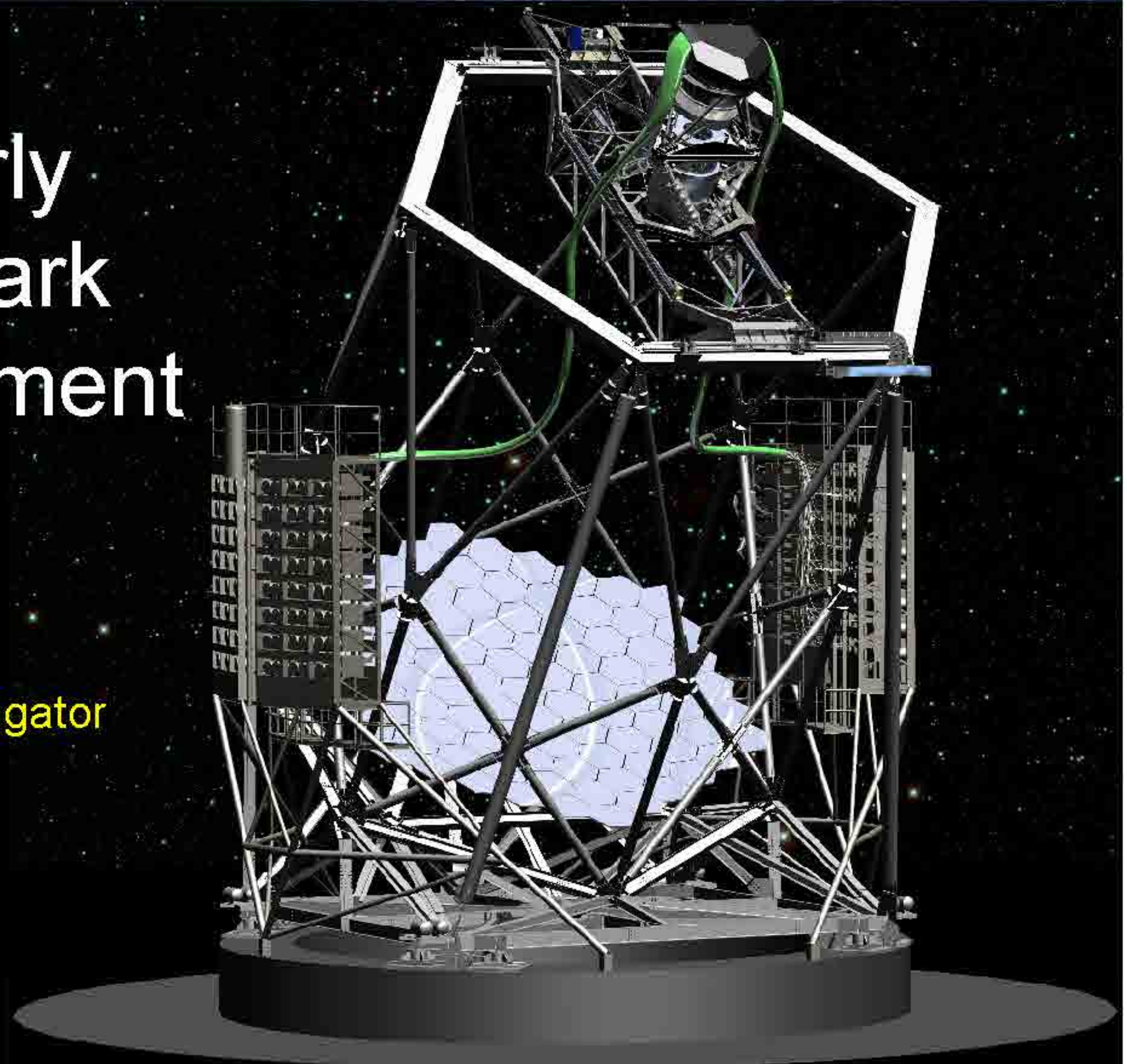
HETDEX

Hobby-Eberly Telescope Dark Energy Experiment

Illuminating the Darkness

Hobby-Eberly Telescope Dark Energy Experiment



Gary J. Hill

HETDEX Principal Investigator

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Overview

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- HETDEX Motivation
  - Dark Energy evolution
  - but really a vast blind integral field spectroscopic survey
- What HETDEX comprises
- VIRUS and the VIRUS prototype
- HETDEX Pilot Survey – LAEs, [OII] emitters
- The HETDEX survey and example science
- HETDEX ∩ SDSS
- Status of the HET Wide Field Upgrade and VIRUS

