Flux Calibration for SN Cosmology

Greg Aldering

Physics Division

Lawrence Berkeley National Lab

DE+SN Sensitivity to Flux Calibration

- $\delta w/\delta\mu$ ~ 2-3
- Nominal 5 mmag μ systematic between low/high z

  → σ_w ~ 0.010 – 0.015 systematic
- Statistically matched by high-z samples with:
  - 600-900 SNe Ia w/ SALT2/Tripp standardization, or
  - ~200 twinned SNe Ia
- Importance highlighted in DOE's Cosmic Visions Small Projects Portfolio whitepaper (arXiv:1802.07216) :

  "Small-scale investments in calibration … could have a large payoff."

Flux Calibration Approaches

- DA white dwarf models
  - Exemplified by the HST+STIS CALSPEC system
    - WDs in local ISM bubble, so no dust
    - Transferred to 79 more stars, spanning -1 < V < 16 and many MK types
  - Idea extended to fainter magnitudes to support wide-field imaging surveys
    - More distant, so must deal with T_{eff}/extinction degeneracy
- Laboratory Referenced (aka Physical Calibration)
  - Reference to calibrated lamps/blackbodies
    - Exemplified by Oke & Schild 1970, Hayes 1985
  - Calibrated reference detector is the modern approach
    - SCALA, StarDICE, NIST Stars, LSST CBP ← SN cosmology folks!

Topics for this Talk

- Transfer of CALSPEC
  - 30 popular Hamuy/Oke spectrophotometric standards
  - w/ David Rubin and SNfactory

- Laboratory-referenced calibration
  - Supernova CALibration Apparatus (SCALA) + SuperNova Integral Field Spectrograph (SNIFS)
  - w/ Daniel Kusters, Marek Kowalski, Saul Perlmutter, Benni Bastian-Querner David Rubin

New SNfactory Flux Calibration

- Previous Flux Calibration in Buton++ 2013
  - Mix of CALSPEC and non-CALSPEC standards
  - Used physical atmosphere – Rayleigh, ozone, aerosols, H_2O
  - Simple wavelength-independent repeatability

- New Calibration
  - Transfer CALSPEC to other standards
  - Done with final results blinded – as for cosmology
  - Use hierarchical Bayesian model to inliers/outliers, measure repeatability, internal tension in CALSPEC, agnostically
  - Treat each wavelength independently
  - 497 photometric nights; median of 54 observation per star
  - 5 stars subsequently confirm or suspected of variability
    - HD 37225, HZ 21, BD+17 4708?, BD+28 4211?, BD+25 4655?
  - 5 stars have problematic, or potentially problematic, companions
    - HZ 43, P041C, Hiltner 600, BD+28 4211 , Feige 34

Blinded Flux Calibration

starflat

$$-2.5\log_{10}(S^{\rm mod}_{i,l}) = m_{j,l} + k_{n,l}\,{\rm X}_i + c_{n,l} + \Delta c_{t,l}(x_{i,l}, y_{i,l})$$

CALSPEC deviations

$$m_{j,l} = \begin{cases} -2.5\log_{10}(f^{\rm CALSPEC}_{j,l}) + \Delta m_{j,l} & \text{if CALSPEC,} \quad \Delta m_{j,l} \sim \mathcal{N}(0, \sigma_l^2) \\ -2.5\log_{10}(f_{j,l}) & \text{if secondary} \end{cases}$$

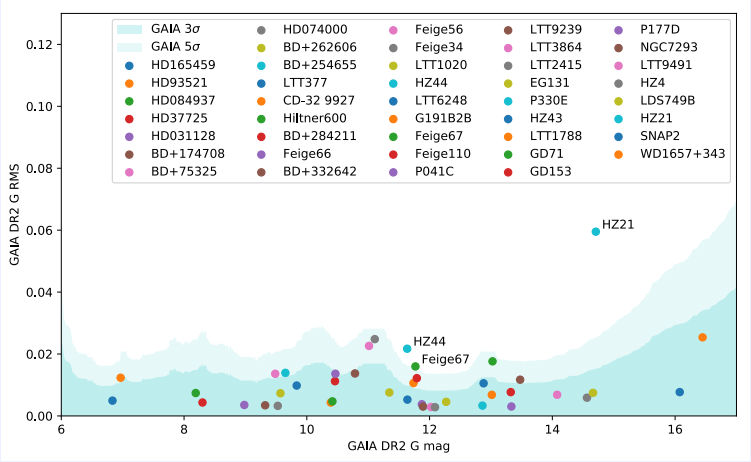
repeatability

$$-2.5\log_{10}(S^{\rm obs}_{i,l}) \sim (1 - f_{{\rm outl}\ t,l})\,\mathcal{N}\left(-2.5\log_{10}(S^{\rm mod}_{i,l}), \left[\frac{2.5\,\sigma_{S\,i,l}}{\ln(10)\,S_{i,l}}\right]^2 + \sigma^2_{{\rm in}\ t,l}\right) +$$

