The Nearby Supernova Factory

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ABSTRACT

The Nearby Supernova Factory will lay the foundation for the next generation of experiments to measure the expansion history of the Universe. It will discover and obtain lightcurve spectrophotometry for ~ 300 Type Ia supernovae in the low-redshift end of the smooth Hubble flow. The search capabilities and the follow-up instrumentation are described; they include wide-field CCD imagers on two 1.2-m telescopes, and an integral-field-unit optical spectrograph on a 2.2-m telescope. The dataset will serve as the premier source of calibration of the SN Ia width-brightness relation and the intrinsic SN Ia colors used for correction of extinction by dust. This dataset will also allow an extensive search for additional parameters which influence the quality of SNe Ia as cosmological probes. The lowest redshift SNe Ia from this program can be used to measure galaxy peculiar velocities and thereby constrain Ω_M.

1. Overview

The recent measurements of Ω_M and Ω_Λ by the Supernova Cosmology Project (SCP) using 42 high-z Type Ia supernovae (SNe Ia; see Fig 1) excludes a simple $\Omega_M = 1$ flat universe, and presents strong evidence for the existence of a cosmological constant ($\Omega_\Lambda > 0$). Through further ground-based and space-based initiatives — such as the Hubble Space Telescope (HST) and the SuperNova/Acceleration Probe (*SNAP*) — we are seeking to confirm this exciting result with observations of SNe Ia at even higher redshift. However, $\sim 50\%$ of the *statistical* uncertainty in the current result stems from the small number (~ 20) of low-z SNe Ia which are suitable to serve as the zero-point for the SNe Ia Hubble diagram. Moreover, it is now critical that SNe Ia be scrutinized even more closely to determine whether *systematic* variations (not already accounted for by the lightcurve width vs. luminosity relation) affect the use of SNe Ia for cosmology. Well-observed nearby SNe Ia, especially in host galaxies spanning a wide range in star-formation histories, are essential for testing for possible systematics. In addition, further study of nearby SNe will allow refinement of known SNe Ia luminosity indicators — and perhaps the discovery of more accurate or economical luminosity indicators — improving SNe Ia as tools for cosmology.

The importance of more detailed study of (nearby) SNe has led to the development of a new collaboration — the Nearby Supernova Factory (*SNfactory*) — to discover and obtain detailed lightcurve and spectral observations for at least 300 nearby supernovae. This new project currently involves scientists at LBNL in the United States and IN2P3[1] & INSU[2] in France. The *SNfactory* will concentrate on SNe Ia, but will also work to develop Type II supernovae (SNe II) as more reliable distance indicators. Since the physics and measurement methods applicable to Type Ia and Type II supernovae are so different, they will serve as crucial cross-checks on each other.

The *SNfactory* represents the next natural step in the study of nearby supernovae — which began with visual discovery and follow-up and has progressed through photographic and then CCD searches, but with often spotty and heterogeneous follow-up. Although modern CCD imagers on (semi-)automated telescopes have made nearby supernova discoveries routine, obtaining the minimal follow-up for even a modest number of supernovae can be daunting (as we found during the SCP's Spring 1999 Nearby Supernova Campaign, in which 20 Type Ia supernovae were found and intensively studied). Improvements, such as automation and tight coordination of the search and follow-up stages, including dedicated and optimized follow-up instrumentation, are now required to build a large sample of well-observed and well-calibrated supernovae.

Several aspects of the *SNfactory* set it apart from other past and on-going nearby supernova projects. Foremost among these is that supernovae will be discovered using a blind wide-area CCD-based survey; other nearby supernova projects target known galaxies, but there is now evidence that this approach misses an important subset of supernovae. In addition, the *SNfactory* will coordinate discovery and follow-up observations, eliminating the delays and spotty early-lightcurve coverage which is now typical. It is expected that with the *SNfactory* detailed follow-up of supernova candidates can begin within as little as 3 hrs of the discovery observations. Finally, *SNfactory* follow-up observations will use an integral field unit spectrograph, data from which can be used to construct both detailed flux-calibrated spectra and broadband images. The regular photometric spectral time series for nearby supernovae the *SNfactory* will generate will revolutionize the study of supernovae (see Fig 2b). This dataset will also eliminate several limitations (wavelength bandpass mismatch, wavelength-dependent slit losses, etc.) of all other currently available instrumentation used to study supernovae.