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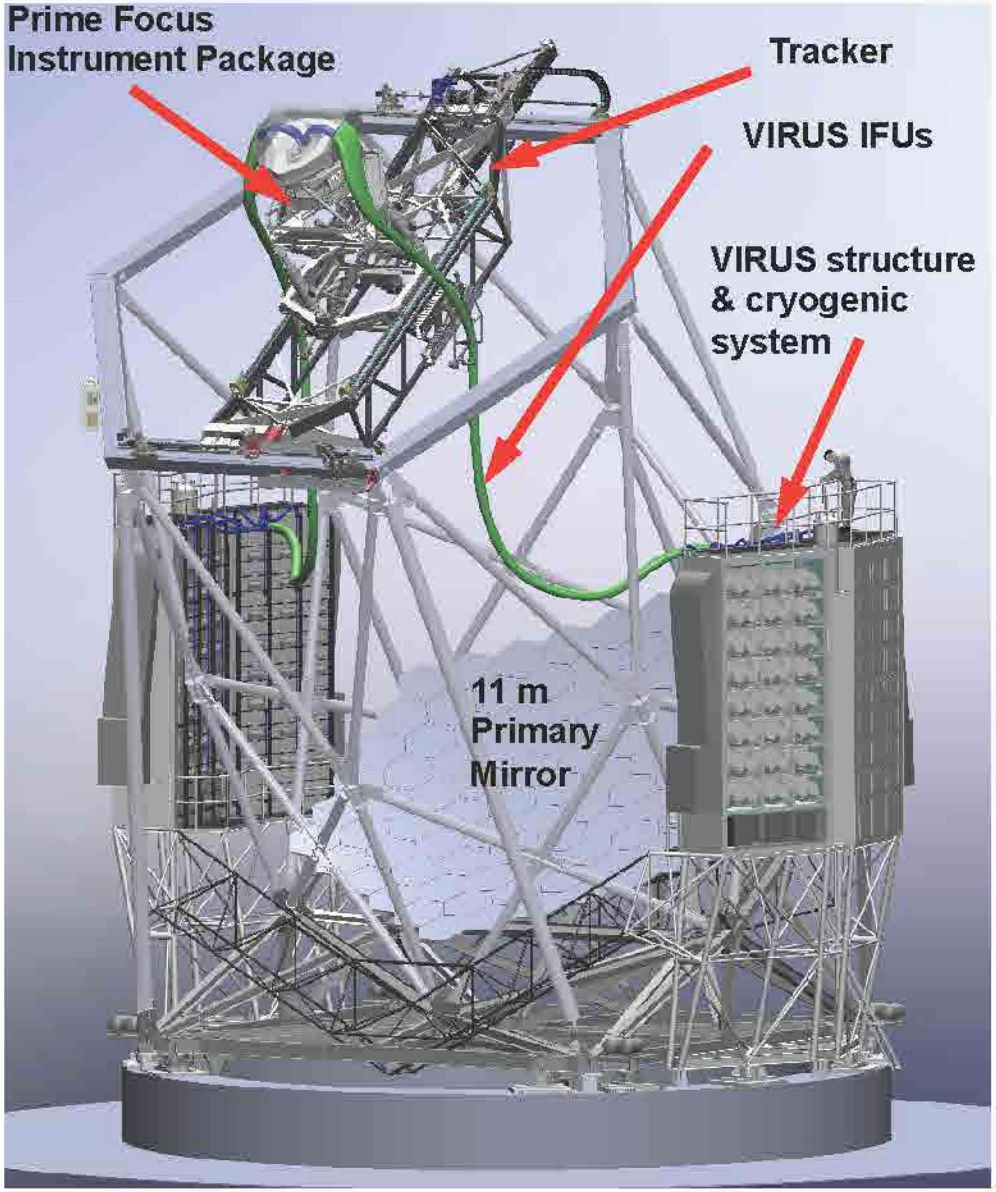
Hobby Eberly Telescope Dark Energy Experiment