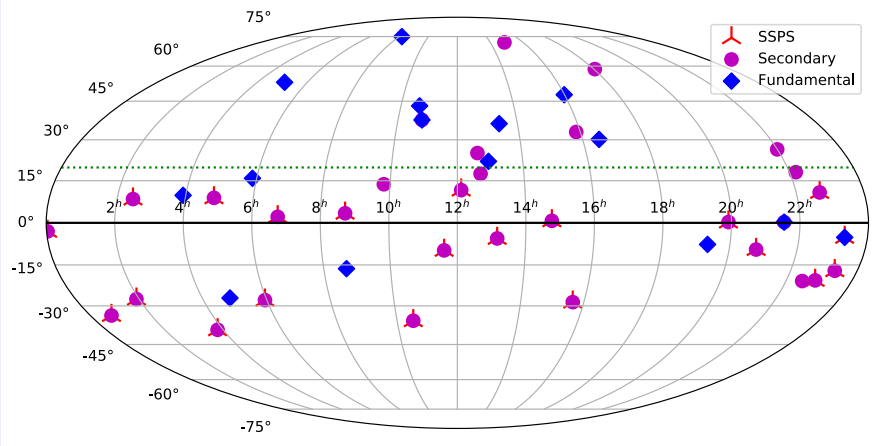
in/out fractions

$$f_{{\rm outl}\ t,l}\,\mathcal{N}\left(-2.5\log_{10}(S^{\rm mod}_{i,l}) + \Delta m_{{\rm outl}\ t,l}, \left[\frac{2.5\,\sigma_{f\,im}}{\ln(10)\,f_{im}}\right]^2 + \sigma^2_{{\rm outl}\ t,l}\right)$$

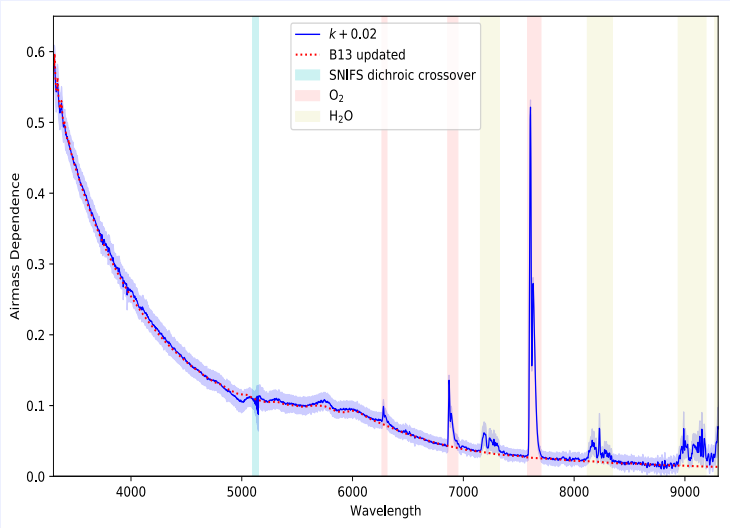
$$k_{n,l} \sim \mathcal{N}(k_{0\ l}, \sigma(k)^2_l)$$



