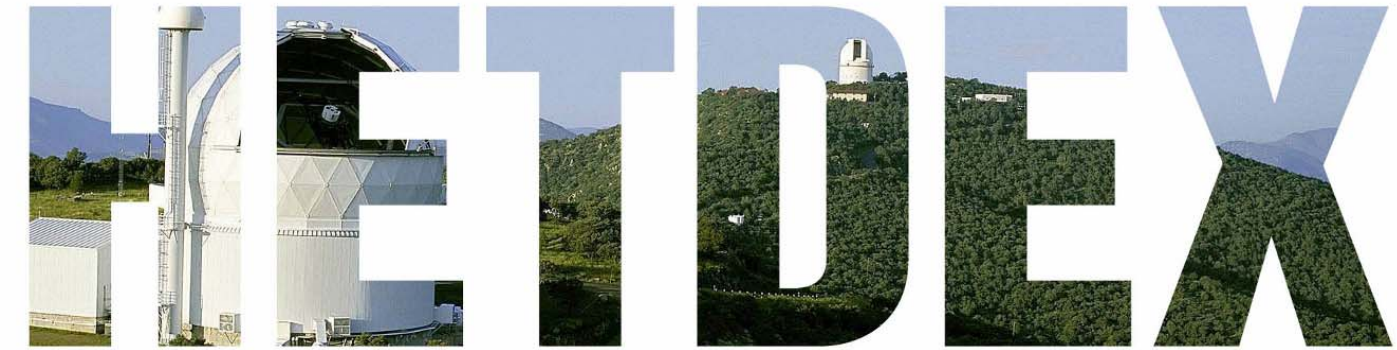

The Hobby-Eberly Telescope Dark Energy Experiment

McDONALD OBSERVATORY
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HET

MPE

PENNSTATE
1855

LMU
USM

AIP

A&M

Overview

- Two observational approaches to make progress on DE
  - Get the tightest possible constraints at low redshift where effect of DE is stronger
  - Go to higher redshift where we can measure the evolution or verify that w(z) = -1
  - Both approaches are needed
- Almost all projects are focused at z<1.5
  - Due to obvious observational constraints
- Spectroscopic BAO at high redshift
  - One method to measure H(z) directly as well as $D_A(z)$
  - Only method that can be applied at z>2
  - Method with smallest systematic worries (particularly at z>1.5)
- Aims of HETDEX
  - Measure the expansion rate to percent accuracy at z>2
  - Provide a direct constraint on the density of DE at z>2
  - Provide the best measure of curvature

Measuring Dark Energy Evolution

Dark energy, or its equation of state w(z), is mathematically well defined. It enters into the cosmological equations as:

$$H(z) = h\sqrt{\Omega_m(1+z)^3 + \Omega_X \exp\left[3\int_0^z \frac{1+w(z')}{1+z'}dz'\right] + \Omega_k(1+z)^2}$$

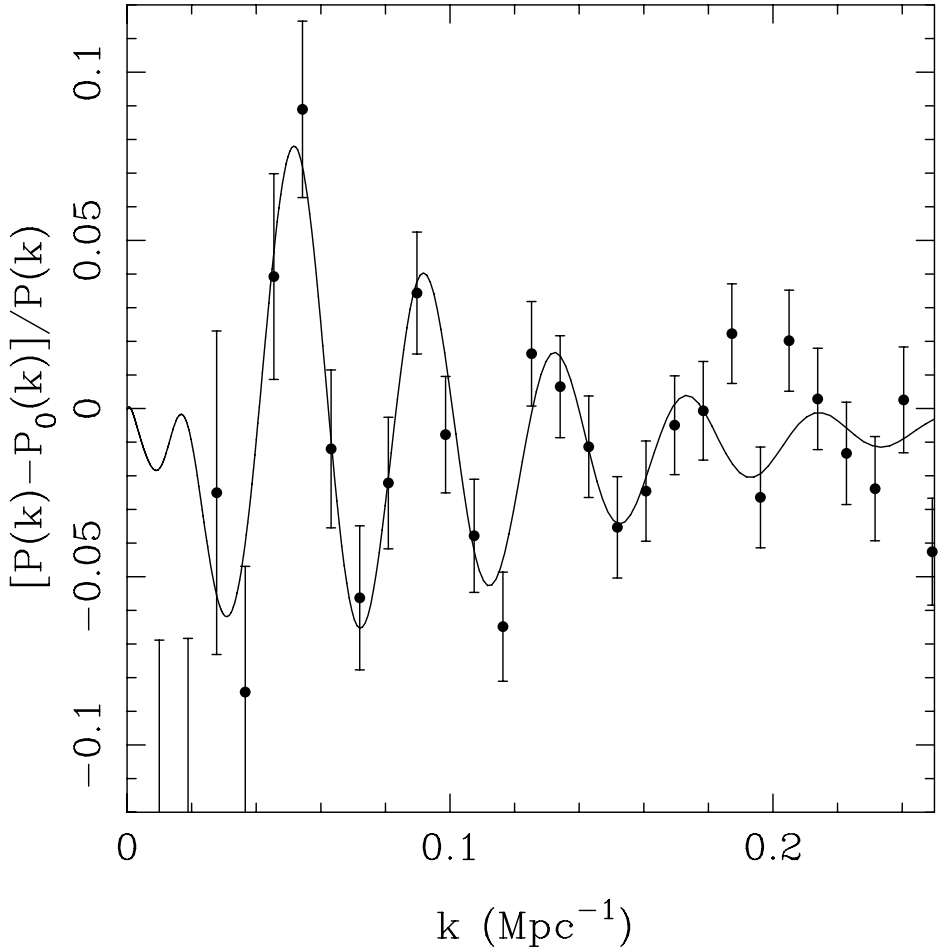
Expansion rate | **Matter term** | **Dark Energy term and w represents history** | **Curvature term**

- With priors on $\Omega_M h^2$ from Planck and 3% on Ho we can achieve
  - σ_H/H ~ 1% at z~3 to directly detect w=-1 constant DE at 3-σ
- D_A(z=1089) will be constrained to sub-% accuracy by Planck
  - σ_{D_A}/D_A ~ 1% at z~3 to measure curvature to 0.2% (e.g. Knox 2006)

HETDEX Approach

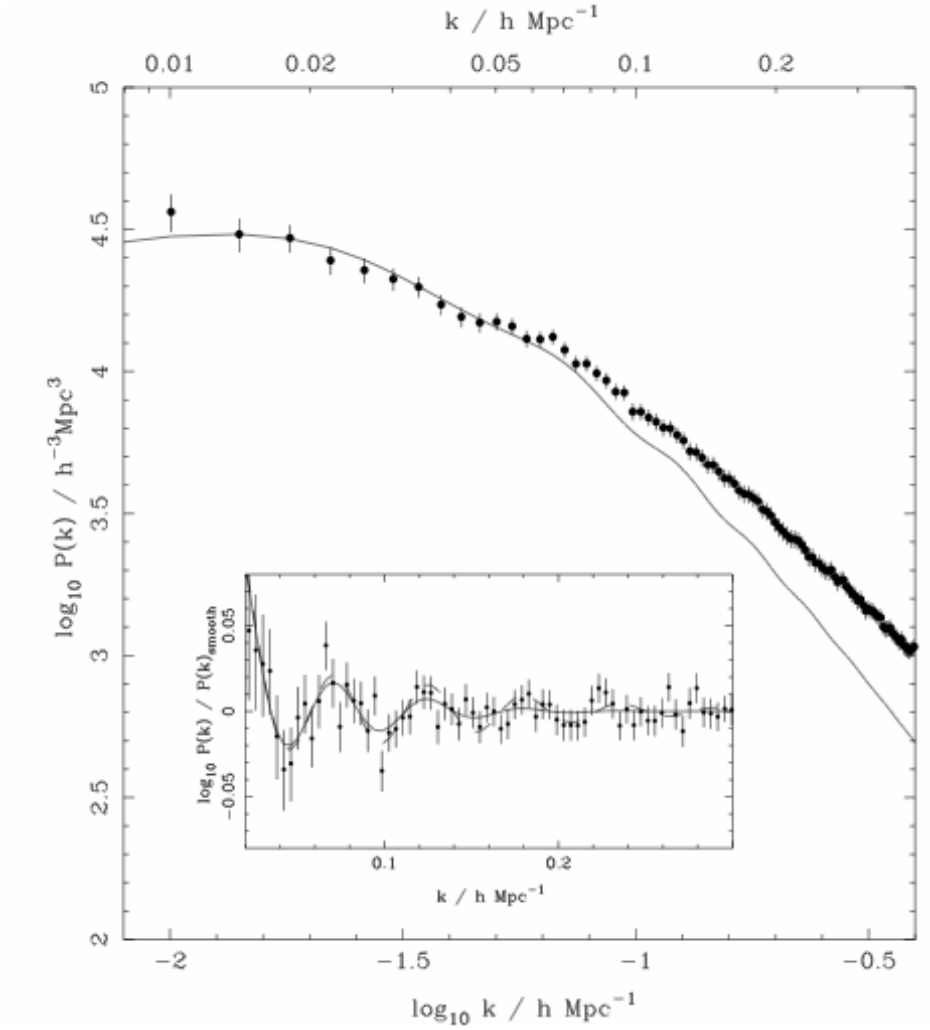
- Survey duration 3 calendar years
- 1 million tracers in 8 cubic Gpc volume
  - Total survey area 400 sq. degrees with redshift range $1.9 < z < 3.8$
  - goal 1.5 million in 650 sq. deg
- Constraints (3 year)
  - H to 1.5-2%, D_A to 1-1.5%
  - Depending on tracer bias
- Ly-α emitting galaxies
  - Numerous
  - Easily detected with integral field spectrograph
- 145 integral field spectrographs, known as VIRUS
  - 42,000 spectra per exposure

