# GEMINI OBSERVATORY

*observing time request summary*

**Semester:** 2015A **Observing Mode:** Fast Turnaround **Gemini Reference:**

**Instruments:** NIRI

**Time Awarded:** NaN **Thesis:** No

**Band 3 Acceptable:** No

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**Title:** **Weighing galaxies that host superluminous supernovae**

**Principal Investigator:** **Franz Bauer**

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**PI status:** PhD

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Giorgos Leloudas: Niels Bohr Institute/Dark Cosmology Centre, giorgos@dark-cosmology.dk

**Reviewer:** Franz Bauer

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**Partner Submission Details** *(multiple entries for joint proposals)*

| | | PI Request | | NTAC Recommendation | | | |
|---|---|---|---|---|---|---|---|
| **Partner** | **Lead** | **Time** | **Min** | **Reference** | **Time** | **Min** | **Rank** |
| | *Total Time* | *1.8 hr* | *1.8 hr* | | *0.0 hr* | *0.0 hr* | |

**Abstract**

*Super-luminous supernovae (SLSNe) are exceptionally bright explosions but are unfortunately poorly understood. To place constraints on their progenitors and their explosion mechanisms we have embarked on a large project to observe and characterise SLSN host galaxies at z~0.5. We have more than doubled the number of host metallicities and determined that H-poor SLSNe are found in more metal-poor environments than hydrogen-rich SLSNe, but similar to gamma-ray-burst host galaxies. Furthermore, we have discovered that a large number of SLSN hosts are similar to extreme emission-line galaxies in their mass and luminosity distributions. Ten galaxies of the 35 galaxies in our sample lack critical NIR data, which is needed to accurately measure the stellar mass content. Among those 10 galaxies four are visible in March. We here propose to obtain J and K band photometry for these hosts. This will allow us to model accurately the spectral energy distributions with a minimum number of assumption, resulting in a significantly better statistical and predictive power of our findings. This is key to put these bizarre galaxies in context of other galaxy samples, e.g. star-forming galaxies in the SDSS, host galaxies of classical SNe, GRB host galaxies, or emission-line galaxies (EELGs, HiZELS), and study their evolution with redshift.*

**TAC Category / Keywords**

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*Extragalactic / High-redshift, Supernovae, Starburst galaxies*

**Scheduling Constraints**

# Observation Details (Band 1/2)

| Observation | RA | Dec | Brightness | Total Time *(including overheads)* |
|---|---|---|---|---|
| **SN2010kd** | 12:08:01.109 | 49:13:31.116 | | 0.2 hr |
| **Conditions:** CC 50%/Clear, IQ 70%/Good, SB Any/Bright, WV Any<br>**Resources:** NIRI None f/6 (0.12"/pix, 120" FoV) K(short) (2.15 um) | | | | |
| **LSQ14mo** | 10:22:41.530 | -16:55:14.400 | 24.00 R AB, 23.00 J AB, 23.00 K AB | 0.3 hr |
| **Conditions:** CC 50%/Clear, IQ 70%/Good, SB Any/Bright, WV Any<br>**Resources:** NIRI None f/6 (0.12"/pix, 120" FoV) K(short) (2.15 um) | | | | |
| **PTF09cnd** | 16:12:08.940 | 51:29:16.116 | | 0.1 hr |
| **Conditions:** CC 50%/Clear, IQ 70%/Good, SB Any/Bright, WV Any<br>**Resources:** NIRI None f/6 (0.12"/pix, 120" FoV) K(short) (2.15 um) | | | | |
| **SN2005ap** | 13:01:14.839 | 27:43:31.404 | 18.20 R Vega | 0.3 hr |
| **Conditions:** CC 50%/Clear, IQ 70%/Good, SB Any/Bright, WV Any<br>**Resources:** NIRI None f/6 (0.12"/pix, 120" FoV) K(short) (2.15 um) | | | | |
| **PTF09cnd** | 16:12:08.940 | 51:29:16.116 | 22.80 R AB, 21.80 J AB, 21.80 K AB | 0.1 hr |
| **Conditions:** CC 50%/Clear, IQ 70%/Good, SB Any/Bright, WV Any<br>**Resources:** NIRI None f/6 (0.12"/pix, 120" FoV) J (1.25 um) | | | | |
| **LSQ14mo** | 10:22:41.530 | -16:55:14.400 | 24.00 R AB, 23.00 J AB, 23.00 K AB | 0.3 hr |
| **Conditions:** CC 50%/Clear, IQ 70%/Good, SB Any/Bright, WV Any<br>**Resources:** NIRI None f/6 (0.12"/pix, 120" FoV) J (1.25 um) | | | | |
| **SN2010kd** | 12:08:01.109 | 49:13:31.116 | 23.10 R AB, 22.60 J AB, 22.60 K AB | 0.2 hr |
| **Conditions:** CC 50%/Clear, IQ 70%/Good, SB Any/Bright, WV Any<br>**Resources:** NIRI None f/6 (0.12"/pix, 120" FoV) J (1.25 um) | | | | |
| **SN2005ap** | 13:01:14.839 | 27:43:31.404 | 23.90 R AB, 22.90 J AB, 22.90 K AB | 0.3 hr |
| **Conditions:** CC 50%/Clear, IQ 70%/Good, SB Any/Bright, WV Any<br>**Resources:** NIRI None f/6 (0.12"/pix, 120" FoV) J (1.25 um) | | | | |