Check for Variability using GAIA

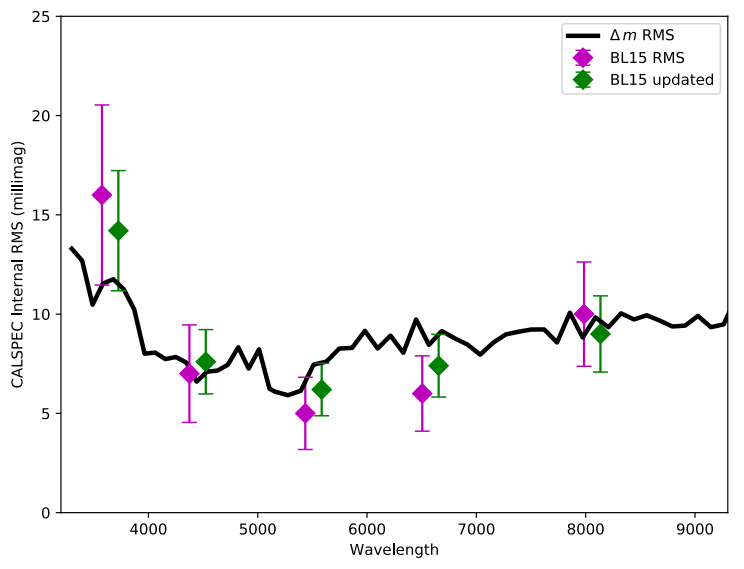


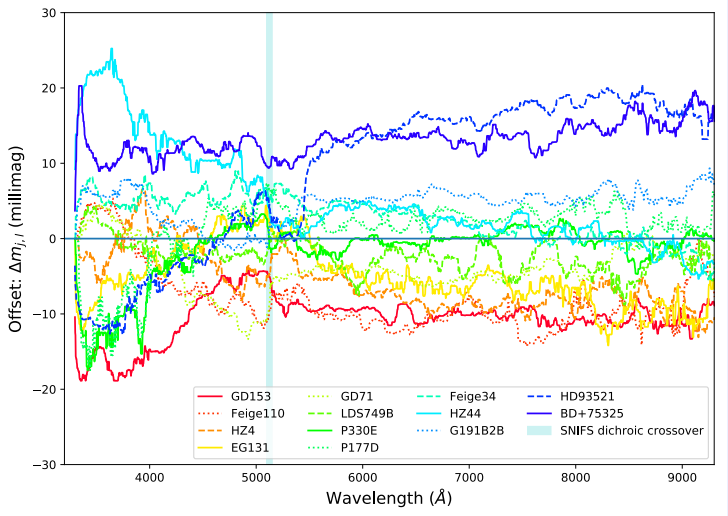
Distribution on the Sky



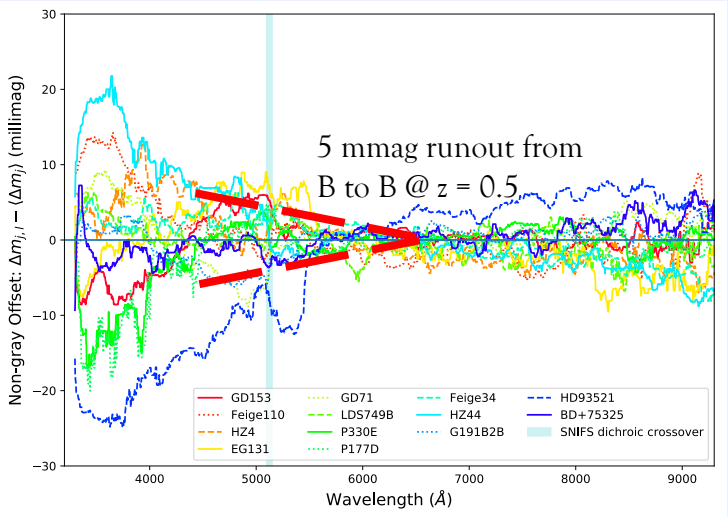
Atmosphere Recovered

Internal Tension in CALSPEC

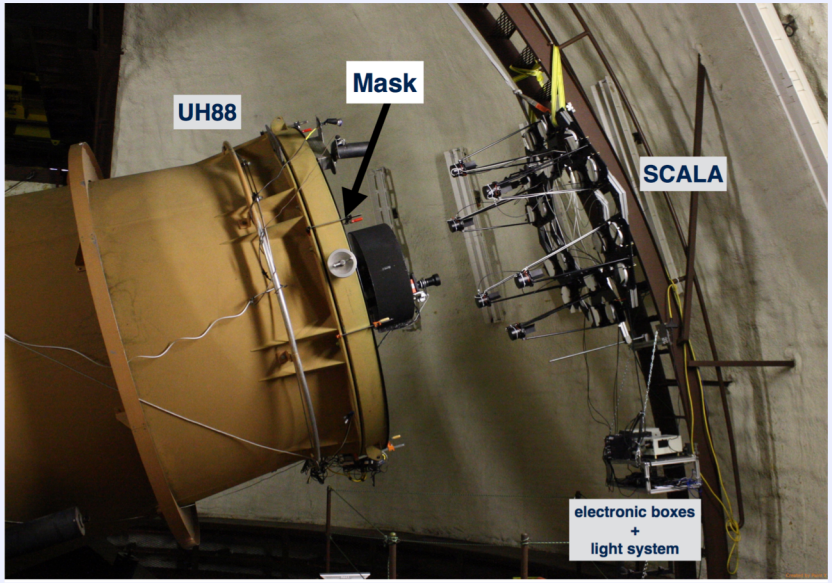




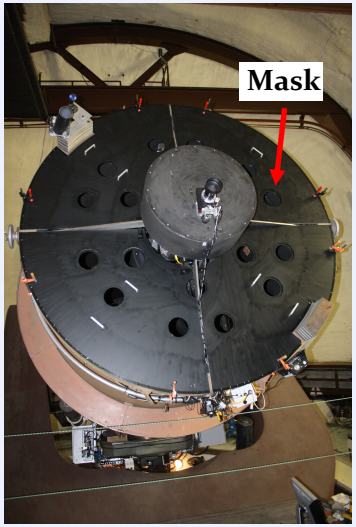
- RMS same as Bohlin & Landolt found
- Most of the scatter is grey
- A few stars have run-out in blue