- HETDEX is:
  - Upgrade of HET to have a new wide 22' field of view
  - Deployment of the hugely replicated spectrograph, VIRUS, putting >33,000 fibers on sky, per exposure
  - 3-5 year blind spectroscopic survey
- HETDEX will:
  - Map 0.8 million LAEs (1.9 < z < 3.5) and a million [OII] emitters (z < 0.5)
  - measure expansion history to 1% precision at z~2.5
    - determine if dark energy evolves, looking back 11 billion years
    - measure curvature of the universe to 0.1%
- Very complementary to BOSS and DES
- HETDEX is a unique blind spectroscopic survey with many other applications
  - In particular in galaxy evolution

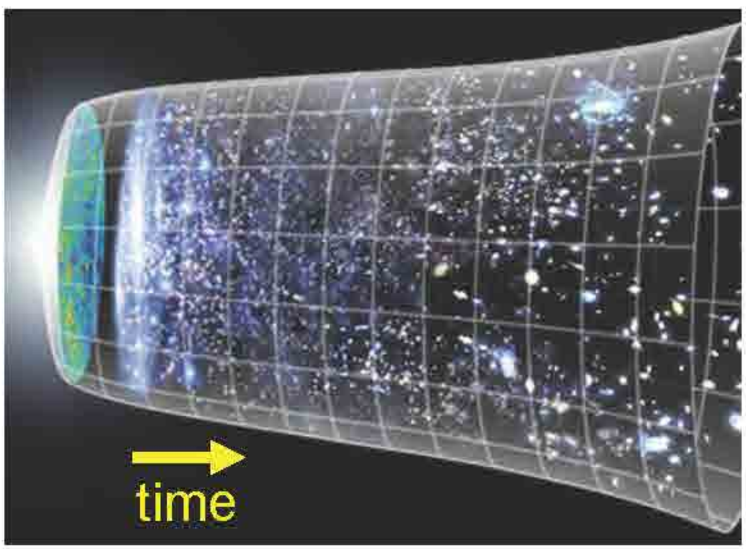


What Controls the Expansion Rate

Different components dominate as follow the arrow of time

$$\left(\frac{H(z)}{H_{100}}\right)^2 = \omega_r(1+z)^4 + \omega_m(1+z)^3 + \omega_k(1+z)^2 + \omega_\Lambda(z)$$

Expansion Rate **Radiation** **Matter** **Curvature** **Dark Energy**



- Observing different epochs allows us to see the influence of different components
- HETDEX probes early epochs, where DE evolution and curvature are important
- HETDEX helps break degeneracies inherent in lower redshift measurements

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Realization of BAO in HETDEX

