Yale Observing Proposal *Standard proposal* **Semester:** *2018B*
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A stellar velocity dispersion for a galaxy lacking dark matter

PI: Pieter van Dokkum **Status:** P **Affil.:** Yale University
Astronomy, P.O. Box 208101, New Haven, CT 06520-8101 U.S.A.
Email: pieter.vandokkum@yale.edu Phone: ____________ FAX: 203-432-5048

CoI: Shany Danieli **Status:** T **Affil.:** Yale University
CoI: Dhruba Dutta Chowdhury **Status:** T **Affil.:** Yale University
CoI: Yotam Cohen **Status:** G **Affil.:** Yale University
CoI: Lamiya Mowla **Status:** G **Affil.:** Yale University

Abstract of Scientific Justification *(will be made publicly available for accepted proposals)*:
We recently discovered a galaxy that is seemingly devoid of dark matter: its dark matter halo is a factor of $\gtrsim 400$ less massive than expected from the standard stellar mass – halo mass relation. The dark matter constraint comes from the radial velocities of ten very luminous globular clusters that appear to be associated with the galaxy: the 10 velocities have a range of only $\sigma_{\rm gc} < 10.5\,{\rm km/s}$. The main uncertainty is that the kinematics of the globular cluster system might be different from that of the rest of the galaxy. Furthermore, due to the small number of clusters we only have an upper limit, not an actual measurement, of the kinematics. Here we propose to use KCWI in its high resolution mode to measure the *stellar* velocity dispersion of the galaxy. The expectation from galaxies of similar luminosity in the Local Group is that $\sigma_{\rm stars} \approx 32\,{\rm km/s}$, whereas we will measure $\sigma_{\rm stars} \approx 8\,{\rm km/s}$ if the galaxy has no dark matter. *Keck+KCWI is the only instrument in the world that can perform this crucial test.* In addition to the kinematics of the smooth galaxy light, we will measure the internal kinematics of two of the luminous globular clusters from the same data. The globular clusters are almost as luminous as ω Centauri, and we will determine whether they are almost as massive as well.

Summary of observing runs requested for this project

Run	Telescope	Instrument	No. Nights	Min. Nights	Moon	Optimal months	Accept. months
1	Keck II	KCWI	3	2	dark/grey	Dec-Jan (if grey)	
2							
3							
4							
5							

Scheduling constraints and non-usable dates *(up to four lines).*

This program can be executed in the dark halfs of grey nights; specifically, 4–6 dark-early grey half-nights in the latter part of the semester would be more efficient than 2–3 full nights. We verified with Keck that it could be combined with the other Keck II program of the PI, which asks for bright time for a target field that is up in the second half of the night.

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

Background: We have developed a telescope, the Dragonfly Telephoto Array, which is optimized for the detection of low surface brightness emission. As part of Allison Merritt's thesis, we imaged a number of nearby galaxies with Dragonfly in 2015 – 2016. Allison focused on the stellar halos of the galaxies, but we also found a large number of low surface brightness "blobs" in these fields. Many of these are previously unstudied dwarf galaxies associated with the primary targets, and some are giant "ultra diffuse" background objects. In Cycle 24 we were awarded HST time to image 23 of these Dragonfly discoveries, to determine distances and other properties (Cohen et al., in prep).

Discovery of an apparently "baryonic galaxy": One of the most interesting object among the 23 is NGC 1052-DF2 (see Fig. 1), in the field of the giant elliptical NGC 1052 at a distance of 20 Mpc. The galaxy is very large, with a half-light radius of 2.2 kpc, and it has an enigmatic population of very bright globular clusters. Their luminosities, sizes, ages, metallicities, and axis ratios are similar to Ω Centauri, the largest and most massive globular cluster in the Milky Way. In 2016 we obtained LRIS and DEIMOS spectra of these clusters and found that they all have a radial velocity of $\approx$ 1800 km/s, with very little variation. The observed velocity spread of $\sigma_{\rm obs} = 8.5$ km/s is consistent with the observational errors, and we derive a 90 % upper limit on the intrinsic dispersion of $\sigma_{\rm gc} < 10.5$ km/s. (see Fig. 2, 3).