- As/More likely to be in CALSPEC



Physical Calibration



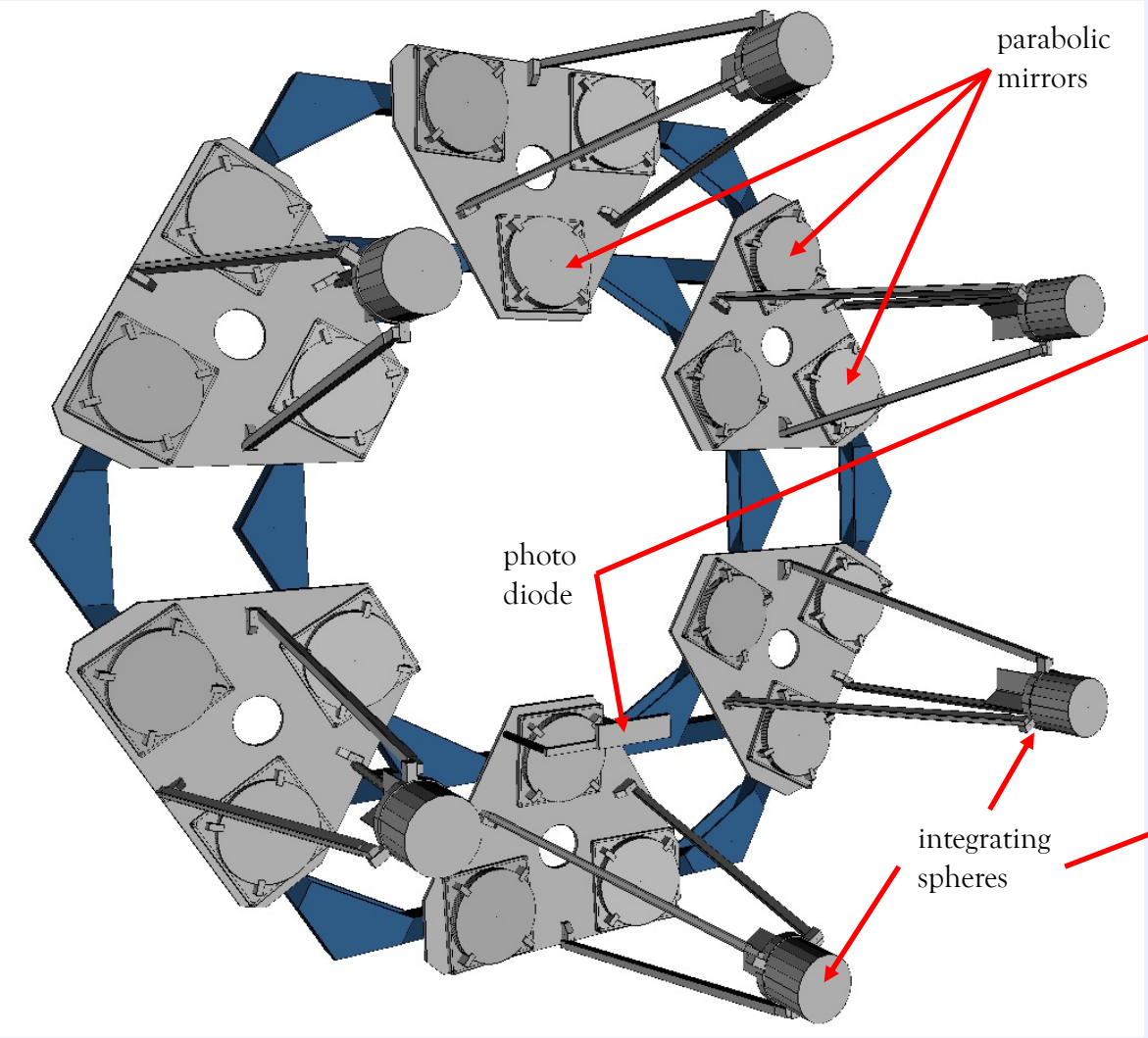
- SNIFS
  - 2.2-m telescope @ bent Cass port
  - on Maunakea – above most aerosols
  - IFU w/ 6.6 x 6.6 arcsec FoV
  - 320 – 1000 nm coverage
  - R ~ 500
  - Parallel imager (w/ pinhole grid filter)
  - Custom script to start SCALA light source and photodiode, open SNIFS shutter, close SNIFS shutter, stop SCALA, readout SNIFS