2. Goals

The primary goal of the *SNfactory* is to determine those properties of SNe Ia affecting their use for cosmology. The most critical of these will be the search for deviations or extra parameters not accounted for by the lightcurve width – brightness relations currently used to standardize SNe Ia for use as cosmological distance indicators. If such deviations are found, it is expected that exclusion criteria or improved standardization methods based on lightcurve shapes and/or spectral features (see Fig. 2) will be found to ameliorate the effect of deviant SNe Ia on measurements of the

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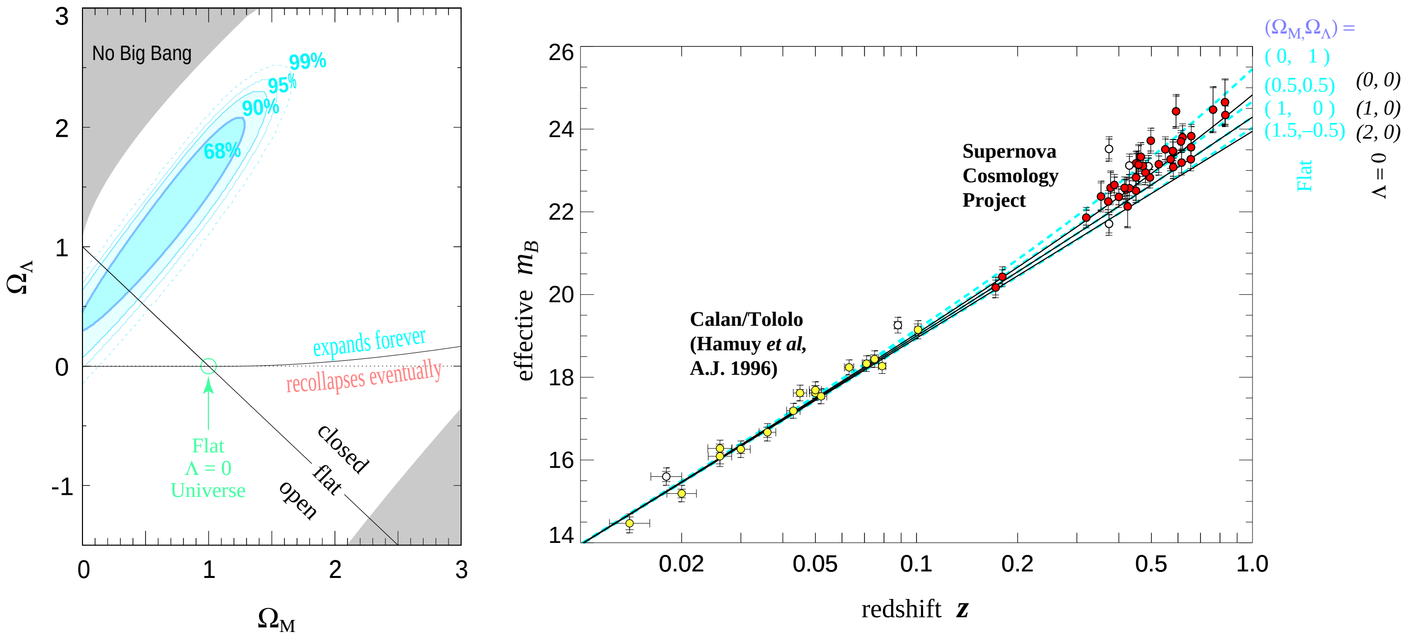

Fig. 1.— **Cosmological constraints from Type Ia supernovae:** Hubble diagram and resulting constraints on Ω_M and Ω_Λ from 42 high-z Type Ia supernovae from Perlmutter *et al* 1998b. At left, the 68%, 90%, and 99% confidence regions for an unconstrained fit for Ω_M and Ω_Λ are shown. At right, the low-z SNe Ia are those currently available which are suitable for analysis using the same methods as used for the high-z SNe Ia.

cosmological parameters. In addition, a number of sample-size and technical issues related to the use of SNe Ia as distance indicators for cosmology will also be addressed by the *SNfactory*. These include to

a) secure the low-z portion of the SNe Ia Hubble diagram (Fig 1) which serves as the zero-point ($\mathcal{M}$) for high-z cosmological measurements.

b) acquire lightcurves at numerous optical (and hopefully near-infrared) wavelengths beginning well before maximum — data currently available for only a handful of nearby SNe Ia, and needed to fit the lightcurves of high-z SNe Ia for which there is now extensive data prior to maximum (see Fig 2a).

c) test and refine the lightcurve width vs. brightness relation used to standardize SNe Ia luminosities, for which a wide range of lightcurve widths is essential.

d) construct an ultraviolet (U-band) template lightcurve and an ultraviolet lightcurve width vs. brightness relation to allow restframe ultraviolet lightcurves of $z > 0.75$ SNe Ia observed with HST to be used.

e) obtain spectral coverage with lightcurve phase, and thereby determine accurate wavelength bandpass corrections (K-corrections) as a function of lightcurve width and time (see Fig 2b).

f) determine intrinsic SNe Ia color-curves needed to establish the correct color zeropoints for host-galaxy dust extinction corrections.

g) test for the existence of abnormal host-galaxy dust extinction laws.