This value is consistent with that expected from the stars alone: the expected dispersion from its stellar mass ($M_{\rm stars} \approx 2 \times 10^8\,{\rm M}_\odot$) is ≈ 8 km/s. If the galaxy had a normal dark matter halo for its stellar mass, the dispersion would be ≈ 32 km/s. We conclude that this is a galaxy without dark matter. The upper limit to its halo mass is $M_{\rm halo} < 1.5 \times 10^8\,{\rm M}_\odot$, a factor of ~ 400 lower than the halo mass of $\approx 6 \times 10^{10}\,{\rm M}_\odot$ that is expected from the canonical stellar mass – halo mass relation (e.g., Behroozi et al. 2013). The results are described in two papers, one in Nature (on the dark matter) and one in ApJ Letters (on the unusual population of luminous globular clusters).[1]

How secure is this measurement? The results have wide-ranging implications for the formation of galaxies and globular clusters, and even for the nature of dark matter: the finding that dark matter is separable from baryonic matter on galaxy scales demonstrates that it is a material substance, ruling out alternatives such as MOND (Milgrom 1983) and emergent gravity (Verlinde 2016). Given these implications we have to carefully consider the assumptions. These are that 1) the globular clusters are associated with the galaxy; 2) the globular clusters are in equilibrium in the galaxy potential; and 3) the velocity anisotropy is small (that is, they are not in a face-on disk). Furthermore, because of the small sample size (the galaxy only has 10 clusters) we only have an upper limit, and not an actual measurement of the velocity dispersion.

This proposal: We propose to address all these issues by measuring the *stellar* kinematics of NGC 1052-DF2, using KCWI. KCWI is optimized for low surface brightness, high spectral resolution spectroscopy – which is exactly what is needed. The medium slicer has a field of $16.5'' \times 20''$, enabling us to integrate the light from the entire area where the galaxy has $\mu \lesssim 24.5\,{\rm mag\,arcsec^{-2}}$ (Fig. 4). The BH2 grating gives a spectral resolution of $\sigma_{\rm instr} \approx 10$ km/s, sufficient for measuring dispersions down to $\sigma_{\rm stars} \sim 7$ km/s. As detailed in the Technical Description, we will also obtain the internal kinematics of two of the bright globular clusters "for free". We will: 1) determine whether the systematic velocity of the galaxy is 1803 km/s, the mean velocity of the globular clusters; 2) determine whether the galaxy has a stellar dispersion of ≈ 30 km/s or ≈ 8 km/s; and 3) determine whether the enigmatic globular clusters are not only bright but also massive.

[1] They will both appear on astro-ph on March 29, the publication date of the Nature paper. We have made the papers available for the TAC at http://www.astro.yale.edu/dokkum/papers/

