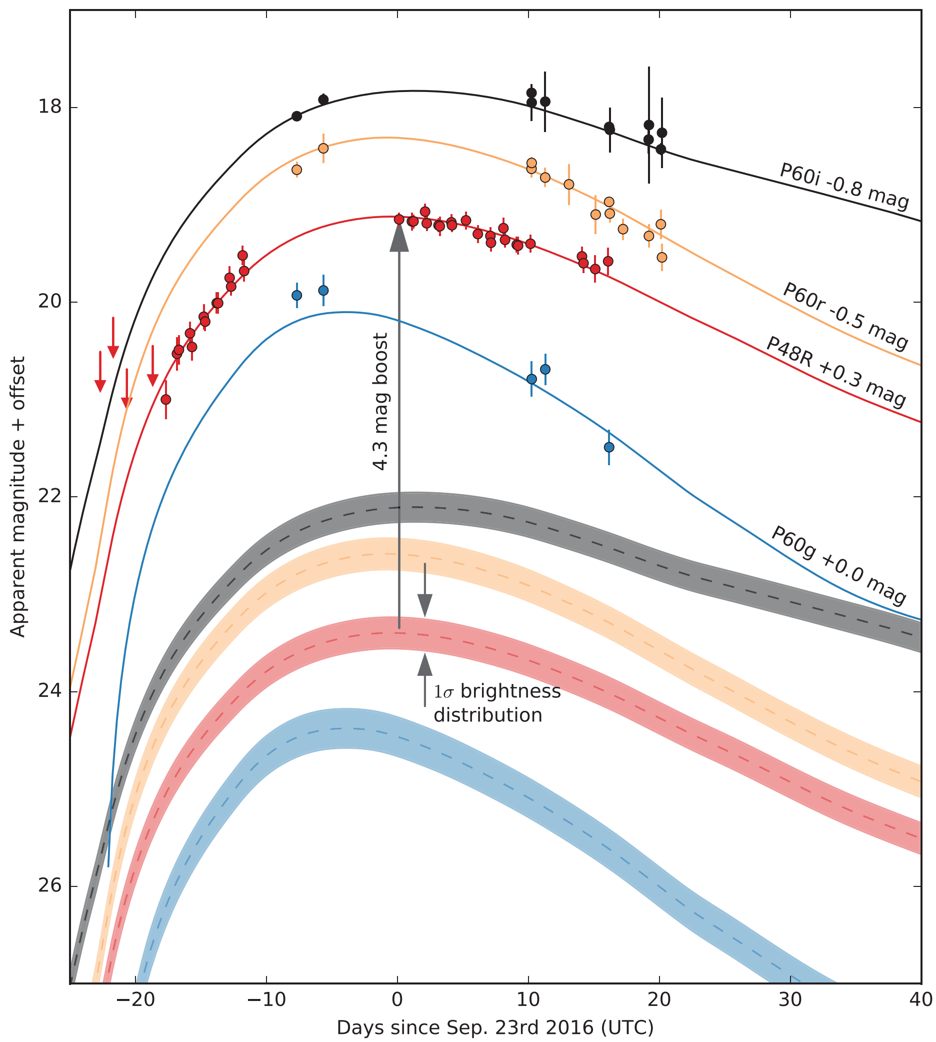


Figure 2: **Multi-color lightcurve of iPTF16geu showing that the supernova is 4.3 magnitudes (30 standard deviations) brighter than expected.** The magnitudes are measured with respect to time of maximum light (Modified Julian Date 57653.10) in $R$-band at P48 and $g$, $r$ and $i$-band with RC on the SED Machine at P60. The filter transmission functions are shown in (*24*). The solid lines show the best fitted SALT2 (*17*) model to data. The dashed lines indicate the expected lightcurves at $z = 0.409$ (without lensing) where the bands represent the standard deviation of the brightness distribution for SNe Ia. In order to fit the observed lightcurves a brightness boost of $4.3$ magnitudes is required.