In principle, *SNAP* could conduct such technical studies itself. The measurements must be obtained in a fashion such that the technical measurements have little covariance with measurement of the cosmological parameters. This requires that the determination be made at very low redshift — for which *SNAP* has not been optimized — or in a very narrow redshift shell at higher-redshift. However, it is much more cost-effective and efficient to obtain these technical observations with the *SNfactory*, and since the data analysis can be completed well before *SNAP* flies, final details of the *SNAP* mission and analysis chain can be fine-tuned prior to launch rather than after *SNAP* has collected the technical data itself.

The resulting *SNfactory* dataset on SNe Ia will also allow detailed exploration of SNe Ia properties never before possible, which will almost certainly lead to a better understanding of SN physics, place strong constraints on progenitor models, and possibly allow improved luminosity estimates. It will enable us to determine

a) the intrinsic luminosity function of SNe Ia.

b) new relations between lightcurve shapes, spectral diagnostics (such as UV continuum slope, Si5180/Si6150 line ratios), etc., and luminosity.

c) SNe properties in different host galaxy environments (as a surrogate for progenitor age, mass, and metallicity).

d) the rates of SNe of all types, including rates as a function of host galaxy properties.

The large sample of *SNfactory* SNe will be important in recognizing the signature of any new supernova sub-types, which could in turn signal the existence of multiple progenitor scenarios. Indeed, the large number of SN and host-galaxy parameters whose exploration is of potential interest requires a large dataset covering parameter space.

3. Components of the Nearby SNfactory

3.1. Discovery

The *SNfactory* will search for supernovae using CCD images obtained by JPL's Near Earth Asteroid Team (NEAT). A proof-of-concept search conducted using two nights of NEAT data found 4 confirmed supernovae. NEAT has since expanded its operation to include a 1.2-m telescope (at the 10,000 ft summit of Haleakala, Hawaii) working 18 nights per month. In addition, since this search covers large portions of the sky irrespective of known galaxies, it will be rid of the biases to which pointed searches are subject due to their reliance on existing galaxy catalogs. NEAT has recently quadrupled its capacity, with a second 1.2-m telescope operating at Mt. Palomar with a large CCD camera, so we expect to discover several supernovae per night. Each patch of sky will be revisited frequently (about every 6 days, since this is the "refresh rate" for NEA's). This will enable early discovery — and hence early lightcurve coverage — and help eliminate Malmquist bias.

As with the proof-of-concept search, NEAT data (up to 80 Gbyte/night) are being transferred in near realtime via high-speed Internet connections to LBNL/NERSC (including a custom-built wireless Internet connection to Palomar). Once there, the images are processed and searched on a PC cluster using automated software developed by the SCP and refined by the *SNfactory*. An important aspect of the *SNfactory* is that the selection of supernova candidates will be quantitative and traceable, something current surveys completely lack and which makes calculations of supernova rates and peculiarity fractions extremely difficult.

3.2. Follow-up — Lightcurves and Spectroscopy

The most revolutionary aspect of the *SNfactory* — aside from the huge numbers of supernovae it will find — is the coordinated follow-up using instrumentation tailored to the study of supernovae. Candidate supernovae found in the NEAT images must first be screened with spectroscopy to confirm the supernovae and reveal its type (Ia, II, Ib, Ic) and redshift. The *SNfactory* will not only discover supernovae closer to explosion that other surveys do, with a 3 hr turn-around it will also begin the follow-up much much sooner. The *SNfactory* plans to have at least two telescopes with optimal instrumentation available every night, waiting to be fed by the stream of supernova candidates coming from the two NEAT sites.