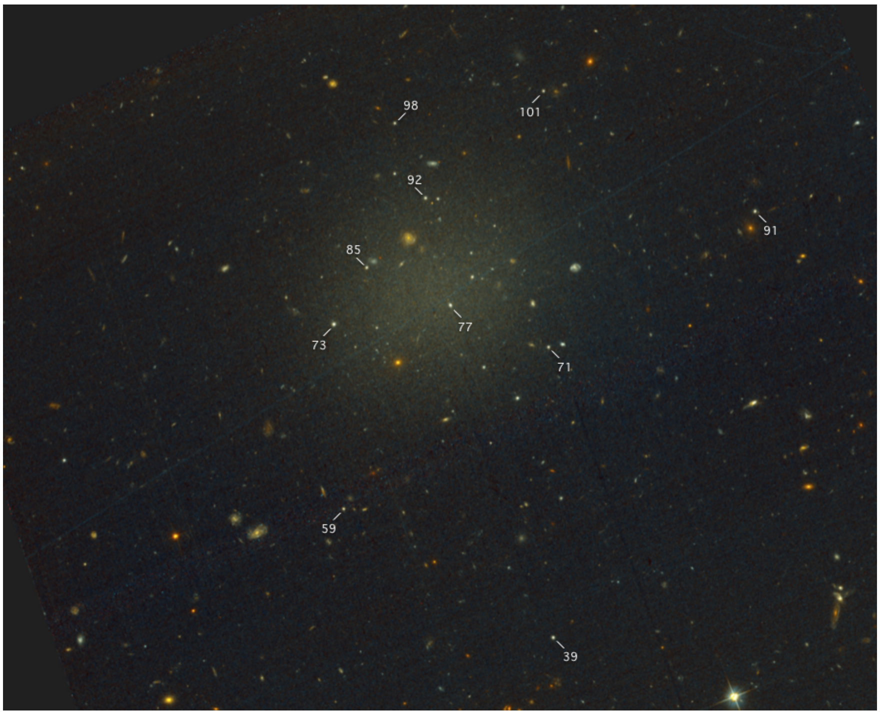

Figure 1: Two-color HST/ACS image of the galaxy NGC 1052-DF2. It is a smooth "blob" with a half-light radius of 2.2 kpc and a central surface brightness of $\mu_V(0) \approx 24.4\,\mathrm{mag\,arcsec}^{-2}$. Globular clusters with Keck LRIS and DEIMOS spectroscopy are marked. From van Dokkum et al. (2018ab); Cohen et al. (in prep).

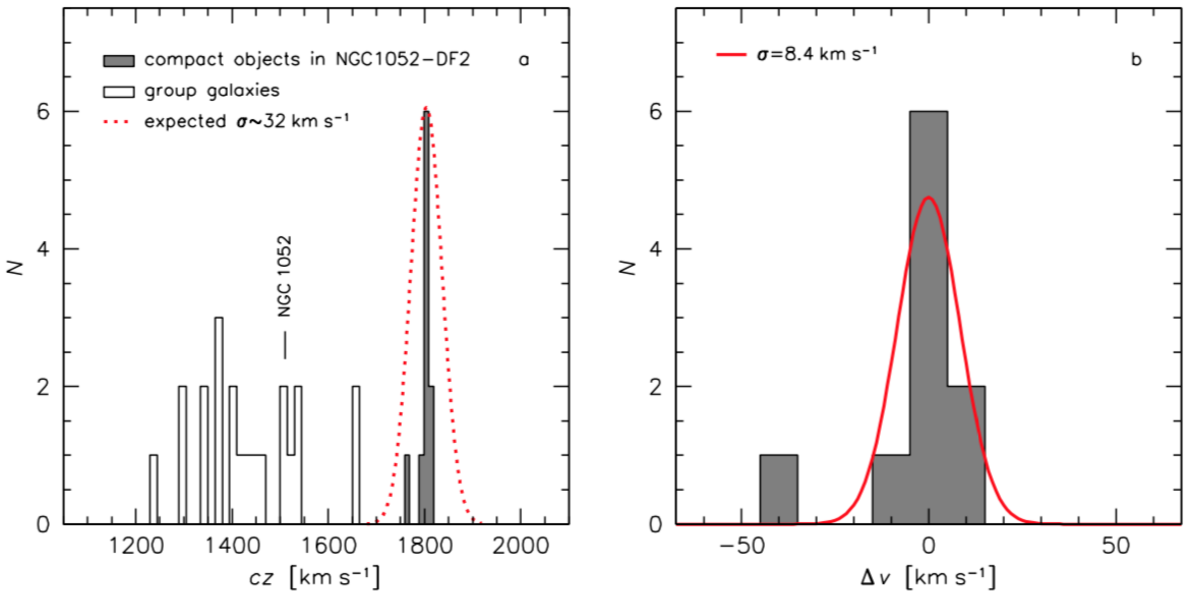

Figure 2: Left: velocities of the globular clusters, along with known members of the NGC 1052 group. The broken red curve indicates the expected velocity spread if the galaxy had a normal amount of dark matter. Right: zoom in on the velocity histogram of the clusters with respect to the mean (1803 km/s). The solid red curve shows the best-fitting observed dispersion of 8.5 km/s. The observed dispersion is consistent with the measurement errors; the 90 % upper limit to the intrinsic dispersion is $\sigma_{\rm gc} < 10.5$ km/s.