Realization of HETDEX



Non-linear evolution

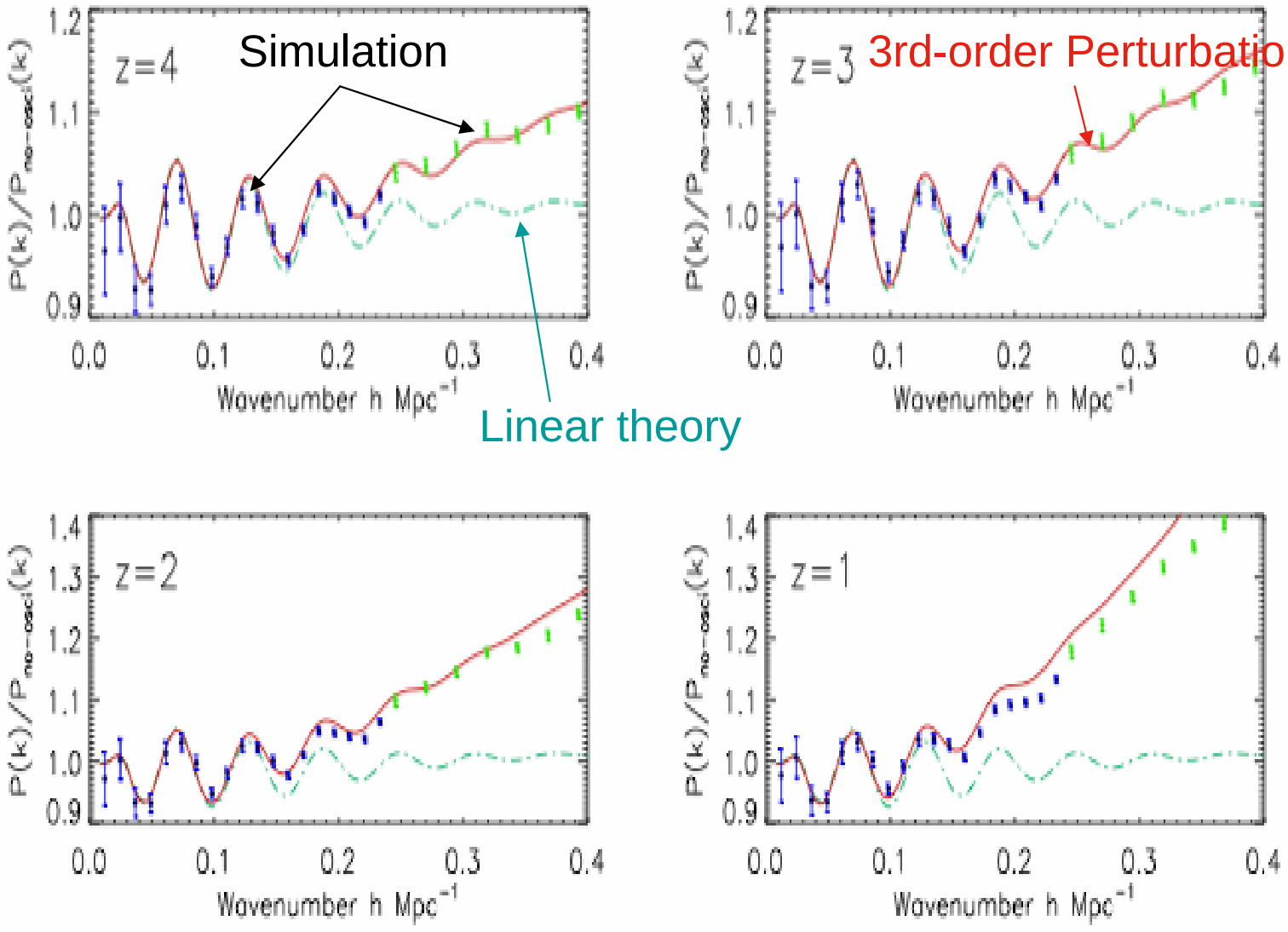
- Evolution of clustering reduces the contrast of higher order BAO peaks in the PS
  - Non-linear evolution of matter clustering
  - Non-linear bias
    - Non-linearity in the way that galaxies trace matter
  - Non-linear redshift space distortion
    - Non-linearity in the peculiar velocity along the line of sight
    - Kaiser effect
    - Finger-of-God effect
- All these are being considered in analysis for HETDEX
  - Bottom line: at z>2 none of these effects will compromise our ability to recover the BAO information
  - Analyses by Eiichiro Komatsu and collaborators



SDSS DR5+LRG Percival et al. (2006)

Non-linearity in BAOs

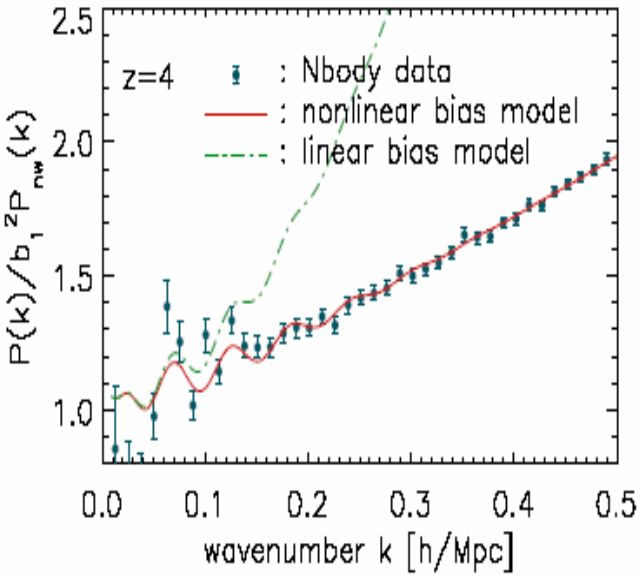
(Jeong & Komatsu, 2006)

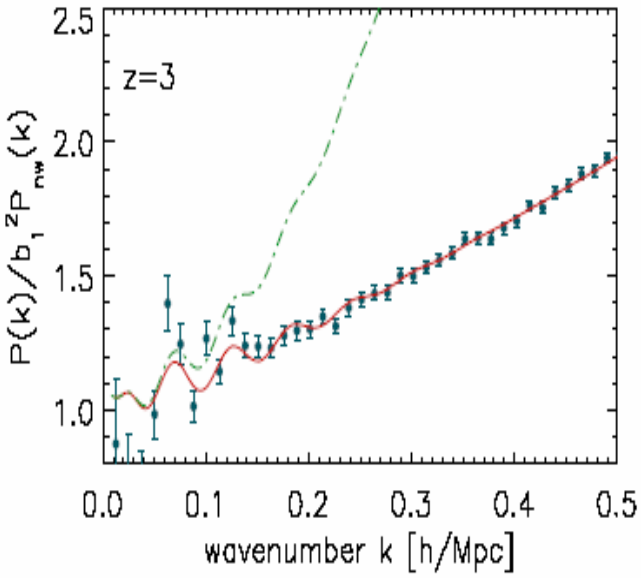


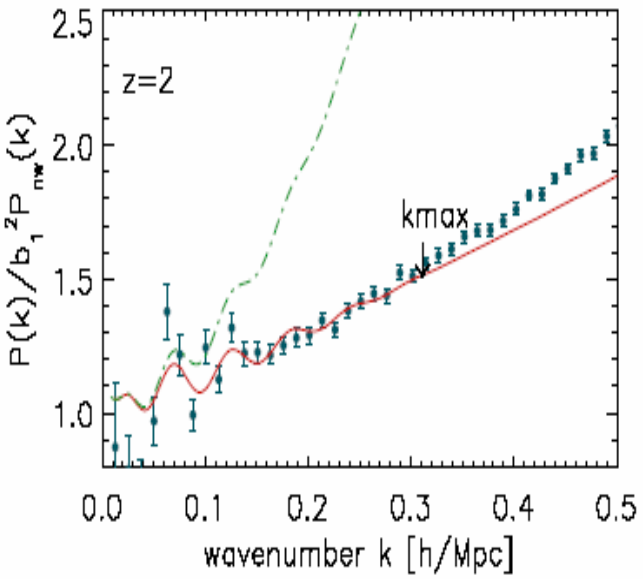
Millennium galaxy catalog bias simulation

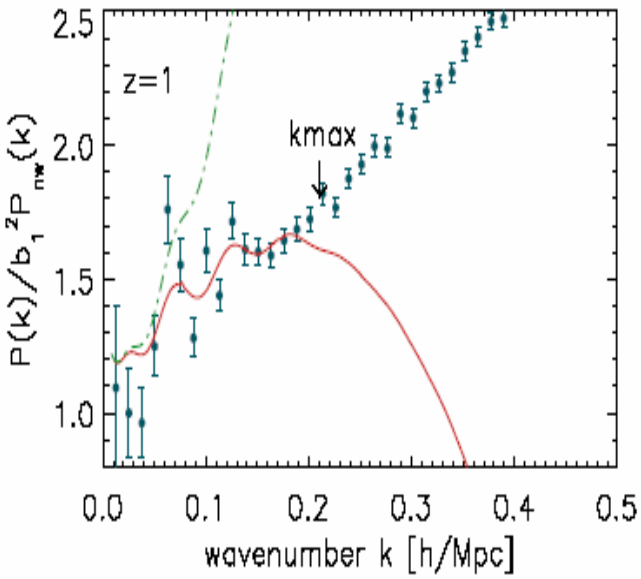
(Jeong & Komatsu, soon)

- Non-linear bias model based on 3rd order perturbation theory (e.g. McDonald 2006)
- Compared to semi-analytic galaxy catalogs from Millennium Simulation
  - Compiled by Durham and MPA groups
- Excellent agreement up to kmax
- Recover the input cosmology