**Scientific Justification** *Be sure to include overall significance to astronomy. For standard proposals limit text to one page with figures, captions and references on no more than two additional pages.*

Although SNe have been studied for hundreds of years, the breadth and depth of new optical and near-infrared surveys, such as PTF, PanSTARRS1, and LSQ, revealed the existence of a previously unknown class of very rare, super-luminous SNe (SLSNe). This new class is defined by a peak magnitude of $M_{\rm peak} < -21$ mag [1], making them $\sim$ 100-times more luminous than previously known SNe. These SNe were unnoticed before because of their preference for faint dwarf galaxies, i.e. environments radically different than those probed by traditional SN searches.

SLSNe come in two flavours [1]: H-rich SLSNe show narrow H emission-lines (i.e. they are luminous Type IIn SNe), and it is widely believed that their extreme luminosities are due to the interaction of the SN ejecta with an H-rich circumstellar medium (CSM). The class of H-poor SLSN [defined by 2] have blue spectra that later evolve into Type-Ic-like spectra [3] and relatively symmetric light curves that are incompatible with radioactive decay. Their explosion mechanism and source of extreme luminosity remain a mystery. Possible suggestions include pulsational pair-instability SN [4], powering of the ejecta by a magnetar [e.g. 5], or interaction with an H-poor CSM [e.g. 6].

Our team has embarked on a large project to observe and characterize SLSN host galaxies at $z < 0.5$. Our purpose has been to obtain multi-wavelength photometry to build the spectral energy distributions (SEDs) of the SLSN hosts, and derive their stellar masses and star-formation rates (SFR), and spectra to measure metallicities and SFRs. We have so far been able to detect the hosts of most known ($\sim 30$) SLSNe and build their SEDs (combining our data with literature and archival data), and secure spectra for $\sim 25$ of them. We have also obtained NIR photometry for a sub-sample of 20 hots and spectra for even 25 of them, a precious dataset not previously available for SLSN hosts. Two papers have been submitted to high-impact journals: Leloudas et al. report on the spectroscopic properties of SLSN hosts at $z < 0.5$ (arXiv:1409.8331) and Thöne et al. on a detailed modeling of the host spectrum of PTF12dam (arXiv:1411.1104). A third paper on the general photometric properties and the galaxy environment is in preparation.