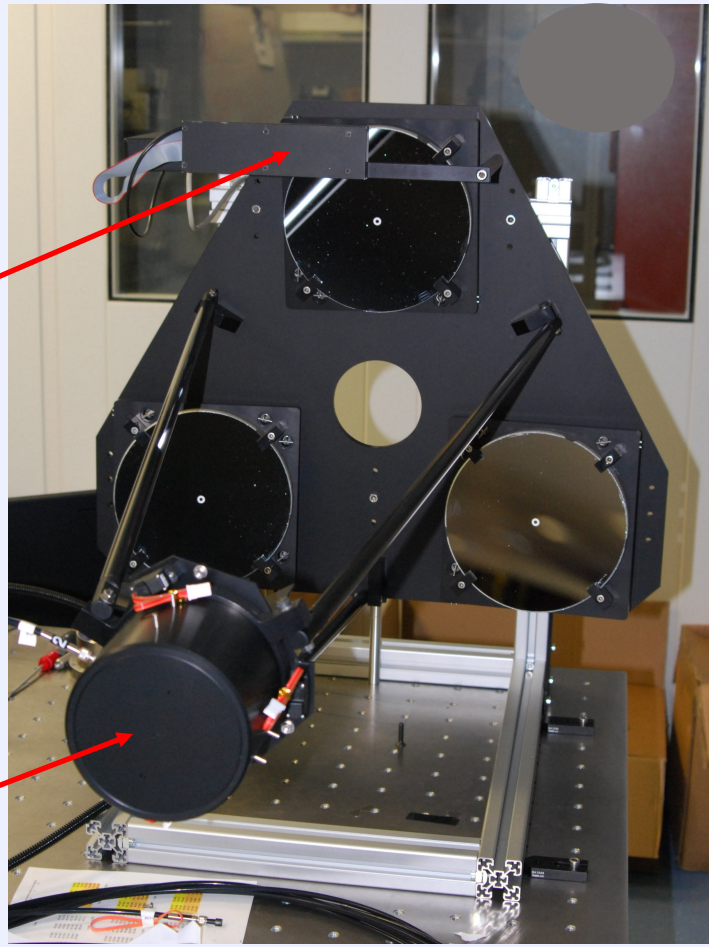


Lombardo++ 2017

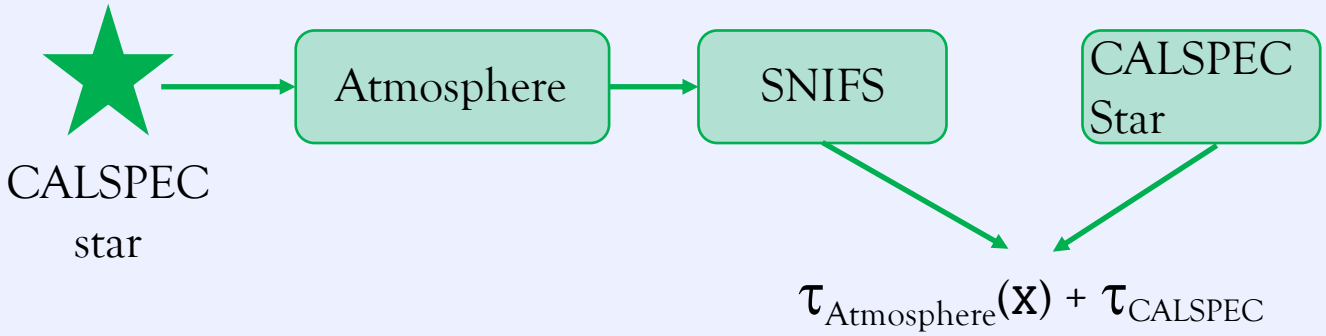
- SCALA
  - Tunable monochromator w/ ~3 nm bandpass
  - 6 integrating spheres – fed by optical fiber – w/ 3 output ports each
  - IS ports feed 18 parabolic mirrors pointed into telescope
  - 18 hole aperture mask at top of telescope aligns with SCALA beams
  - Artificial “planet” roughly 1 degree in diameter
  - CLAP photodiode (from LPNHE) inserted into 2 of the 18 beams
  - Dedicated PC for instrument control and data acquisition
  - Remotely operable, except for mask installation