Traditionally supernovae have been followed with $BVRI$ optical photometry, and spectra beyond the initial confirmation spectrum are rare. The *SNfactory* will change all that. Using a integral field unit on a two-channel (blue & red) optical spectrograph, the *SNfactory*'s **S**uper**N**ova **I**ntegral **F**ield **S**pectrograph (**SNIFS**; under construction in France) equipped with LBNL's red-enhanced CCD's, will allow spectroscopy of supernovae at all epochs. Because these spectra will be spectrophotometric, $UBVRIZ$ photometry can be synthesized from these spectra, without the uncertainties due to photometric color terms and K-corrections. **SNIFS** will retain one advantage of the traditional approach, which allows surrounding field stars to be used for flux scaling when conditions are non-photometric, by also having an imager which integrates on the field immediately surrounding each supernova, using the exact same exposure as the integral field unit.

4. More about SNIFS

The opto-mechanical layout of **SNIFS** is shown in Fig. 3. The operation of **SNIFS** is intended to be fully automated. An observer/technician is needed to prepare the telescope for observing at the start of the night, close the telescope in the morning. Ancillary *SNfactory* software will plan the observations and command the telescope to point at specific targets. **SNIFS** and its associated software will take focus data which will be used to adjust the telescope focus, recognize star fields near requested targets using the **SNIFS** imager, adjust the telescope pointing to place the desired target on the integral field unit, and acquire and guide on a suitable star. It will then execute an observing sequence for the spectrograph and imager, read out the date, determine the quality of the data, and take its own calibration. Moving parts on **SNIFS** are limited to a shutter, filter wheel, and pick-off mirror (feeding the spectrograph). The electronic components consist of detector readout (for 4 CCD's), a shutter, filter wheel, calibration lamps, and status-monitoring. Software interface to the telescope control system to execute pointing and focus adjustments, and to obtain information for the data headers and control software exists, and is being refined at University of Hawaii.

SNIFS continuously covers a $6'' \times 6''$field of view with a sampling of $0.4''$. It has blue and red channels, which are operated simultaneously, generating spectra on a thinned Marconi 2k$\times$4k CCD in the blue and a 2k$\times$4k LBNL red-enhanced CCD's in the red at resolutions of 4.5Å and 6.6Å, respectively. The imager consists of a 2k$\times$4k LBNL red-enhanced CCD with 15μm pixels, which views the sky surrounding the spectrograph pick-off mirror. The built-in guider/focuser consists of a second identical CCD. The imager and guider are used directly, without re-imaging optics.

The *SNfactory* currently has plans to place the first **SNIFS** on the University of Hawaii 2.2-m telescope on Mauna Kea. It will be permanently mounted, and continuously available for use of up to 20% of the night using time supplied to the *SNfactory*.

5. Cosmology with the SNfactory

The *SNfactory* will concentrate its intensive follow-up observations on Type Ia supernovae in the Hubble flow at $0.03 < z < 0.06$ so that the radial component of the peculiar velocities of the host galaxies (typically 300 km/s) is a minor portion of the overall error budget. For $z < 0.03$ these peculiar velocities will be measurable, and are proportional to $\beta = {\Omega_M}^{0.6}/b$, where b is the scaling between galaxy and dark matter density fluctuations. A large all-sky sample of $z < 0.03$

supernova distance measurements, in conjunction with galaxy maps from redshift surveys, will allow an excellent determination of β and so will constrain the value of Ω_M . Moreover, these distance measurements, including those from even somewhat higher redshift *SNfactory* supernovae, will be able to determine the spatial scale over which the velocity field converges. This in turn determines the spatial scale at which the universe becomes homogeneous.

6. The SNfactory as a Prototype for SNAP

The *SNfactory* will be placing 3 LBNL CCD's into long-term use, where their behavior — including any rare failure modes — can be observed. The *SNfactory* will also be used to demonstrate the efficacy of *SNAP*'s IFU spectrograph in all respects, including automated target acquisition, data reduction, calibration, and science analysis. Presently there is no published direct demonstration that an IFU can deliver spectrophotometric spectroscopy with very wide wavelength coverage, and at the 1% level there are a number of important issues to address. The *SNfactory* is developing the reduction and calibration techniques to make accurate spectrophotometric spectroscopy possible.

Besides determining the basic Type Ia supernova properties needed for the *SNAP* mission and prototyping some *SNAP*-like instrumentation, the *SNfactory* will develop and apply many of the software algorithms needed to search for and follow supernovae. These will be directly applicable to *SNAP*. The raw data rate for the *SNfactory* will be up to 30 Tbyte/yr, and ~ 1000 supernovae (at all types and redshifts) will be discovered. The search and follow-up will be mostly automated, just as they must be for *SNAP*. The datasets will have their differences, but they will have enough similarities that the algorithms developed for the *SNfactory* should be portable to *SNAP*. Moreover, the *SNfactory* will have a significant run-time prior to *SNAP* so that any rare bugs can be found.