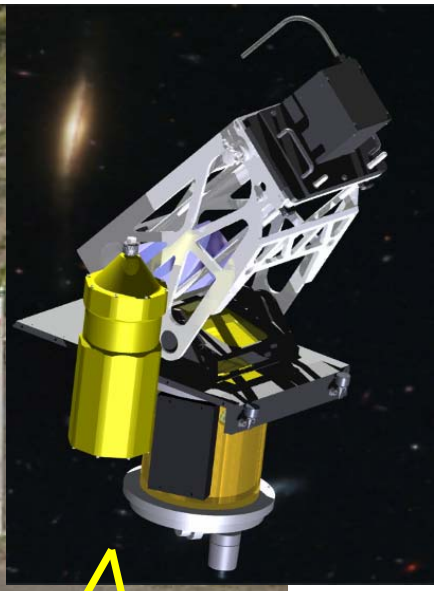




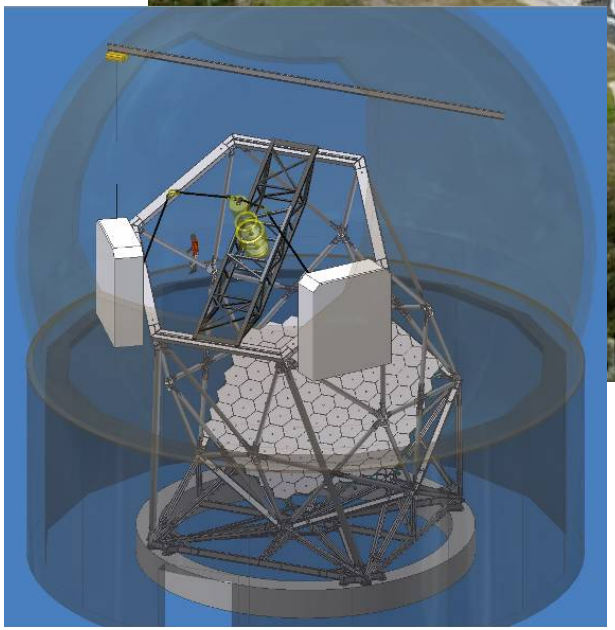


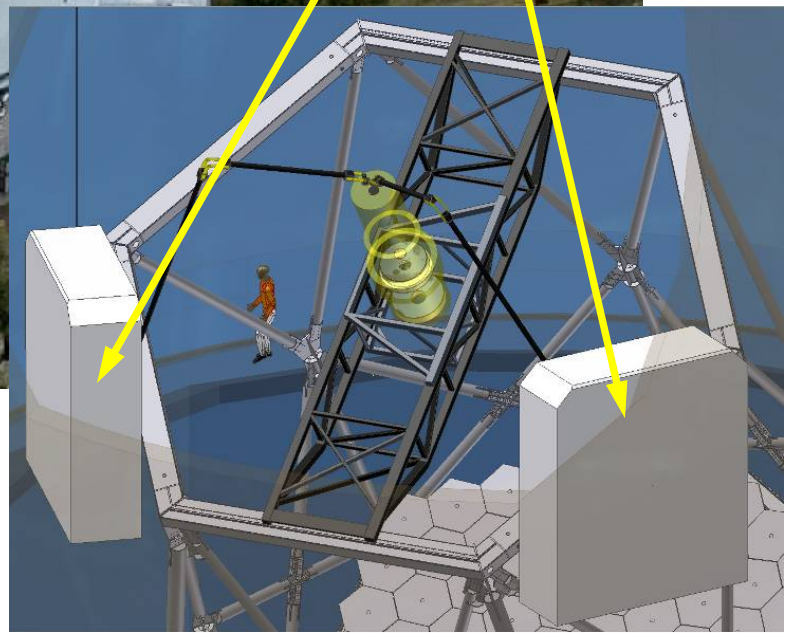


VIRUS Mounted on the HET



VIRUS consists of 145 units mounted on HET



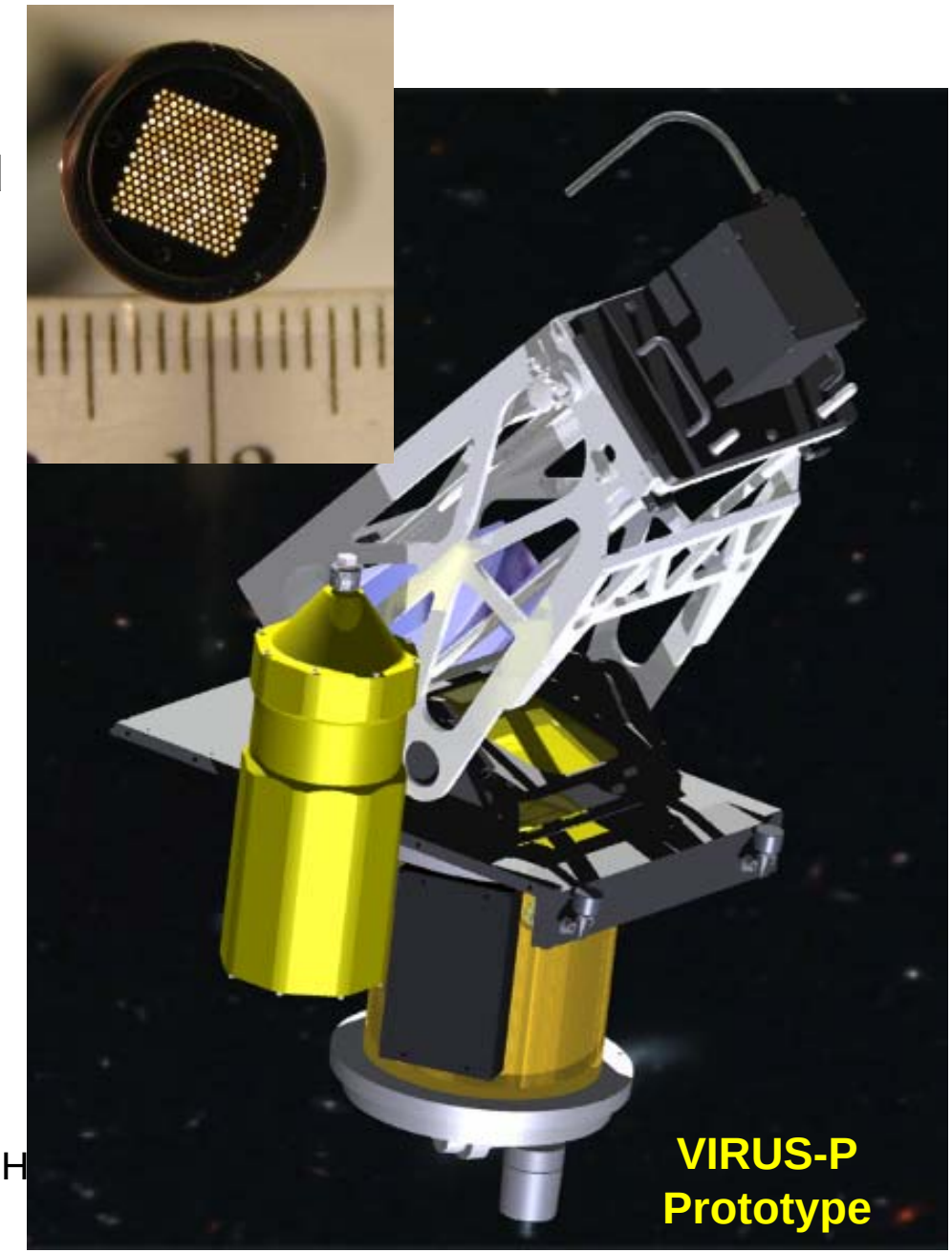


HET
Mt. Fowlkes west Texas

Gary J. Hill

Technical Approach

- Replicated integral field spectrographs (VIRUS)
  - Inexpensive fiber-fed unit IFS copied 145 times
  - 1/3 fill-factor dense-pak IFU
  - Each with 288 fibers of 1 sq. “ area
  - Surveys 11.6 sq. arcmin per exposure ~42,000 spectra
  - Three exposures fill area of IFU and observe 35 sq. arcmin total area
  - 350-580 nm coverage



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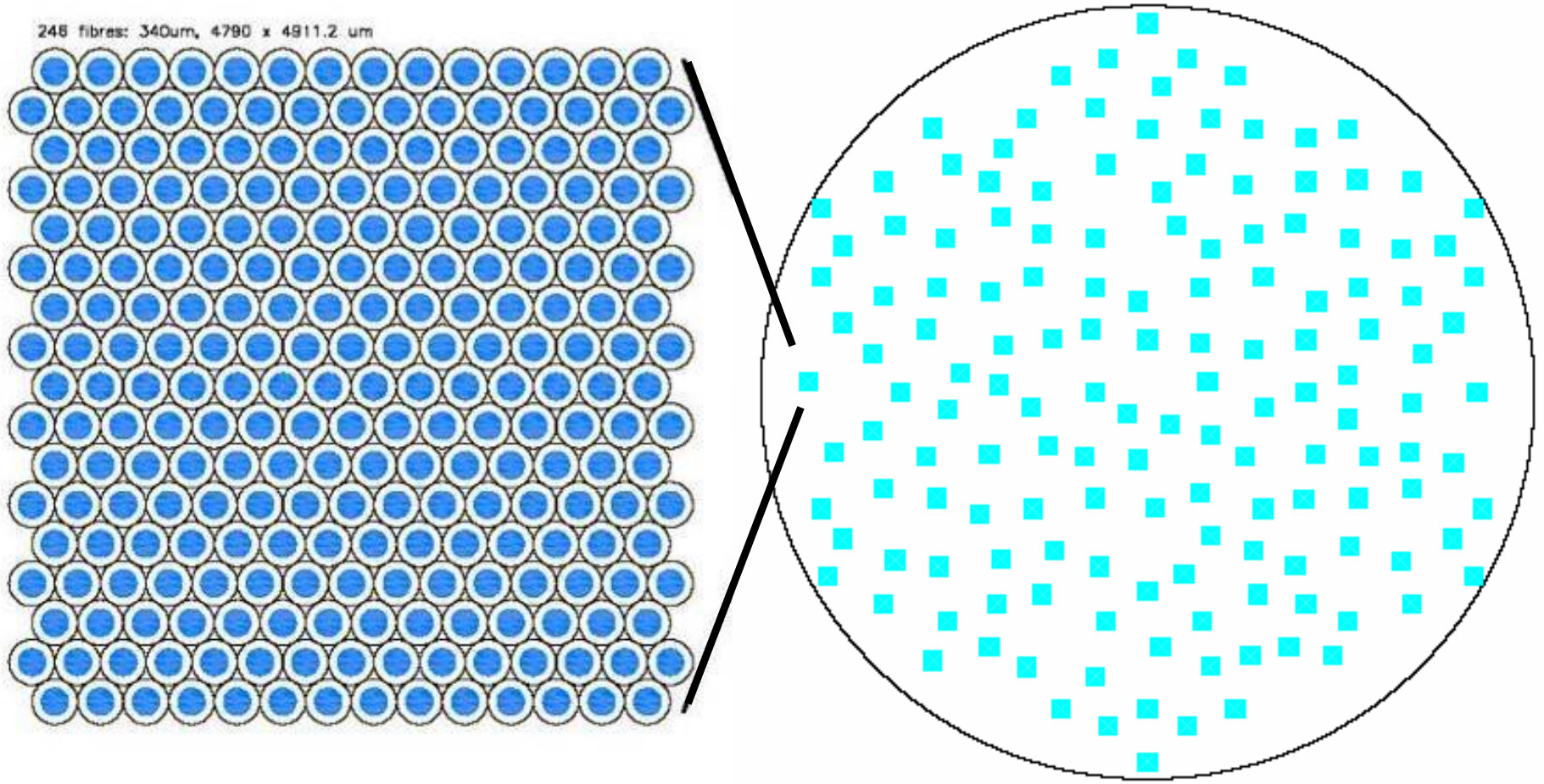
  - 350-580 nm coverage
- Wide field upgrade of HET
  - New wide field corrector covering 22 arcmin diameter field
  - New tracker
  - New metrology system to maintain alignment during observations
  - Integrated control system to allow rapid set up and low overhead

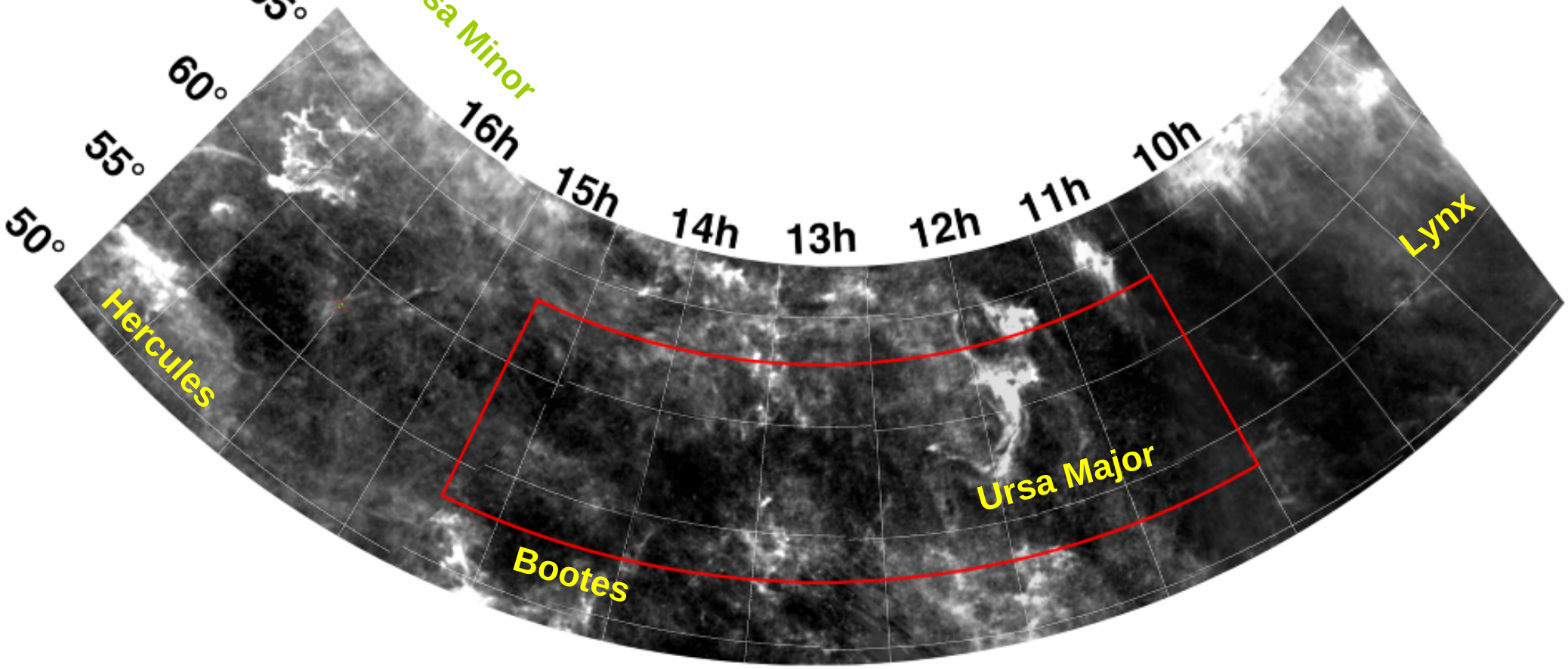
IFU arrangement

Fibers in hexagonal close pack with 1/3 fill factor
Will be arrayed randomly within 22 arcmin diameter field of view
With ~1/9 fill factor