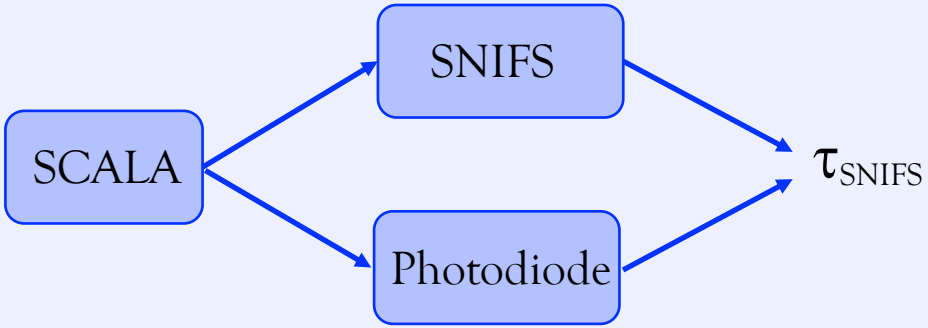
SCALA Structure & Optics





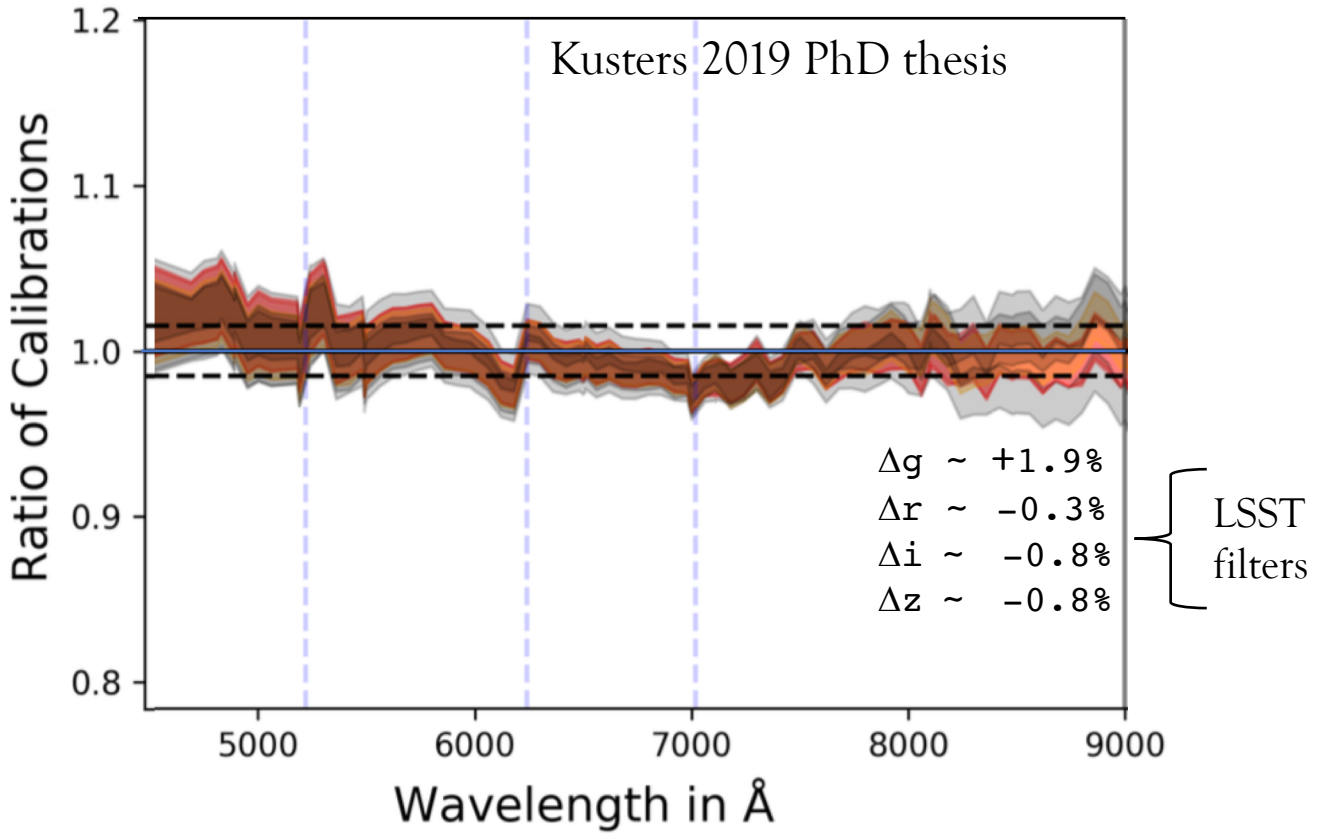
Measurement Principle





- Compare τ_{SNIFS} and $\tau_{CALSPEC}$
- Ultimately build hierarchical Bayesian model

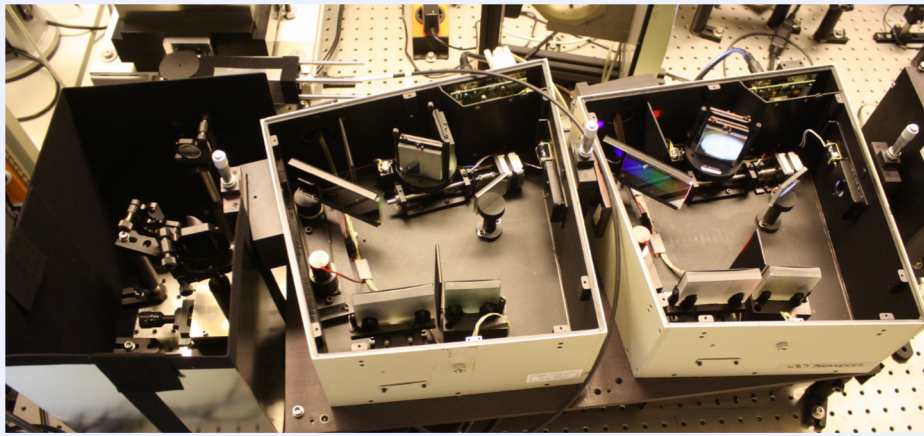
First Round Results Encouraging!



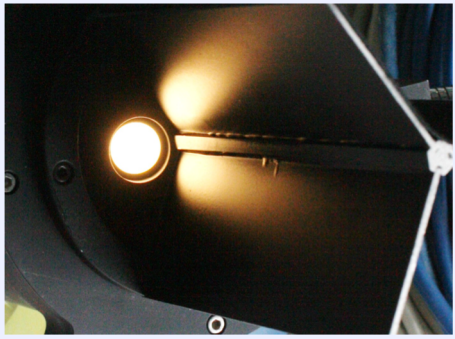
Already as good as older physical calibration
Sub-percent calibration is within reach with SCALA + SNIFS

Current Lab work

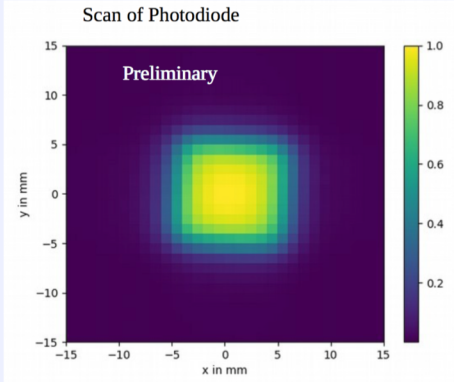
- Double-pass monochromator
  - suppresses out-of-band light by ~1000x
  - tested in lab – grating angle calibration, bandwidth, throughput