In summary, we find that (*i*) H-poor SLSNe explode in low-mass, metal-poor galaxies with high specific SFR (median values: $10^8\ M_\odot$, $0.27\ Z_\odot$, $10^{-8.8}\ M_\odot\ {\rm yr}^{-1}$). (*ii*) They occur close to the galaxy nucleus (Fig. 1). (*iii*) Our H-poor sample also includes a number (3/16) of very metal-poor galaxies ($< 10\%$ solar). (*iv*) About $\sim 50\%$ of our H-poor sample share many properties of extreme emission-line galaxies [11]. These special environments can likely harbor very luminous SNe in very dense stellar supercluster environments. (*v*) GRBs explode, on average, in less extreme and higher mass galaxies than H-poor SLSNe. (*vi*) We suggest that H-poor SLSNe are the result of the first stellar explosions in a starburst and that they occur earlier, on average, than GRBs. This indicates that they probably result from very massive stars [see also 13]. (*vii*) These findings indicate that the IMF in starburst environments may be bottom-light. (*viii*) H-rich SLSN-II occur in different environments than H-poor SLSNe: more massive, more metal-rich and with softer radiation fields. This suggests that the progenitors of these systems are fundamentally different and that SLSNe-II can not just be SLSNe-I surrounded by some additional H-rich CSM.

A key ingredient to understand the peculiarity of these galaxies is their stellar mass. Accurate mass measurements require rest-frame NIR observations, the part of the galaxy spectrum which is dominated by low-mass stars. In our sample of 30 galaxies, $\sim 10$ lack of accurate mass measurements. We here propose to secure NIR data with Gemini-N/NIRI in J and K band of 4 hosts with $r \sim 22$–$24$ mag that are too faint for any other NIR imager on the northern hemisphere to which we have access to. Together with the rest-frame optical data (observed in 4 bands), we model the SEDs to extract accurate mass measurements (to within 0.2 dex). We recently extended our survey to higher redshifts. Understanding the properties of of SLSN host galaxies at $z < 0.5$ is crucial for us to understand their evolution with cosmic time.

# References

[**1**] Gal-Yam 2012, Science, 337, 927; [**2**] Quimby et al. (2011 Nature, 474, 487); [**3**] (Pastorello et al. 2010, ApJ, 724, 16); [**4**] (Woosley et al. 2007, Nature, 450, 390); [**5**] Kasen & Bildsten 2010, ApJ, 717, 245: [**6**] Chatzopoulos et al. 2013, ApJ, 773, 76; [**7**] Modjaz et al. 2008, AJ, 135, 1136; [**8**] Leloudas et al. 2014, MNRAS, submitted, arXiv:1409.8331; [**9**] Kniazev et al. 2004, ApJS, 153, 429; [**10**] Amorin et al. 2014, A&A submitted, arXiv:1403.3441; [**11**] Amorin et al. 2012, ApJ, 749, 185; [**12**] Thöne et al. 2014, MNRAS, submitted, arXiv:1411.1104

Table 1 -- Tartgets Requested for this Project

| Object | Airmass limit | Brightness (AB mag) | S/N | Integration time (s) | Observing time (min) |
|---|---|---|---|---|---|
| SN2010kd | <1.5 | JK=22.3 | 10/10 | J: 480, K: 360 | 23.2 |
| SN2005ap | <1.5 | JK=22.9 | 10/10 | J: 840, K: 660 | 36.3 |
| PTF09cnd | <1.5 | JK=21.8 | 10/10 | J: 180, K: 180 | 13.9 |
| LSQ14mo | <1.5 | JK=23 | 7/7 | J: 840, K: 660 | 36.3 |

Total: 109.7 min (=1.83 h)