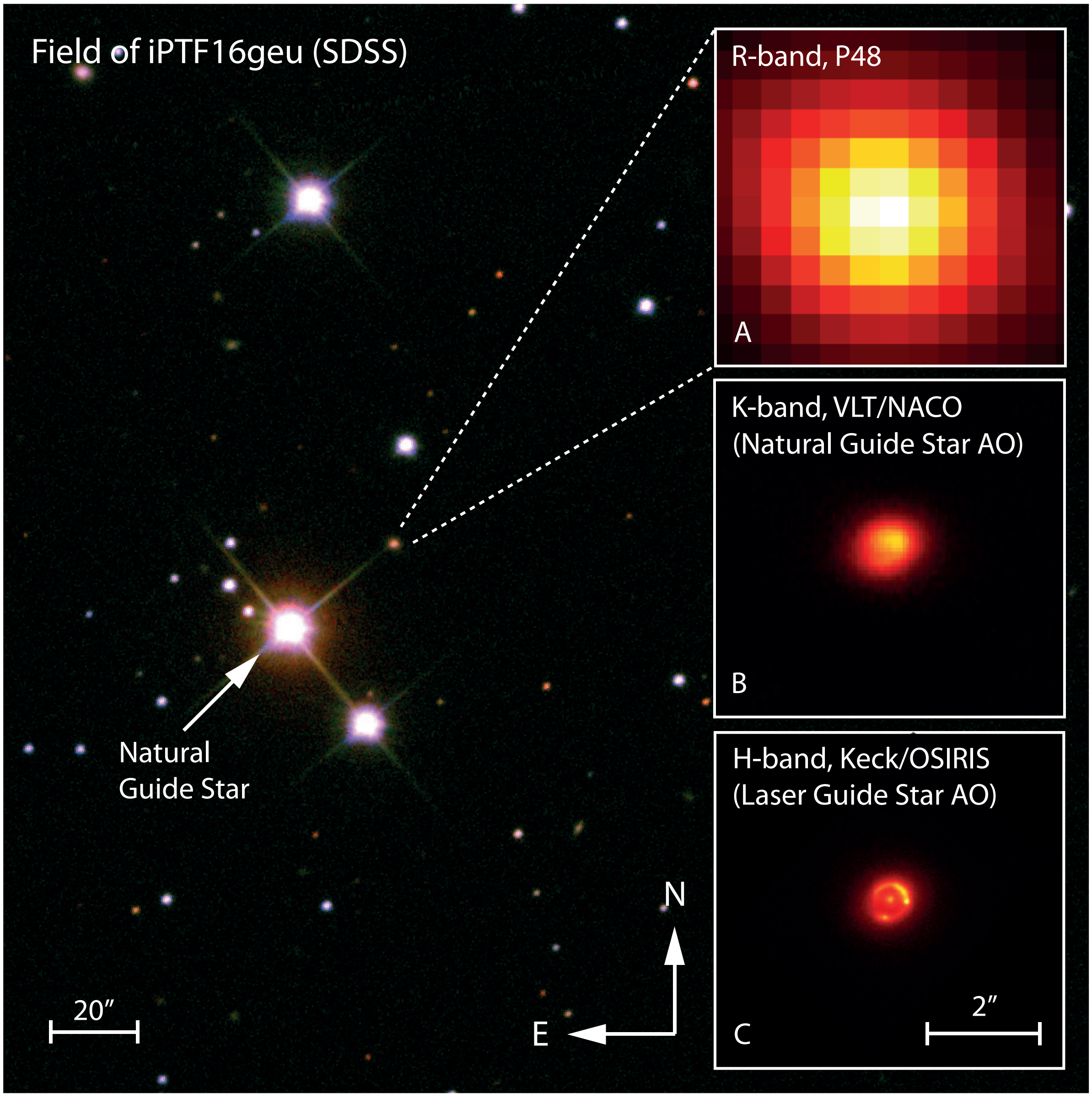


Figure 3: **Image of the field of iPTF16geu showing the spatial resolution of the ground based instruments used in this work.** A pre-explosion multicolor image from SDSS indicating the bright natural guide star and the position of the SN detection in R-band at P48 (zoomed in panel A) near the galaxy SDSS J210415.89-062024.7. The improved spatial resolution using a Natural star Guide System AO (NGSAO, panel B, and further using the Laser Star aided AO System (LGSAO, panel C) is shown.