HETDEX Survey on sky

400 sq. degrees ~ 2000 moons
Geometry at high declination is well-suited to HET

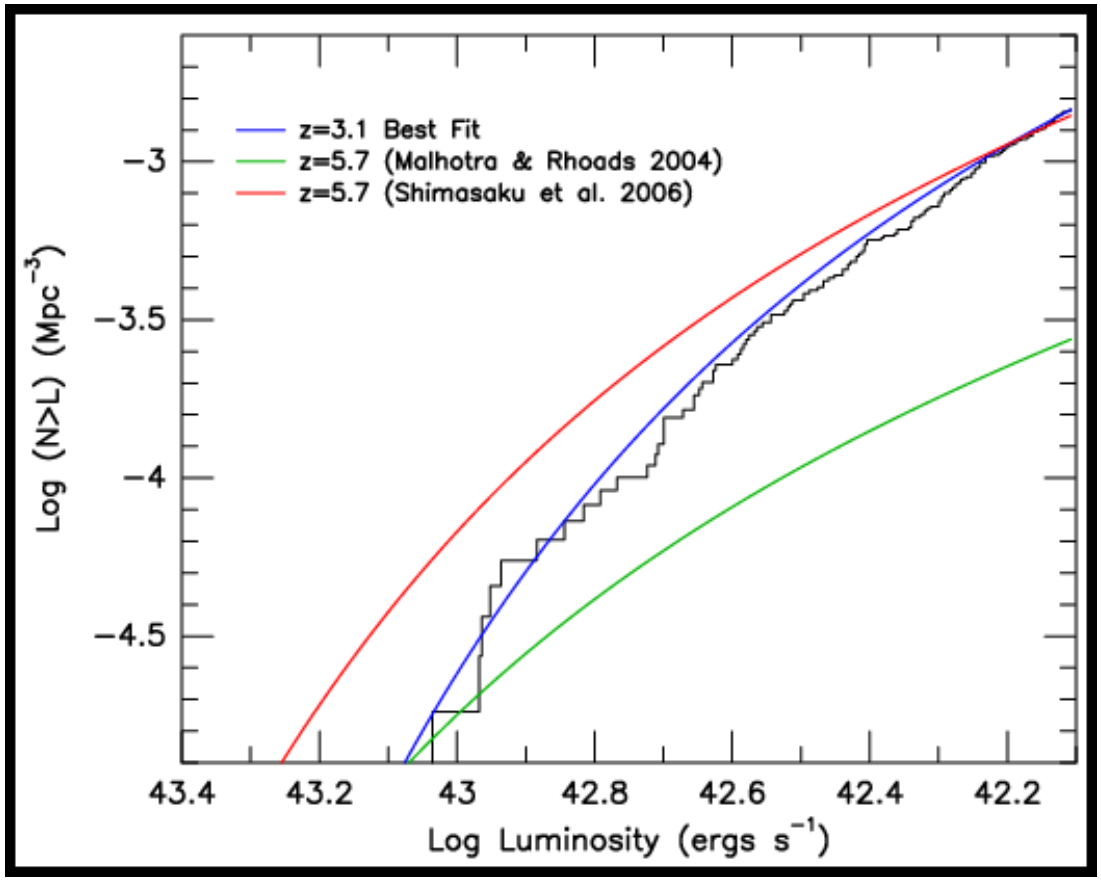


Map of dust distribution over the HETDEX survey area

LAEs as tracers

We do not yet know:

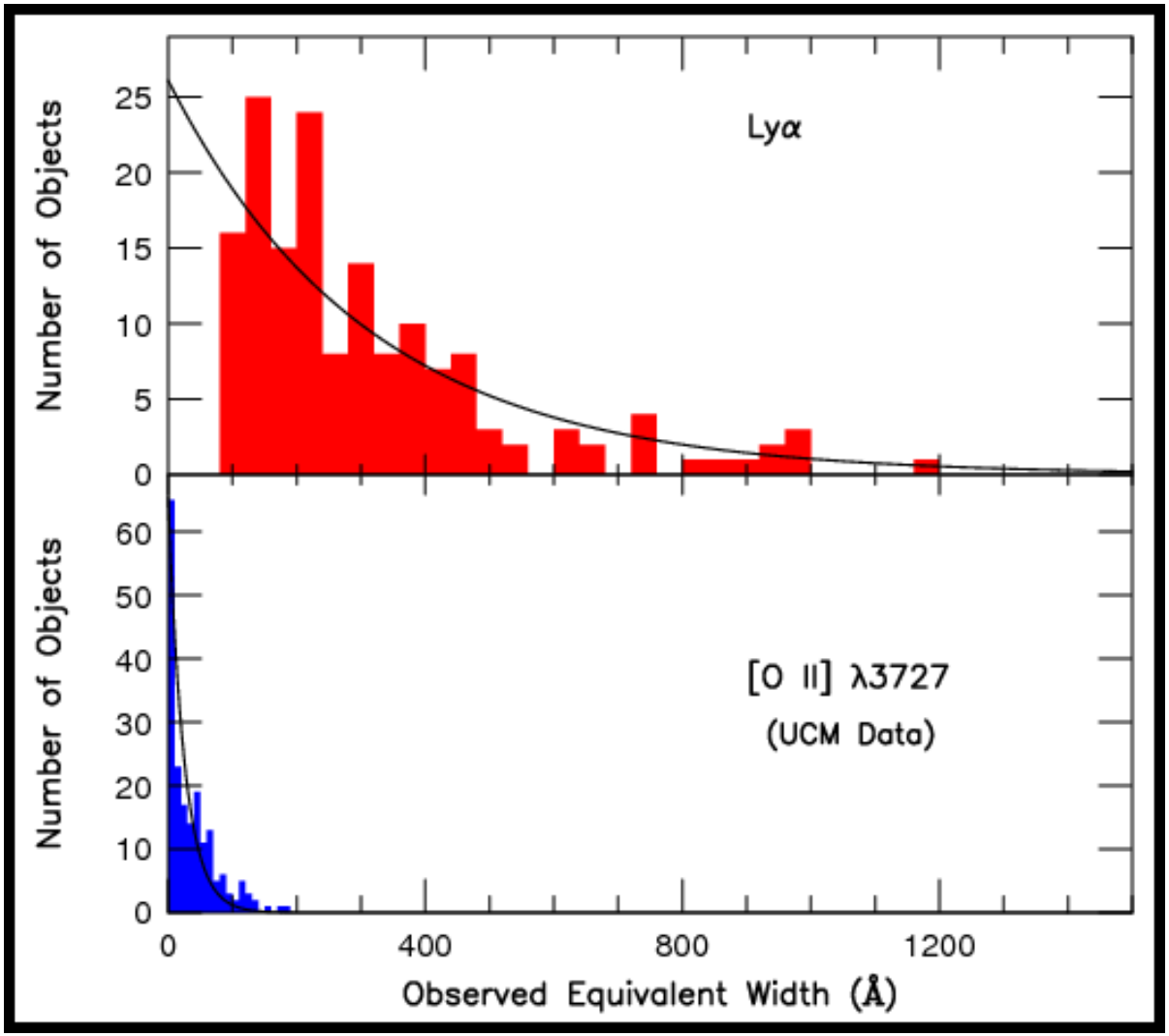
- how the LAE luminosity function changes with redshift at z<3
- how LAEs trace the mass distribution (*i.e.*, the bias)
  - The constraints go as Nb^2
- Bias from few blind fields:
  - b=1.8+/-0.4 @ *z* = 3.11 (E-CDFS; Gawiser *et al.* 2007)
  - b=3.3+/-0.3 @ *z* = 4.86 (Subaru Deep; Ouchi *et al.* 2003)
  - b=4.5+/-1.3 @ *z* = 6.6 (Ouchi *et al* in prep)



Need Nb^2 ~4 million for HETDEX

[OII] emitters

- The best way to eliminate foreground [O II] systems is via the emission-line equivalent widths
- This requires an imaging survey
  - SDSS and PanStarrs cover our entire survey region
- At faint magnitudes, most emission-line galaxies are Lyα emitters.
  - Can tolerate 20% contamination of sample