- Improve baffling against grazing incidence reflections



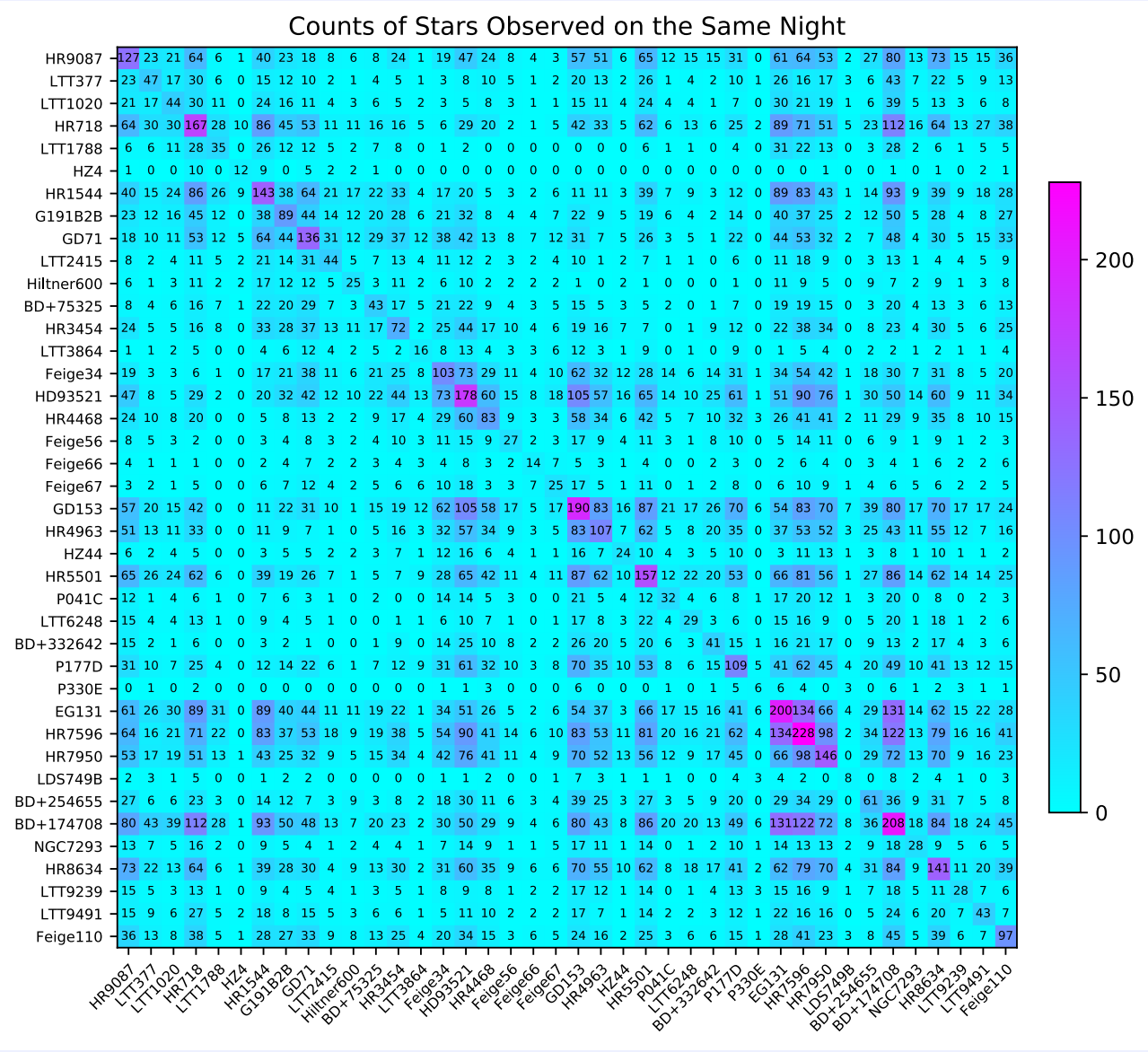
- Testing detectors for all 18 beams
  - Eliminates need for cross-beam calibration at summit
  - Linearity test bench done – 10^7 range
  - x, y, tilt stage to scan detectors and ensure normal incidence
  - Calibrate CMOS imagers (e.g. Zwo ASI)
    - Tests are well underway – linearity, dark current, amplifier glow, reciprocity, persistence
    - Could convert to pinhole camera when installed to examine light scattered by structure
  - Hamamatsu 10 x 10 mm photodiodes (S12915-1010R)



Next Steps

- Soon (Nov.):
  - Install double-pass monochromator in Hawaii
  - Calibrate the grating turrets to align wavelengths
  - Upgrade control software
- Next calibration (summer 2020):
  - Install new baffling
  - Add chopping shutter
  - Take new set of calibration data
  - Remove current photodiodes and recalibrate
  - Produce 2nd round of calibration
- Next iteration (2021) :
  - Recoat the 18 mirrors
  - Install detectors for all 18 beams
  - Produce 3rd round of calibration

Summary

- Successful transfer of CALSPEC optical flux calibration to 30 popular Hamuy and Oke spectrophotometric standards
- SCALA upgrades have potential for getting below nominal LSST 5 mmag calibration requirement
- With multiple efforts led by the SN Ia community, an *external* uncertainty on calibration can be determined

Standard Star Network