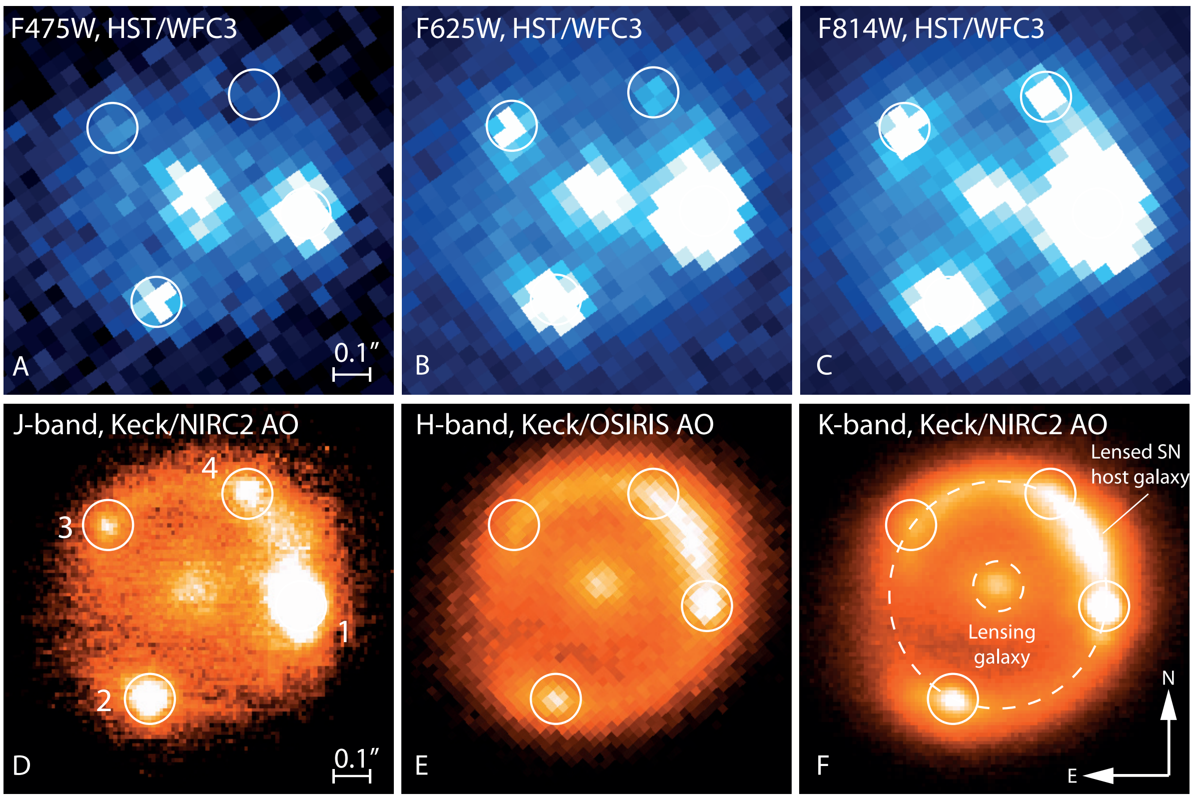


Figure 4: **High spatial resolution images from the Hubble Space Telescope and the Keck Observatory used to resolve the positions of the SN images, the partial Einstein ring of the host galaxy and the intervening lensing galaxy.** HST/WFC3 observations of iPTF16geu obtained on 2016 October 25 in the $F475W$, $F625W$ and $F814W$ bands. are shown in the panels A,B and C respectively. The images reveal four point sources, except for $F475W$ where SN images 3 and 4 are too faint. The NIR images obtained using Adaptive Optics aided Keck observations in the $J$, $H$ and $K_s$ bands are shown in panels D, E and F. All four SN images are clearly seen in $J$-band (panel D). For the $H$ and $K_s$ images, both the lensing galaxy at the center of the system and the lensed partial Einstein ring of the host galaxy are visible.