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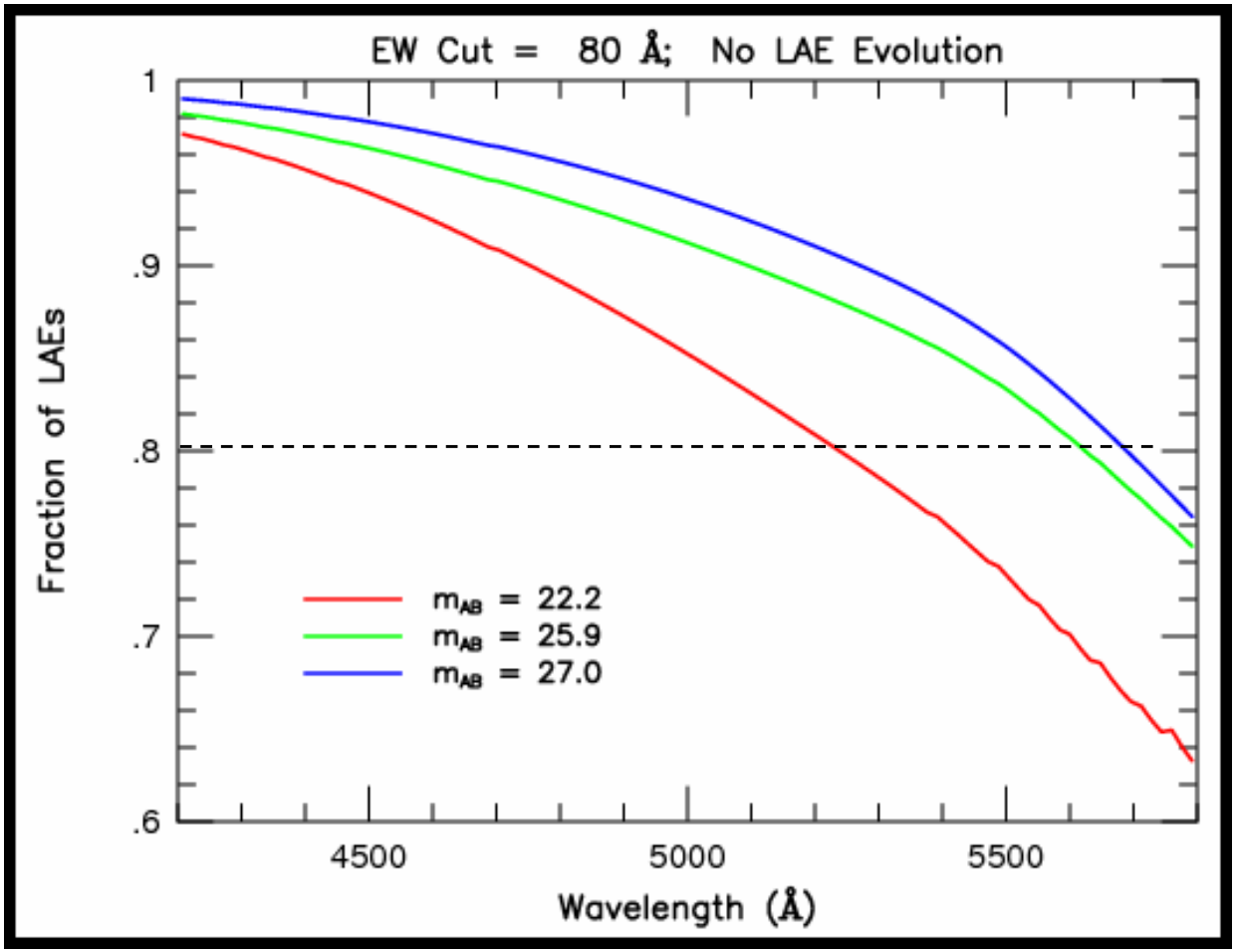
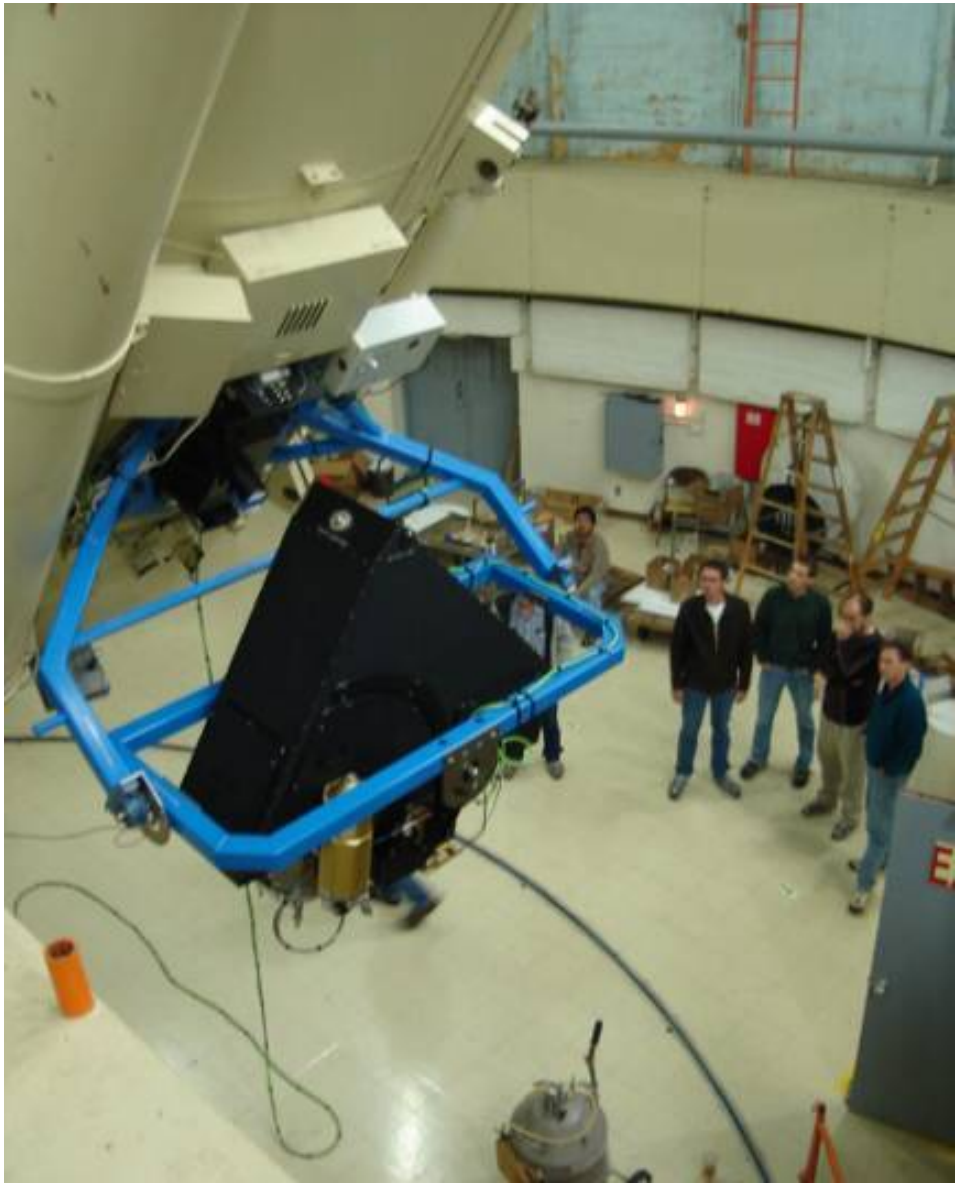


SDSS continuum limit: $m_{AB} \sim 22.2$
PanStarrs 3π continuum limit: $m_{AB} \sim 25.9$

VIRUS-P and HETDEX Pilot Survey

- VIRUS-P has been in regular science operation since October 2006
  - Fed at f/3.65 (4.1 “ dia fibers)
  - 3.5 sq. arcmin coverage
  - Coverage in to UV
- Pilot survey is measuring properties of LAEs
  - MUNICS-deep, COSMOS, GOODS-N
  - Verifying performance of VIRUS
  - Developing and testing software pipeline
- Will test in HET in Feb/Mar



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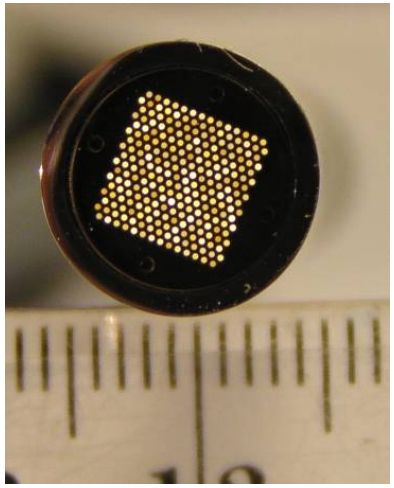
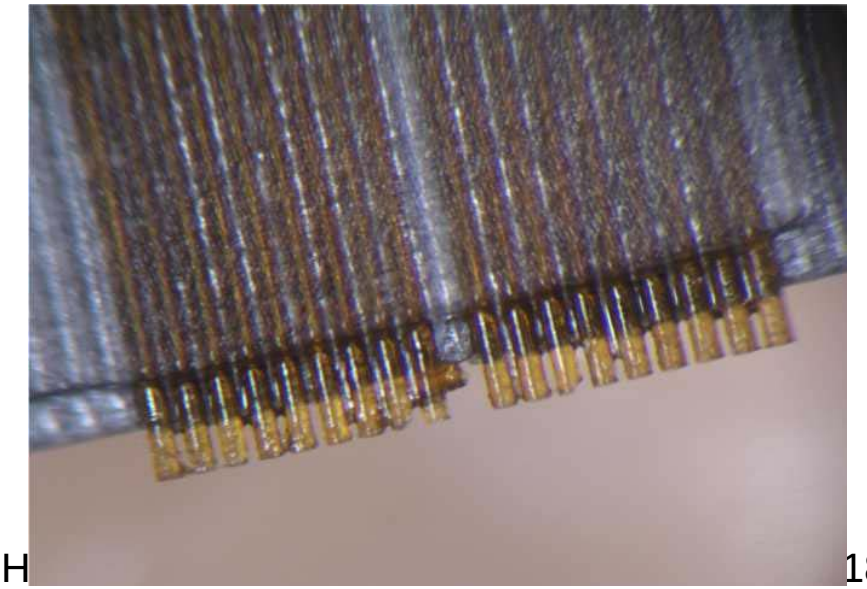
VIRUS Integral Field Unit

- The integral Field Unit reformats the sky to feed into the spectrograph
  - Bundle of 246 fibers that is spread out into a slit
  - Fiber spacing set by packing fused silica capillary tubes
  - Constructed by AIP (Potsdam)