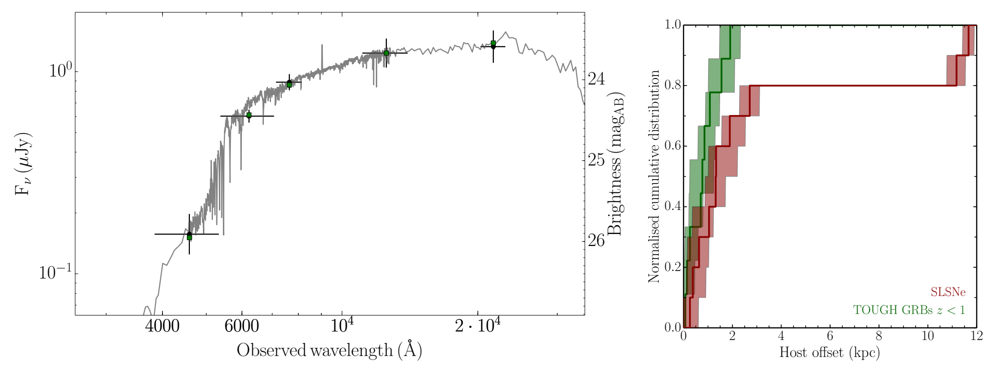


Figure 1: ***Left****: Spectral energy distribution of the host galaxy of SN2006oz and its best fit* ($z = 0.396$ *(fixed), SFR* $= 0.03 \pm 0.14\ M_\odot\,\mathrm{yr}^{-1}$, $\log(M/M_\odot) = 8.27 \pm 0.19$*).* ***Right****: Host-offset distribution of the SLSNe in our spectroscopic sample. The offset is typically very small and for a large number negligible within errors. One of the very few exceptions is SN 1999as that occurred 11.1 kpc off the galaxy centre. The host has a disturbed morphology and interacts with other galaxies. Considering that all SLSNe having much smaller offsets than SN 1999as, it cannot be ruled out that the true host is a very faint satellite galaxy that evaded detection. (Figures taken from Schulze et al. in prep.)*

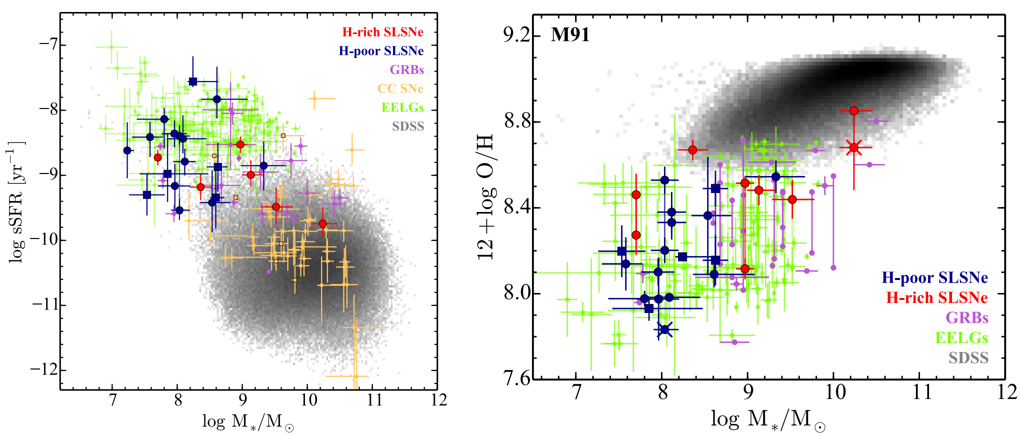


Figure 2: ***Left***: *Although SLSN hosts have very low SFRs, they have extremely high specific star-formation rates when normalized to stellar mass. The time to double the stellar mass can be as short as a few tens of millions of years. Compared to the sample of extreme emission-line galaxies in Amorin et al. (2014), SLSN host galaxies populated the same parameter space.* ***Right***: *Mass-metallicity relation for SLSN hosts at $z < 0.5$. The loci of the host galaxies of H-poor SLSNe coincide with the region occupied by extreme emission-line galaxies [EELGs]. These elusive galaxies, which are defined by a rest-frame [O*III*]$\lambda$5007 equivalent width of $> 100$ Å and which constitute only 0.5% of the whole SDSS sample of star-forming galaxies, represent a transient phase in galaxy evolution where a galaxy undergoes a galaxy-wide starburst. (Figures taken from Leloudas et al. 2014, MNRAS, submitted, arXiv:1409.8331)*

**Experimental Design** *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science. (Limit text to one page)*

Our survey targets $\sim$ 35 SLSN host galaxies. Among those 30 of them are brighter than 25th magnitude in the optical. For these we obtain multi-band data covering the rest-frame UV, optical and NIR. For objects brighter than 24th magnitude ($\sim$ 20), we also secure spectra. Ten of 30 hosts lack of NIR data of which 4 are visible in March.