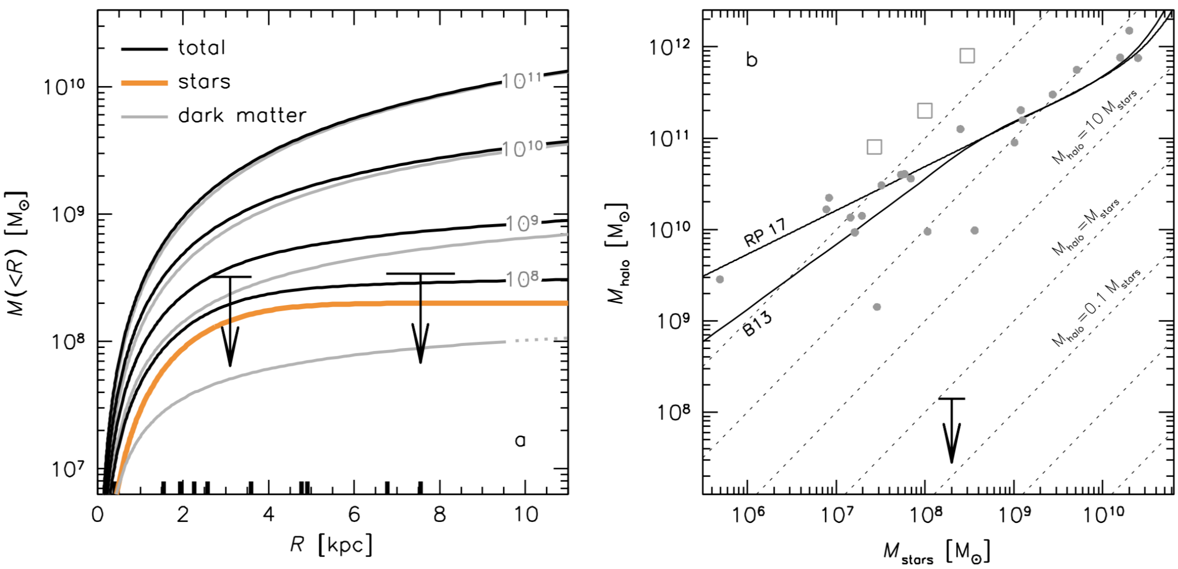

Figure 3: Constraints on the halo mass of NGC 1052-DF2, assuming that the kinematics of the globular clusters are representative of the galaxy. Left: radial mass profile. The upper limits are consistent with the mass in the stars alone (orange line), leaving little room for dark matter. Right: upper limit on the halo mass, compared to canonial stellar mass – halo mass relations (lines). From van Dokkum et al., Nature, in press.

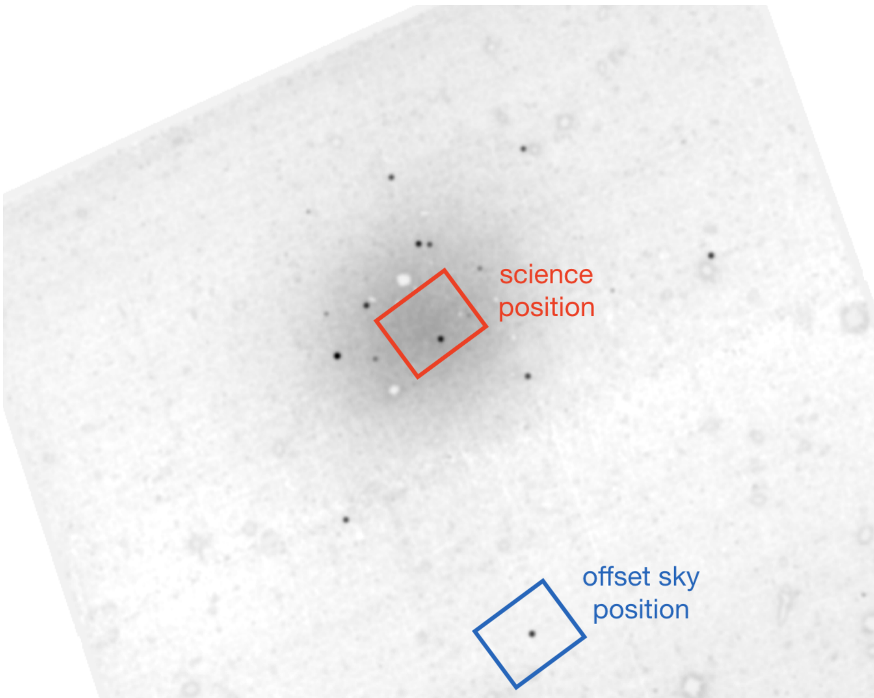

Figure 4: Planned KCWI pointings, on a version of Fig. 1 that just shows the smooth emission and the globular clusters. The science pointing will cover the entire region where the surface brightness is $\lesssim 24.5\,\mathrm{mag\,arcsec^{-2}}$. Every 45 minutes we will obtain an offset exposure in an empty field to facilitate sky subtraction. The science position and the offset sky position both cover a luminous globular cluster, so we can measure the internal kinematics of two of these enigmatic objects “for free”.