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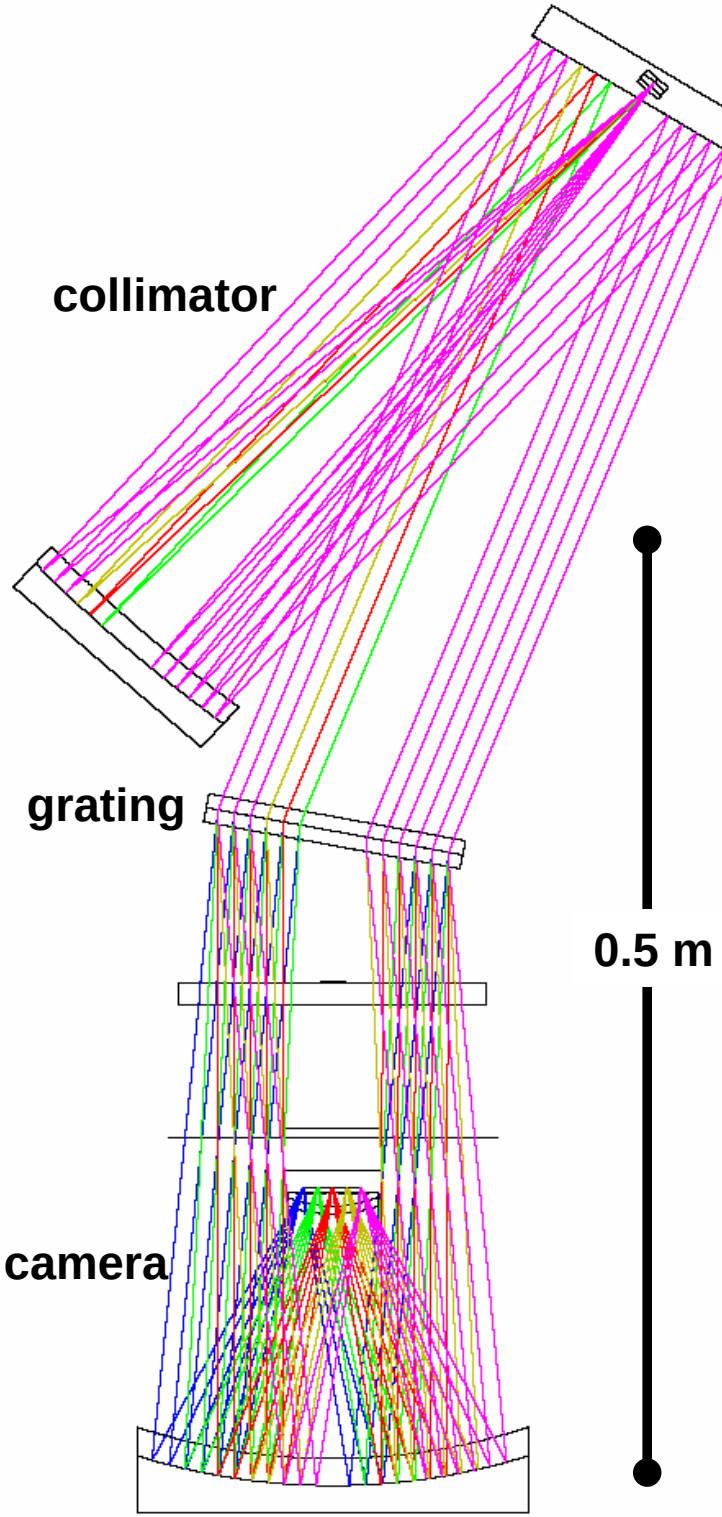
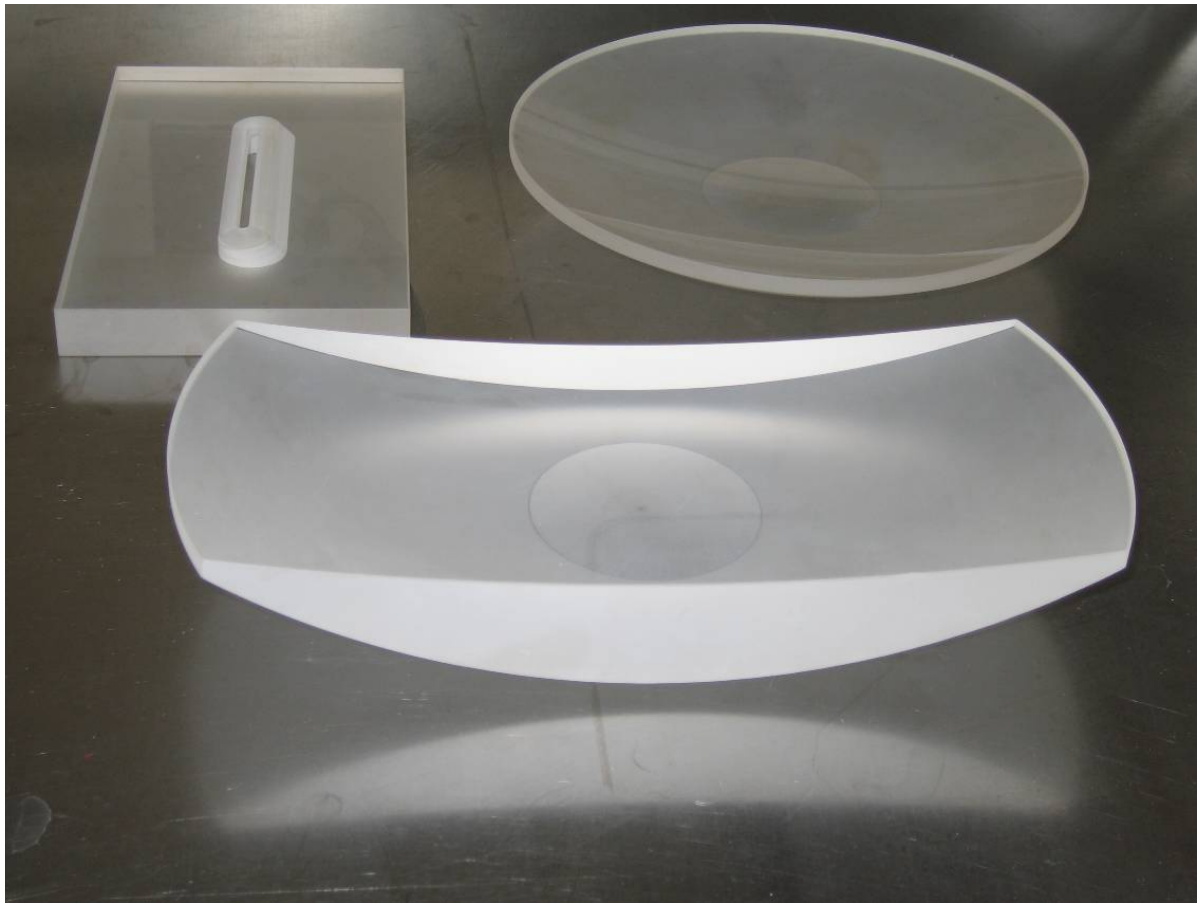
VIRUS-P Optics



- Optics are simple
- Can be replicated very cheaply
- Image quality is superb
- 99% reflective dielectric coatings on mirrors



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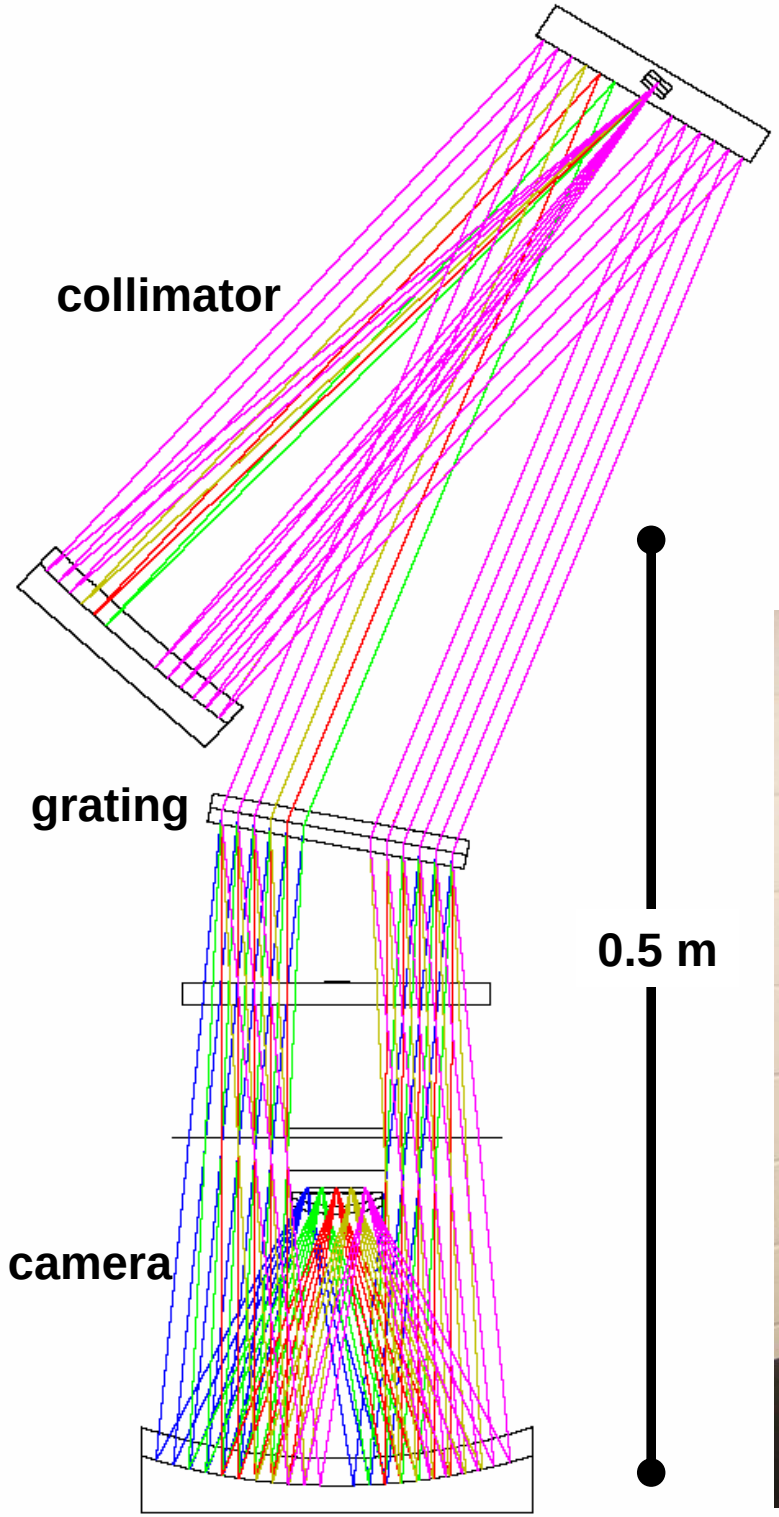