The inclusion of NIR data presents significant advantages in the accuracy of spectral energy distribution (SED) modeling. Especially the $K$-band is essential for the determination of the galaxy stellar mass. For instance, we modelled the SED of the host of SN2006oz with and without NIR data. The difference in the stellar mass is about *one* order of magnitude and thanks to the inclusion of NIR data, the error on the stellar mass also halved. Due to the complexity of SED fitters, the SFR can also differ significantly if no NIR data is included, e.g. it differs by a factor of 100 for the host of SN2006oz. Putting this together the specific star-formation rate of the host of SN2006oz differed by a factor of 20. One of our key results is that hosts of H-poor SLSN have very high specific star-formation rates (normalized to mass) of $10^{-8.8}\ M_{\odot}\,\mathrm{yr}^{-1}$ (average). Without NIR data we would not have come to this conclusion.

We plan to submit the third paper of our survey in June/July. Unfortunately, we missed the last call for proposal. The Fast-Turnaround program will allow us to secure NIR data of four hosts and include them in that paper. Having NIR data for four additional hosts would not only allow us to have more accurate masses, specific star-formation rates and mass-to-light ratios for 20% more objects but more importantly it would break degeneracies in the SED fitting and remove systematic errors in the fitting procedure, which are otherwise hard to quantify. We stress that other studies of SLSN host galaxies at $z < 0.5$ (e.g. Chen et al. 2013, ApJ, 763, 28) lack rest-frame NIR data. They involve more crude assumptions on the galaxy properties and do not provide an accurate estimate of the stellar mass. Our findings will be based on very few assumptions, resulting in a significantly better statistical and predictive power of our findings. This is needed to put these bizarre galaxies in context with other galaxy samples, e.g. star-forming galaxies in the SDSS, host galaxies of classical SNe, GRB host galaxies, or emission-line galaxies (EELGs, HiZELS).

**Proprietary Period:** 18 months

**Use of Other Facilities or Resources** *(1) Describe how the proposed observations complement data from non-Gemini facilities, including those available through NOAO. For each of these other facilities, indicate the nature of the observations (yours or those of others), and describe the importance of the observations proposed here in the context of the entire program. (2) Do you currently have a grant that would provide resources to support the data processing, analysis, and publication of the observations proposed here?*

In the past two years we have extensively used the 3.5-m CAHA telescope to obtain NIR for the brightest hosts in the northern hemisphere. The remaining targets 10 targets are too faint for CAHA ($J(\mathrm{AB}) > 21$, $K(\mathrm{AB}) > 21$). Gemini-N is the only telescope to which we have access to that can observe these faint objects and provide data with the desired S/N of 10 in $J$ and $K$ band.

The investigators of this proposal have either a permanent position or hold long-term postdoc positions, and have expertise and computing power to reduce the NIR imaging data immediately.