7. Conclusion

The *SNfactory* will revolutionize all phases of experimental work on supernovae. The rate of discoveries will exceed the current rate by an order of magnitude, the discovery biases will be lessened (and traceable), and the quality and quantity of follow-up data will exceed that of current programs by a large factor. With such data, it is expected that great strides can be made in improving supernovae as cosmological distance indicators. In addition, the *SNfactory* study of the peculiar velocities of supernova host galaxies should provide strong dynamical constraints on the value of Ω_M.

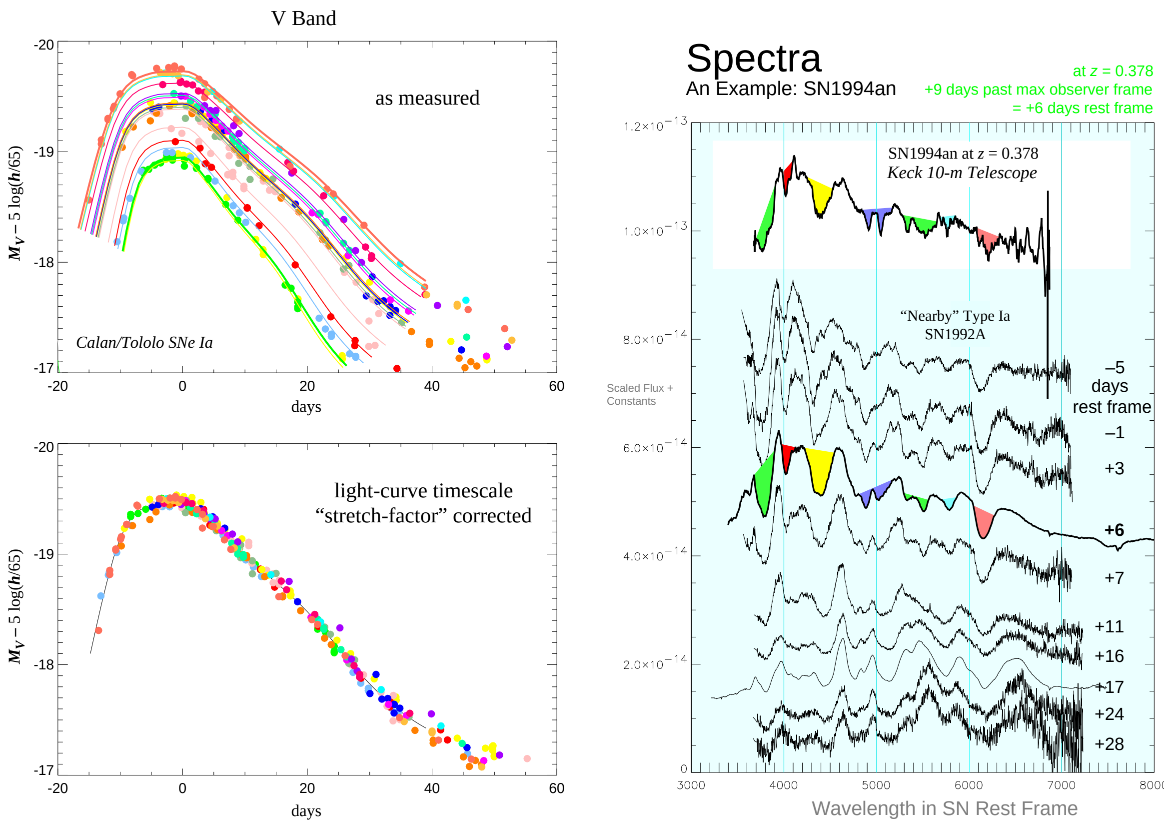

Fig. 2.— **Photometric and Spectral Time Evolution of Type Ia supernovae:** At left, lightcurves for nearby SNe Ia. The upper panel shows lightcurves for individual SNe Ia, corrected for relative distance using Hubble's law. Template lightcurves have been fit to the lightcurve for each SN and indicate that the brighter SNe have lightcurves which are broader and decline more slowly. The lower panel at left shows the superposition of these data after using a brightness correction derived from the lightcurve width. At right, the evolution of the spectrum of a Type Ia supernova as the explosion ages (constructed from different SNe Ia). The shaded regions highlight portions of the spectra which are seen to change with time; some of these are luminosity indicators. Both datasets offer important clues to the physics of SNe Ia.