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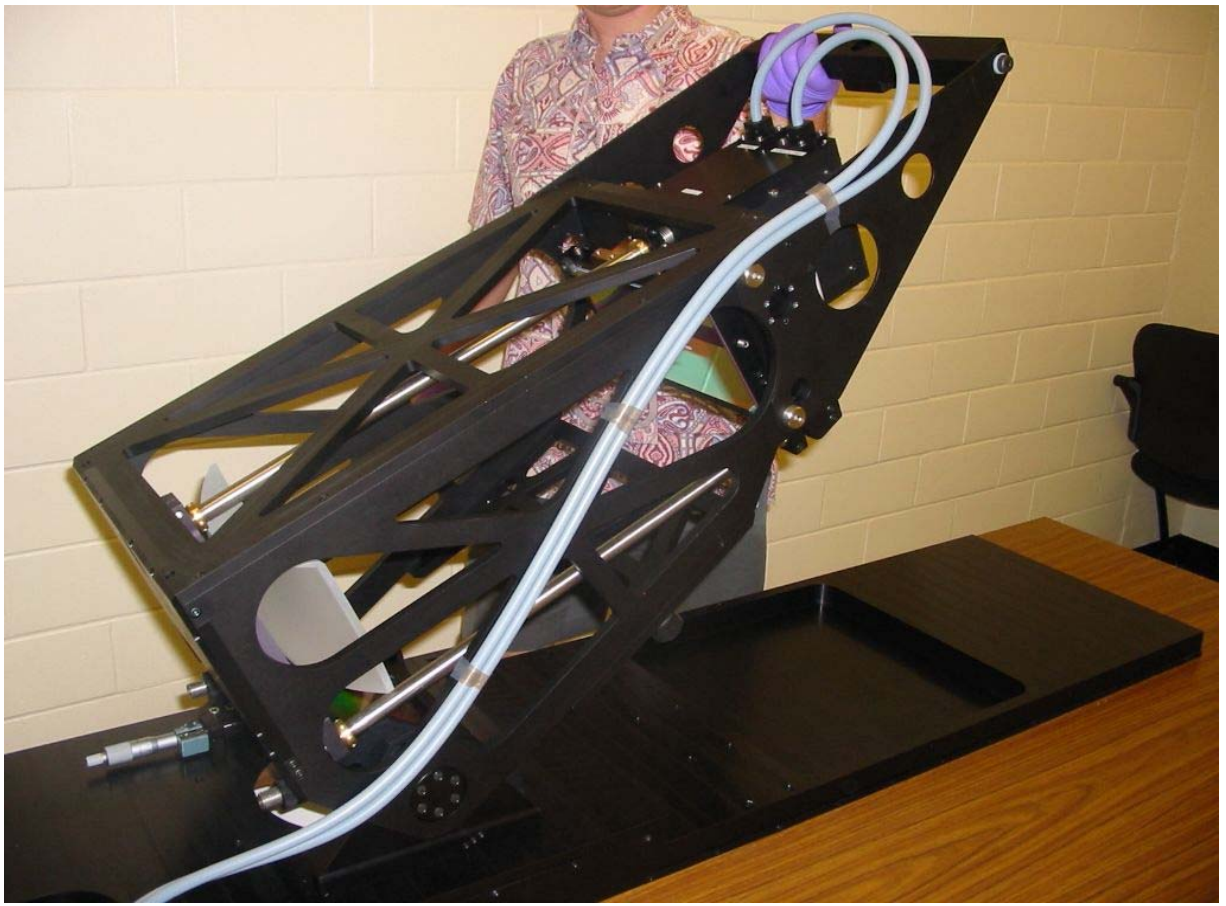
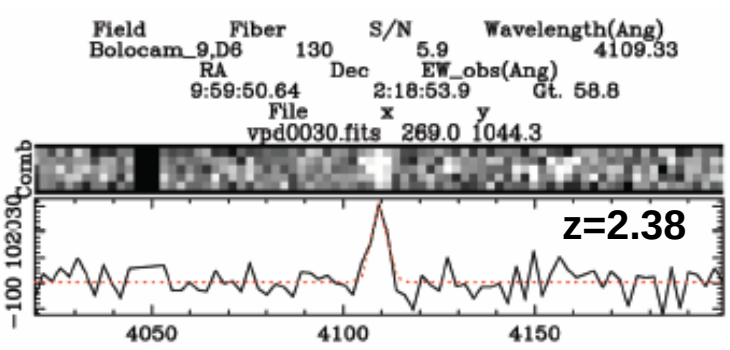
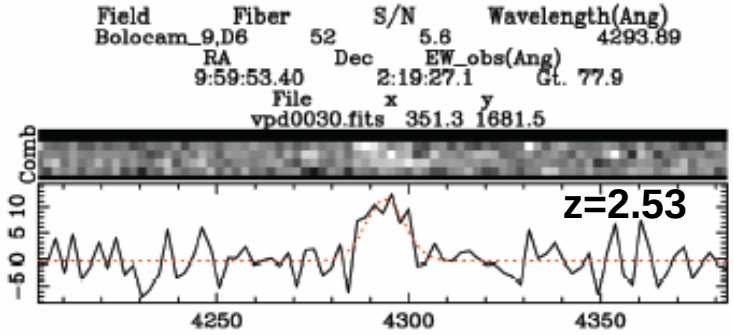
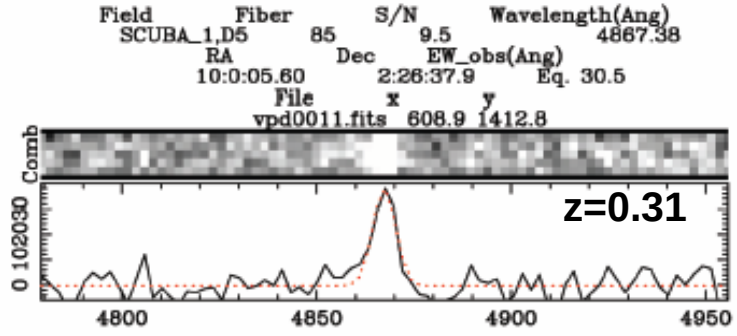


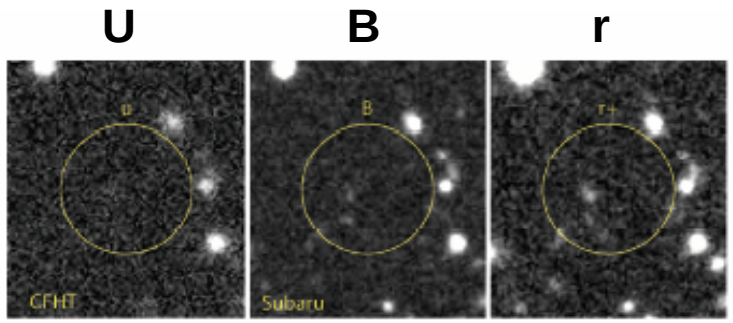
LAEs and [OII] galaxies

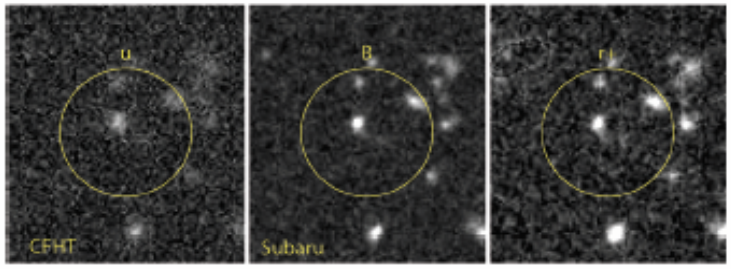
- VIRUS-P is finding star-forming galaxies
  - 2 < z < 3.6 (LAEs)
  - 0 < z < 0.5 ([OII])
- In COSMOS, GOODS-N we have very deep imaging
- LAEs and [OII] emitters easily discriminated on EW