**Previous Use of NOAO Facilities** *List allocations of telescope time on facilities available through NOAO to the PI during the last 2 years for regular proposals, and at any time in the past for survey proposals (including participation of the PI as a Co-I on previous NOAO surveys), together with the current status of the data (cite publications where appropriate). Mark with an asterisk those allocations of time related to the current proposal. Please include original proposal semesters and ID numbers when available.*

**Technical Description** *Describe the observations to be made during this observing run. Justify the specific telescope, the exposure times, and the constraints requested (seeing, cloud cover, sky brightness, and, if appropriate, water vapor). If applying for instruments on both Gemini North and South, state the time request for each site. If a Band 3 allocation is acceptable, give the Band 3 time requested from each partner.*

We propose to observe 7 SLSN host galaxies with insufficient NIR data with Gemini-N/NIRI. We would like to use NIRI in the f/6 mode without any NGS or LGS support. To estimate exposure times we use instrument-specific exposure-time calculators. We assume average weather conditions (image quality 70%-ile, cloud coverage, 50%-ile, but no constraints on water vapor and sky brightness). The exposure times is chosen to be 60s in JK bands, built from $2 \times 30$ s co-added images in $J$-band , and $4 \times 15$ s co-added images in $K$ bands. Our objects are compact hence we assume a duty cycle of 100% for.

Our targets have an expected AB-magnitude between 21.8–23 mag in the NIR. In Table 1 we summarize the exposure times and observing times, airmass constraints and the desired S/N (7–10 sigma). To estimate the observing time, we simulated the observation with the OT2015.1.1. In total we ask for 1.83 hours, including all overheads.

**Band 3 Plan** *If applying for queue time and it is acceptable for the proposal to be scheduled in Band 3, describe the changes to be made to allow it to be successful in Band 3 (limit text to half a page). Band 3 observations are used to fill the queue when no Band 1 or 2 programs are available. Successful Band 3 programs generally use poorer than median observing conditions, have targets away from the most popular regions of the sky, do not require strict timing or other constraints, and do not require special instrument configurations.*

This program is not suitable for band 3.

**Classical Backup Program** *If applying for classically scheduled time, describe the program you will pursue should the weather be worse than the requested observing conditions (limit text to half a page).*

N

**Justify Target Duplications** *If your targets have been previously observed by Gemini using similar or identical setups to those proposed here, justify the duplication below. Duplicate observations can be identified through a search of the Gemini Science Archive.*

The GSA search revealed no duplicate observations

**ITC Examples** *Attach representative Gemini ITC output for each instrument requested.*

# Gemini Integration Time Calculator
# NIRI version 4.2

Click here for help with the results page.
software aperture diameter = 0.83 arcsec
fraction of source flux in aperture = 0.61
enclosed pixels = 40.21

derived image size (FWHM) for a point source = 0.70 arcsec.

Contributions to total noise (e-) in aperture (per exposure):
Source noise = 92.97
Background noise = 1478.65
Dark current noise = 24.56
Readout noise = 76.10

Total noise per exposure = 1483.73
Total signal per exposure = 8644.72

Derived number of exposures = 6 , of which 6 are on source.
Taking 6 exposures, the effective S/N for the whole observation is 10.10 (including sky subtraction)

Required total integration time is 360.00 secs, of which 360.00 secs is on source.

Observation is background noise limited.

The peak pixel signal + background is 54713. This is 27% of the full well depth of 200000.

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**Input Parameters:**
Instrument: NIRI

Source spatial profile, brightness, and spectral distribution:
The z = 0.3 point source is a 22.3 ABmag spiral-galaxy in the K band.

Instrument configuration:
Optical Components:
- Filter: Kshort
- Fixed Optics
- Camera: f6
- Detector - 1024x1024-pixel ALADDIN InSb array
- Read Mode: lowNoise
- Detector Bias: lowWell

Pixel Size: 0.116

Telescope configuration:
- silver mirror coating.
- side looking port.
- wavefront sensor: pwfs

Observing Conditions:
- Image Quality: 70.00%
- Sky Transparency (cloud cover): 50.00%

- Sky transparency (water vapour): 100.00%
- Sky background: 100.00%
- Airmass: 1.50

Frequency of occurrence of these conditions: 35.00%

Calculation and analysis methods:

- mode: imaging
- Calculation of integration time from a S/N ratio of 10.00 for exposures of 60.00 with 100.00 % of them were on source.
- Analysis performed for aperture that gives 'optimum' S/N and a sky aperture that is 1.00 times the target aperture.