Impact to Yale Astronomy *Describe how this program fits into the Yale astronomy program. Will the data analysis and resulting papers be based at Yale? If the project is led by a faculty member, does the project involve students? What is the role of the PI viz-a-viz other non-Yale co-Is. Are the resources in place to analyze the data and come to a timely publication? (limit text to one page)*

The work is firmly rooted at Yale. It builds on the Dragonfly Nearby Galaxy Survey, which was Allison Merritt's thesis, a follow-up HST program (PI: van Dokkum), and three Yale-led papers (one in Nature) that are based on this HST program plus Yale Keck time. The analysis will be led by some combination of the PI and graduate students Shany Danieli and Dhruba Chowdhury. We have all the resources in place for timely analysis and publication: during the last KCWI run in February, we reduced the data and obtained extracted spectra *during each night.*

Previous Use of Yale Facilities and Publications *Please list previous use of Yale observing facilities and any publications resulting from these data in the past 3 years. If this is a long term project, please state this here and describe the overall strategy of the project.*

An overview of Keck time allocated to the PI in the six previous semesters is given below.

• 2015B: 2 OSIRIS nights, December 2015. Weathered out. Also 2 NIRES nights in January 2016, which we converted to DEIMOS nights as NIRES was not available. These DEIMOS nights were combined with the 4 nights from 2016A, for a deep study of the ultra diffuse galaxies Dragonfly 44 and DFX1 in the Coma cluster.

• 2016A: 4 DEIMOS nights (partially shared with Marla Geha) for Dragonfly 44 and DFX1. The combination of the 2015B and 2016A DEIMOS time yielded spectra with a depth of 33.5 hrs for both galaxies. The velocity dispersions derived from these spectra are published in two ApJ Letters: van Dokkum et al. 2016, ApJ, 828, L6, and van Dokkum et al. 2017, ApJ, 844, L11.

• 2016B: 3 DEIMOS nights. Partly weathered out, but several hours on candidate globular clusters in NGC 1052-DF2. Also 3 LRIS nights; these were allocated as OSIRIS nights but OSIRIS was taken off the telescope due to its failure. Partly weathered out; we took more data on the globular clusters. The combined LRIS+DEIMOS dataset led to the two papers that are the basis of the present proposal: one accepted to Nature, the other an ApJ Letter. Both will be on astro-ph on March 28, and are available at http://www.astro.yale.edu/dokkum/papers/

• 2017A: 2 LRIS nights, to study the stellar populations of three Coma UDGs. Weathered out. Also 3 NIRSPEC nights, in February 2017. These were as successful as is possible with NIRSPEC: we obtained spectra for paired high redshift galaxies for Lamiya Mowla's thesis. We expect that these data will be combined with NIRES spectra that we are proposing for in another 2018B proposal.

• 2017B: 2 KCWI nights, in January 2018, to begin studying the radial dispersion profile of Dragonfly 44. We had asked for 10 nights over two semesters. Largely weathered out, unfortunately. The 2.5 hrs we did get will be added to the 2018A time from Yale, Caltech, and UC (see below).

• 2018A: 2 KCWI nights (as 4 half-nights) in February 2018, to continue the study of the radial dispersion profile of Dragonfly 44. Three of the 4 half-nights were good; we added 9 hrs to the on-source exposure time. This will be added to the 2018A time from Caltech and UC. The Caltech time was also largely weather out; the UC time is scheduled for April 2018. Also 1 LRIS night, for April 2018, to measure distances of "blobs" discovered with Dragonfly.

Observing Run Details for Run :

Technical Description *Describe the observations to be made during the requested observing run. Justify the specific telescopes, the number of nights, the instrument, and the lunar phase. List objects, coordinates, and magnitudes (or surface brightness, if appropriate) in the Target Tables section.* **For Keck proposals only:** *Please include below whether your proposal can be implemented on a different instrument and describe what the resulting impact to your program. This information will not be used unless a program will not otherwise be awarded time on the primary instrument requested.*

KCWI is a new instrument and it has not yet been fully characterized. We therefore scale the required resolution and integration time from the KCWI data that we obtained on the galaxy Dragonfly 44 in the Coma cluster. NGC 1052-DF2 has the same central surface brightness and (presumably) a similar age and metallicity. In contrast to Dragonfly 44 it covers the entire IFU; Dragonfly 44 covers only $\sim 1/3$. NGC 1052-DF2 has an expected dispersion of ≈ 8 km/s, compared to a measured dispersion of ≈ 45 km/s for Dragonfly 44.