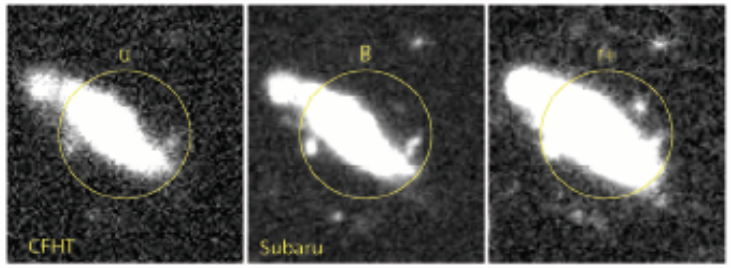






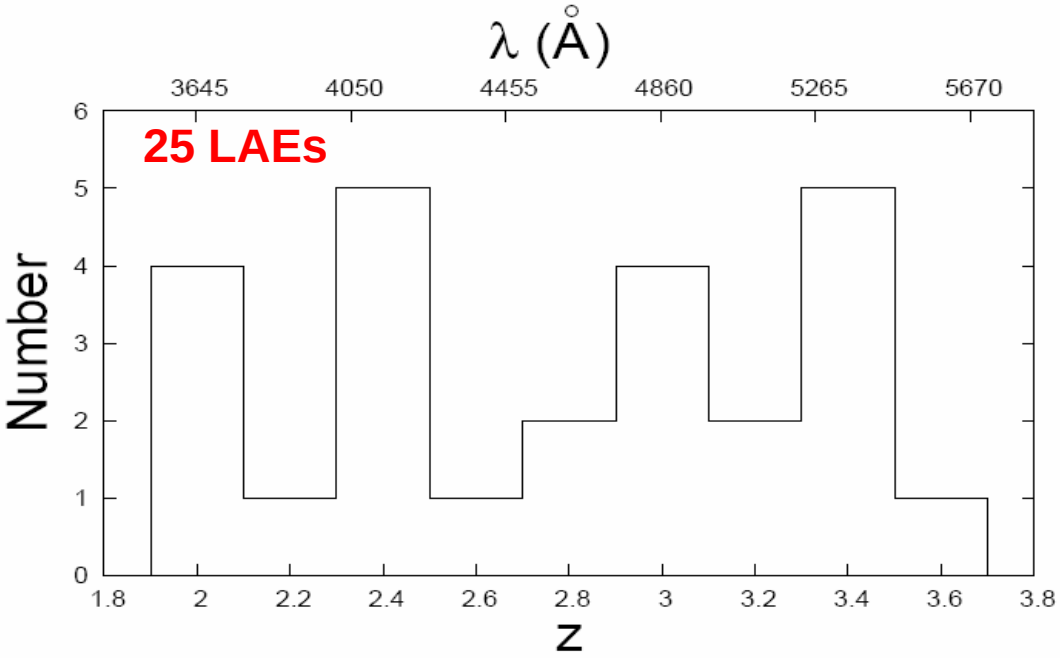


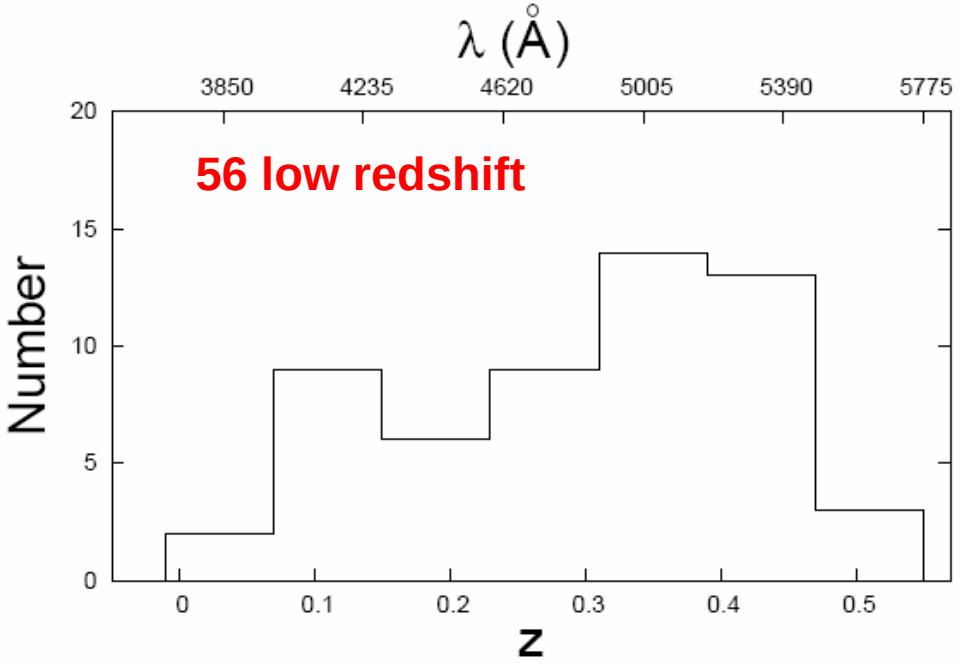




Circle is 8 arcsec in diameter; fiber is 4.1 arcsec diameter

LAE and [OII] galaxy redshift distributions



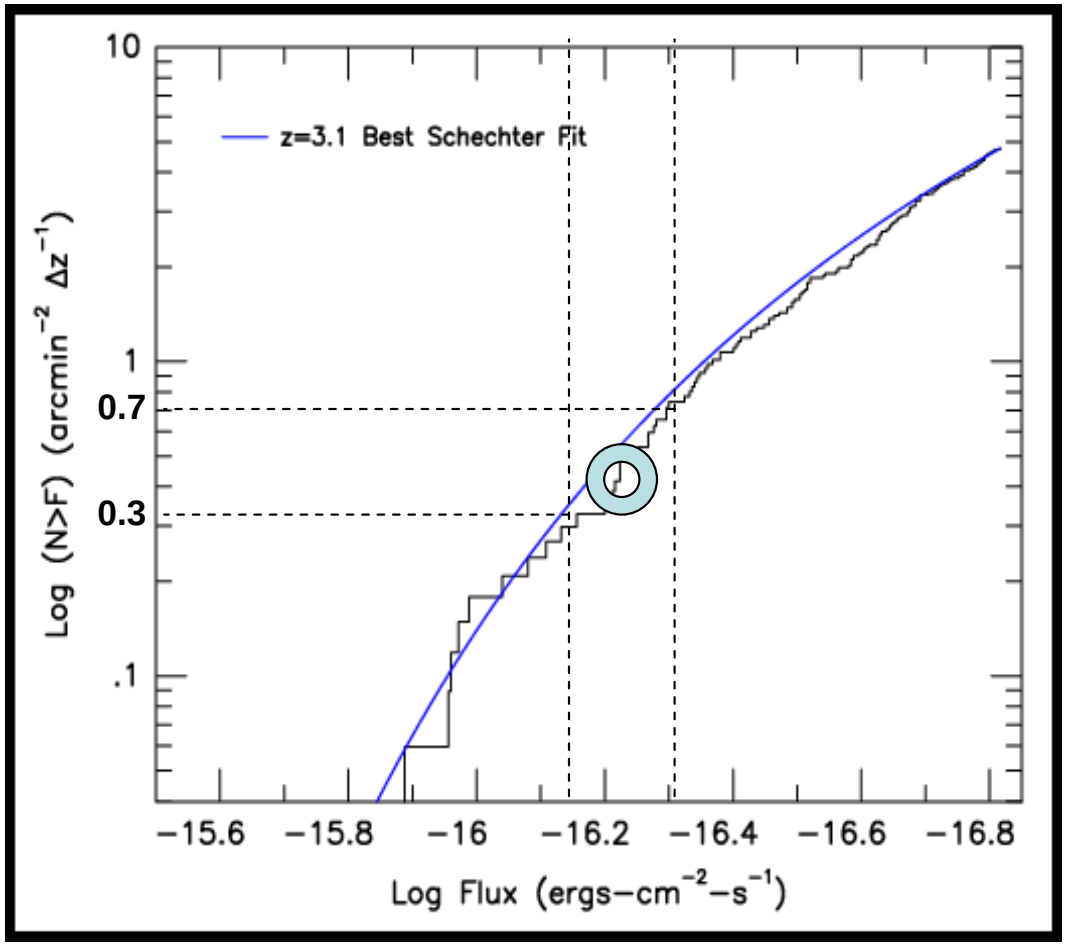


- In 13 fields covered to May 07 detect 25 LAEs and 56 low z galaxies
  - 45 sq. arcmin., $\Delta z \sim 1.5$, 2.4×10^5 cubic Mpc co-moving volume
  - 0.6 LAEs and 1.3 low z per sq. arcmin area

- Redshift distributions are very encouraging
  - We're detecting a significant # of z~2 galaxies
  - Low z population evolves strongly towards z~0.5 as expected

Sensitivity and number of LAEs

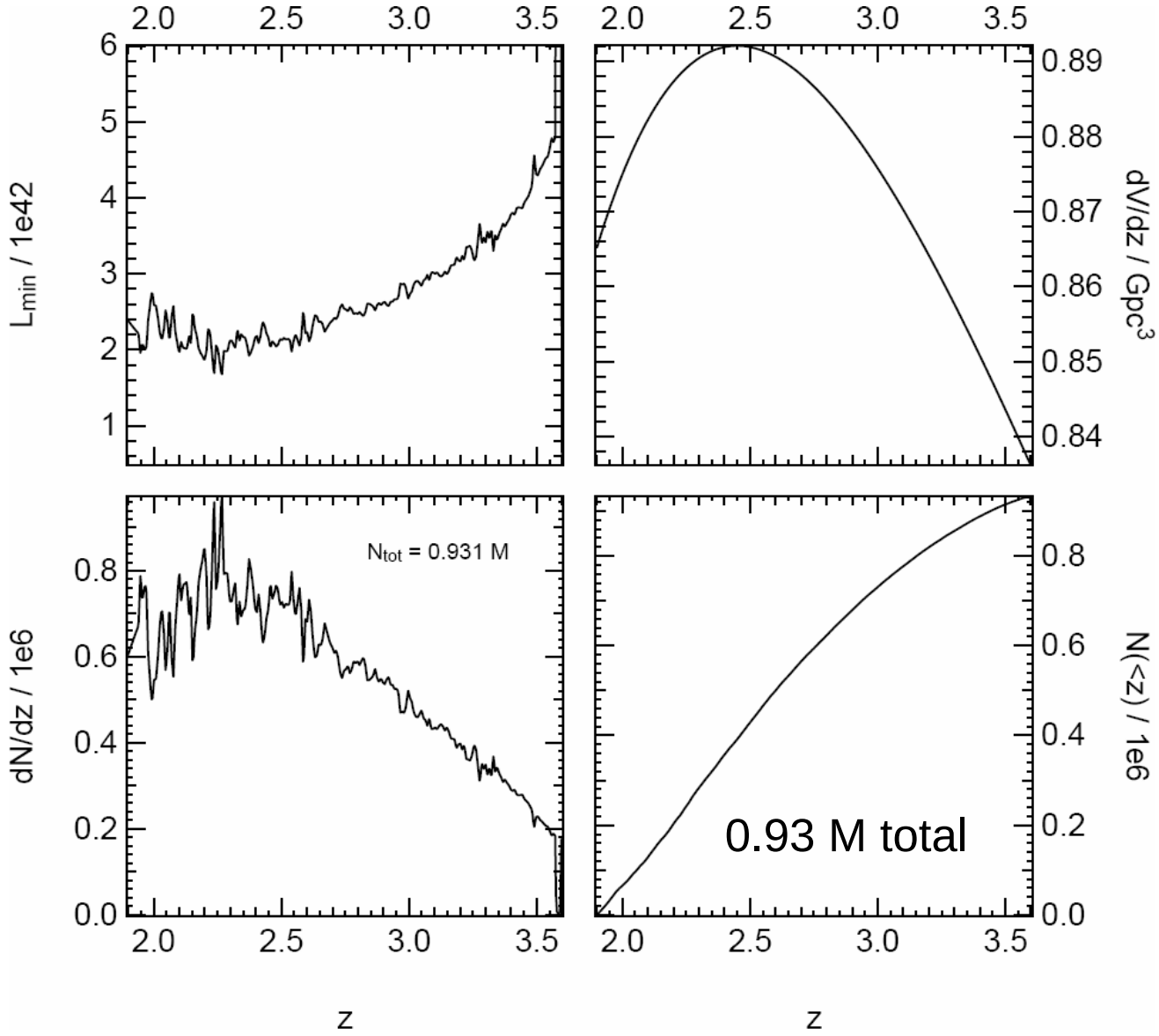
- Sensitivity
  - Predict 5-7e-17 erg/cm^2/s 5-σ line flux limit in 1 hour on 2.7 m
  - Agrees well with direct measurement from data
- # LAEs is in line with z~3 LF and sensitivity limit
  - Luminosity function is steep
- Pilot survey will continue for a year (60 nights allocated)
  - Expect ~200 LAEs and 500 [OII] galaxies



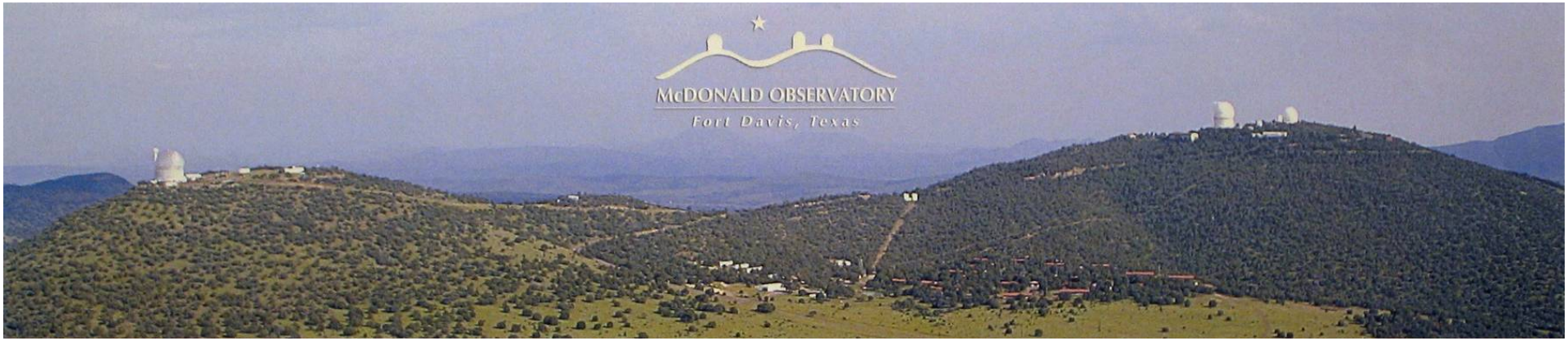
z=3.1 LAE LF (Gronwall et al 2007)

Number of LAEs in HETDEX

- Line flux sensitivities predicted for HET
  - 3e-17 erg/cm^2/s
- Baseline prediction for non-evolving LAE population
  - Most objects in $2 < z < 3$ range
  - But evolving bias may counter this
- Further information on LAE properties is needed to optimize the survey in detail



Summary



- The cost of HETDEX is estimated to be $34M
  - $20M has been raised or pledged by partners
  - Sufficient to do HET upgrade and develop VIRUS to production
- We are assembling the full Project team
- Construction phase for the HET wide field upgrade and VIRUS
  - will go from the PDR in early 2008 to late 2010
- The observing phase will go from late 2010 to mid 2013

- **Beyond HETDEX, the VIRUS instrument will provide an unmatched survey facility to open up the emission-line universe for the first time**

The HETDEX Collaboration

- HETDEX is
  - **UT Austin:** Gary Hill (PI), Karl Gebhardt (PS), Marc Rafal (PM), Eiichiro Komatsu, David Lambert, Phillip MacQueen, Povilas Palunas, John Booth, Mike Smith, John Good, Richard Savage, Josh Adams, Guillermo Blanc, Donghui Jeong, Jeremy Murphy, Joel Barna
  - **USM/MPE Munich:** Niv Drory, Ralf Bender, Ralf Koehler, Ulrich Hopp
  - **AIP:** Martin Roth, Andreas Kelz, Matthias Steinmetz
  - **Penn State U:** Caryl Gronwall, Robin Ciardullo, Don Schneider, Dan vanden Berk
  - **Texas A&M:** Nick Suntzeff, Darren DePoy

Engineers Mike Smith and Pedro Segura
Making a fine adjustment to VIRUS-P

http://www.as.utexas.edu/hetdex/