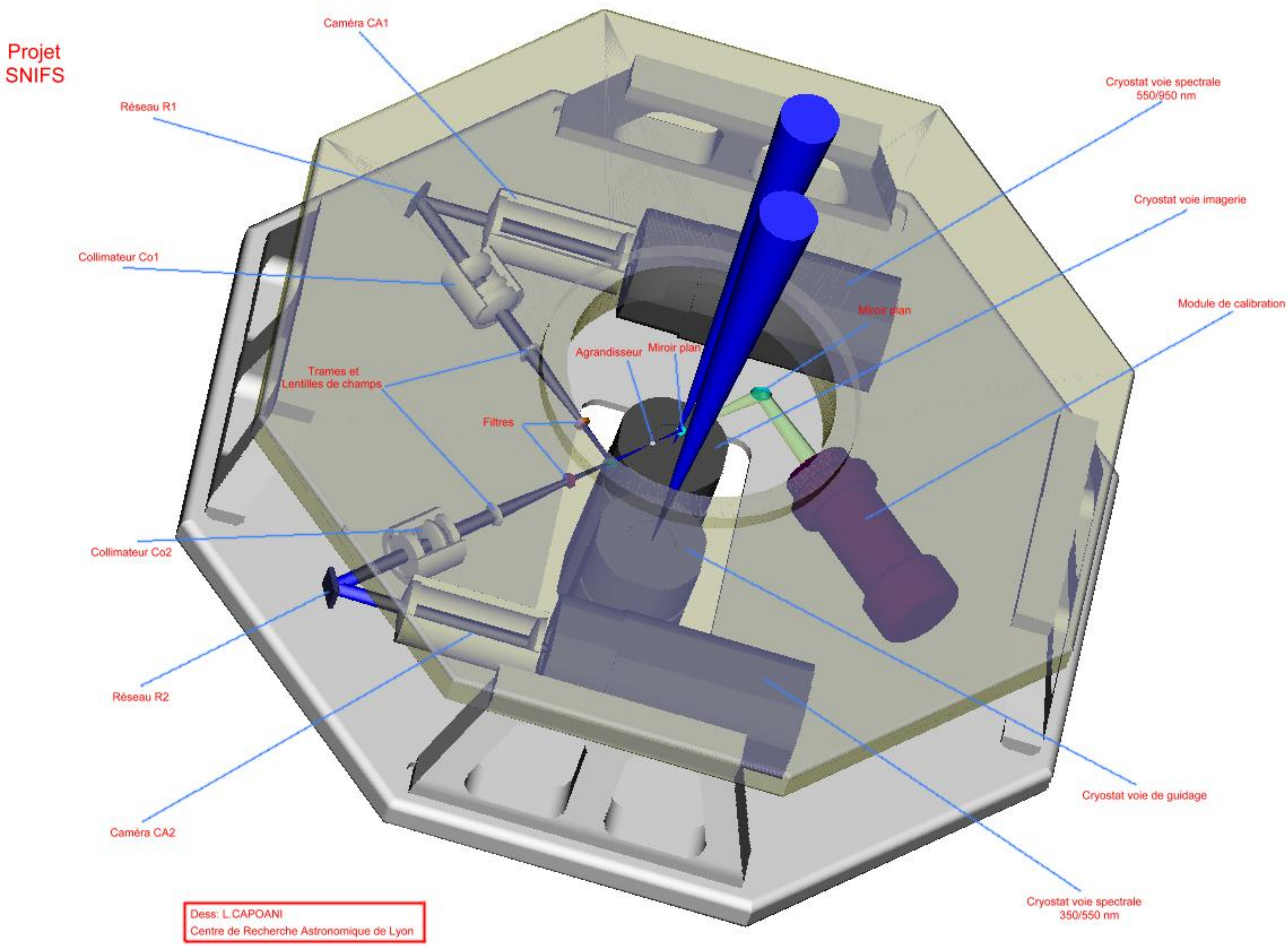

Fig. 3.— Mock-up of *SNIFS* spectrograph for UH 88-inch telescope. The on-axis f/10 beam from the telescope impinges on a total internal reflection pick-off prism which directs light into the two-channel spectrograph. The light is then split by a dichroic, sent through custom collimators, grism, camera, and CCD's for each of the two channels. Light from the surrounding area illuminates the photometry camera. An off-axis beam illuminates the guider camera at all times, allowing fast guiding during spectroscopy, and focusing or offsetting between exposures (i.e. during readout of the spectrograph and photometry detectors).