Instrumental setup: For Dragonfly 44 we used the medium resolution BM grating, the medium slicer, and 2×2 on-chip binning. This combination gives a spectral resolution $\sigma_{\rm instr} = 22$ km/s, a field size of $16.5'' \times 20''$, and exposures of $\gtrsim 20$ minutes are required to be sky-dominated (rather than read noise dominated). For NGC 1052-DF2 we need higher spectral resolution as the expected velocity dispersion is lower. We will therefore use the BH2 grating, which has a spectral resolution that is $9000/4000 = 2.25\times$ higher than the BM grating. Scaling from the measured resolution with the BM grating the spectral resolution will be $\sigma_{\rm instr} \approx 10$ km/s, sufficient to measure dispersions down to $\sim \sigma_{\rm instr}/\sqrt{2} \sim 7$ km/s. The minimum exposure time to be sky-dominated is ≈ 45 minutes with this setup, which is just feasible. An alternative setup that gives roughly the same spectral resolution is the (slightly more sensitive) BM grating in combination with the small slicer, but for that setup 1×1 binning is required to properly sample the spectral resolution. With that binning we would be read-noise dominated for all reasonable integration times, greatly reducing the S/N that we would obtain.

Observing strategy: As shown in Fig. 4 the galaxy is larger than the KCWI field, which means that offset exposures are required to do a proper sky subtraction. (We used the same technique for Dragonfly 44, even though that galaxy is smaller than NGC 1052-DF2). These blank field exposures do not have to be completely empty, as any objects in the field can simply be masked before extracting the sky spectrum from the rest of the field. We will use this aspect to obtain a spectrum of an additional globular cluster (along with one that we can cover in the science field), as shown in Fig. 4. These globular clusters are remarkably bright, and their inferred velocity dispersions are $\gtrsim 15$ km/s – larger than that of the galaxy! We plan to observe the sky field with identical exposure times as the primary field (45 min). We will not use nod-and-shuffle, as this is not really required in the blue and would reduce the spectral coverage by a factor of ~ 3.

Required exposure time: To measure a stellar velocity dispersion a S/N ratio of $\gtrsim 15$ per resolution element is required (see, e.g., van Dokkum et al. 2016). We obtained this with KCWI in 3 hrs of on-source time for Dragonfly 44, with a nearly noise-less sky spectrum; this produced a velocity dispersion with a 15 % error. Scaling from this result, we require 3 hrs $\times R \times S^{-1} \times T^{-1} \times I \times 2$, with $R = 2.25$ the difference in spectral resolution between the NGC 1052-DF2 and the Dragonfly 44 data, $S \approx 3$ the difference in spatial extent, $T = 0.5$ the fraction of time spent on the science field, $I = 1.2$ instrument overheads, and the final factor of 2 due to the noise in the sky spectrum. The required exposure time is ≈ 11 hrs, or 2 nights.

Scheduling; grey nights: The observations need to be taken in dark time: this is low surface brightness work in the blue, and even a quarter moon is going to make this impossible. Yale has no dark nights on Keck II in its suggested 2018B allocation, but we can use the dark portions of grey nights. Specifically, we verified that KCWI and NIRES can be scheduled in the same night. The PI has a second Keck II proposal for NIRES, and as it happens the target field for that proposal becomes available just when NGC 1052-DF2 is setting. As an example, dates around 28 December have a 50 % moon and yet both this program and the NIRES program could be done under near-ideal conditions (if both were granted $3-6$ half nights instead of $1.5-3$ full nights).

Other instrument option: There is no other instrument that can do this measurement. Even if LRIS or DEIMOS could match the spectral resolution, KCWI is a factor of $15-20$ more efficient due to the huge gain offered by the $16.5'' \times 20''$ "light bucket".

R.A. range of principal targets (hours): One target, with RA $= 2^{\mathrm{h}}41^{\mathrm{m}}$

Dec. range of principal targets (degrees): One target, with DEC $= -8$ degrees.

Instrument Configuration

Filters:
Grating/grism: BH2
Order: 1
Cross disperser:

Slit: medium slicer
Multislit:
λ_{start}:
λ_{end}:

Fiber cable:
Corrector:
Collimator:
Atmos. disp. corr.:

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