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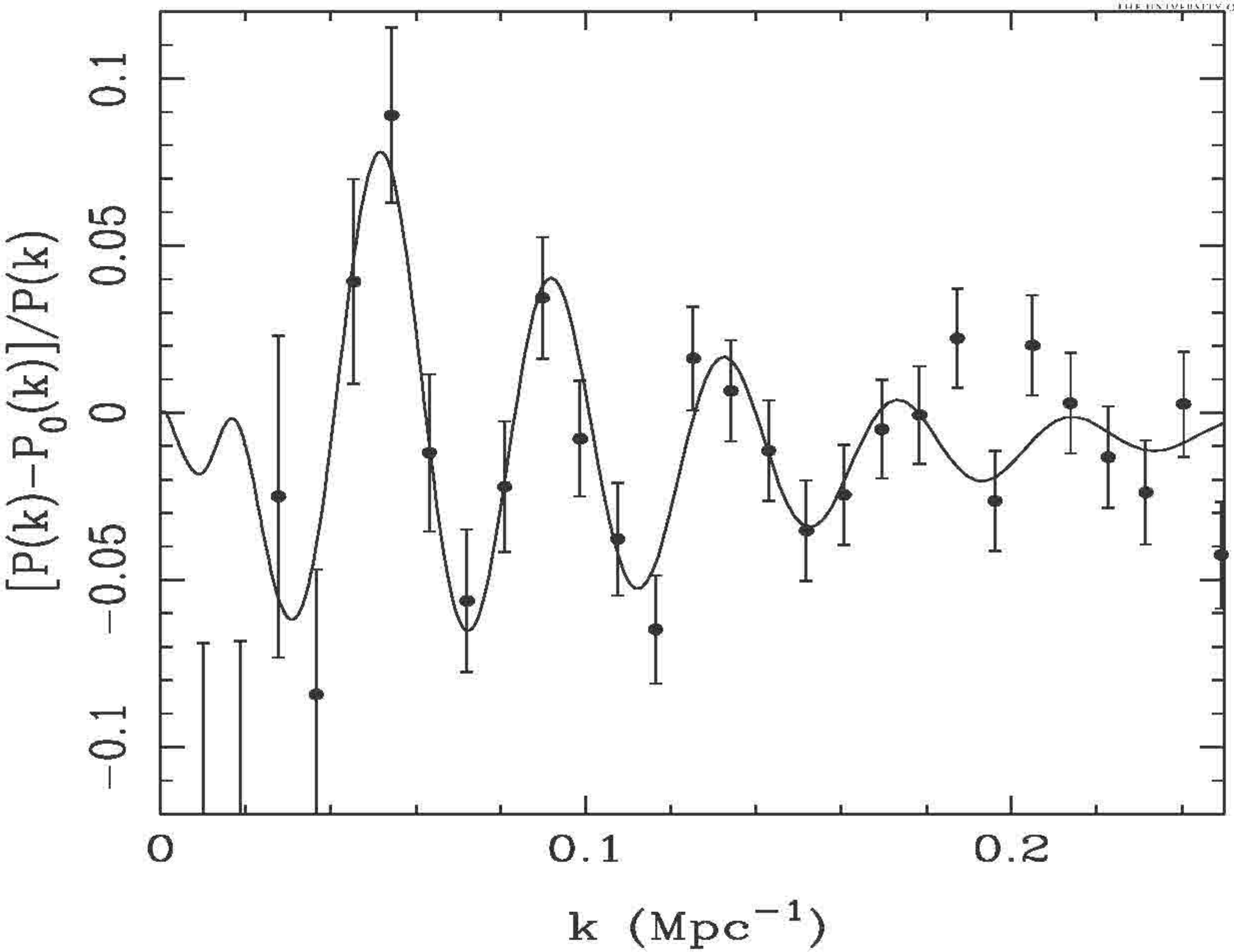
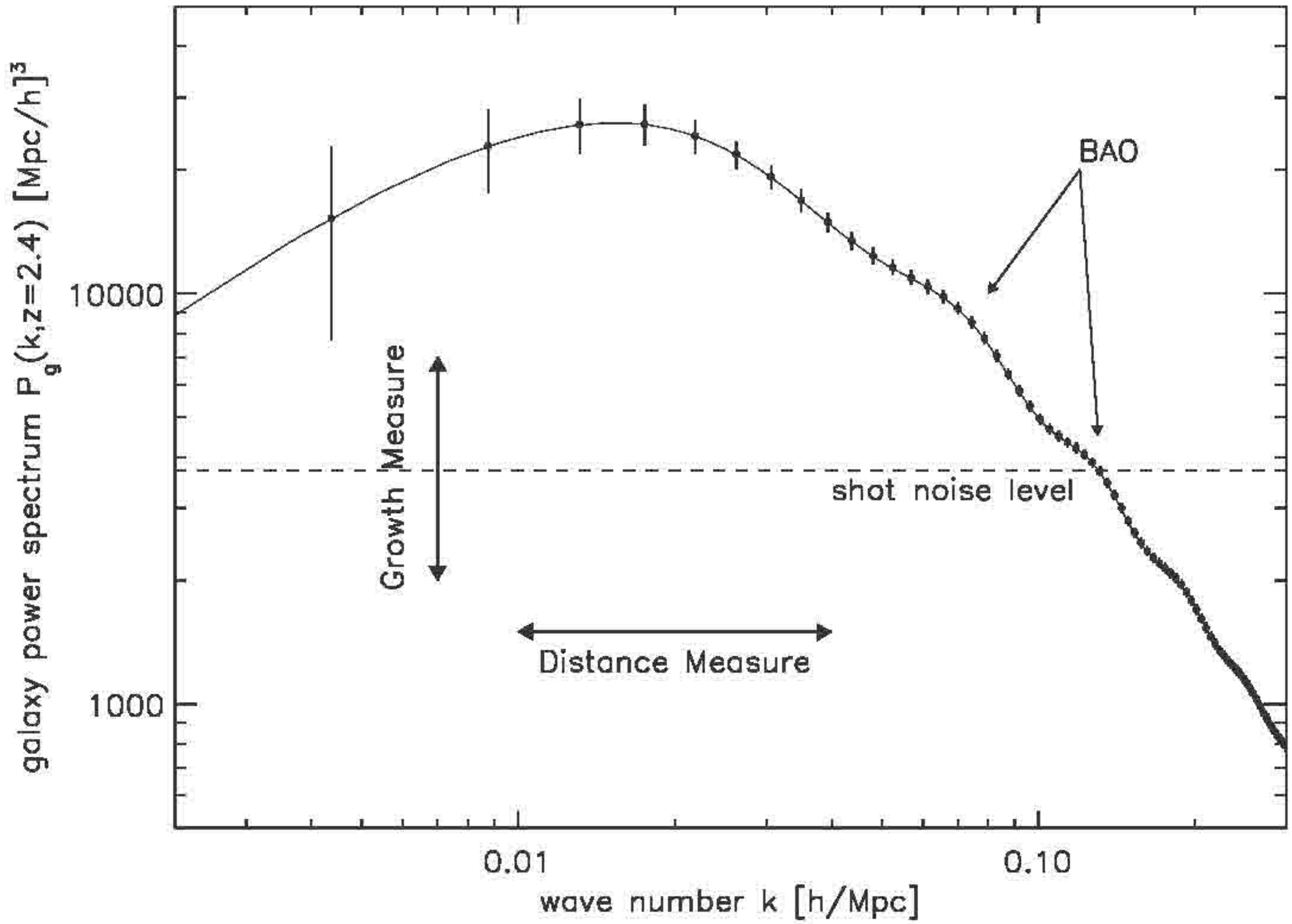


The power of the power



Entire shape of power spectrum in 2-D (Alcock-Paczynski Effect) constrains H,d_A and contains information about structure growth – if non-linear growth and redshift space distortion at high k can be understood (Shoji, Jeong & Komatsu, 2009)

Three Non-linearities to Worry About

- Non-linear evolution of the density field
  - Non-linearity in continuity and Euler equation
- Non-linear bias
  - Non-linearity in the way that galaxies trace matter
- Non-linear redshift space distortion
  - Non-linearity in peculiar velocity along the line of sight

Solid framework: **Perturbation Theory (PT)**

- Validity of the cosmological ***linear*** perturbation theory has been verified *observationally* (WMAP!)
- So, we go beyond the linear theory, and calculate higher order terms in perturbations.
- **3rd-order perturbation theory (3PT)**

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Non-linearity in Matter Clustering

(Jeong & Komatsu, ApJ 651, 619, 2006)

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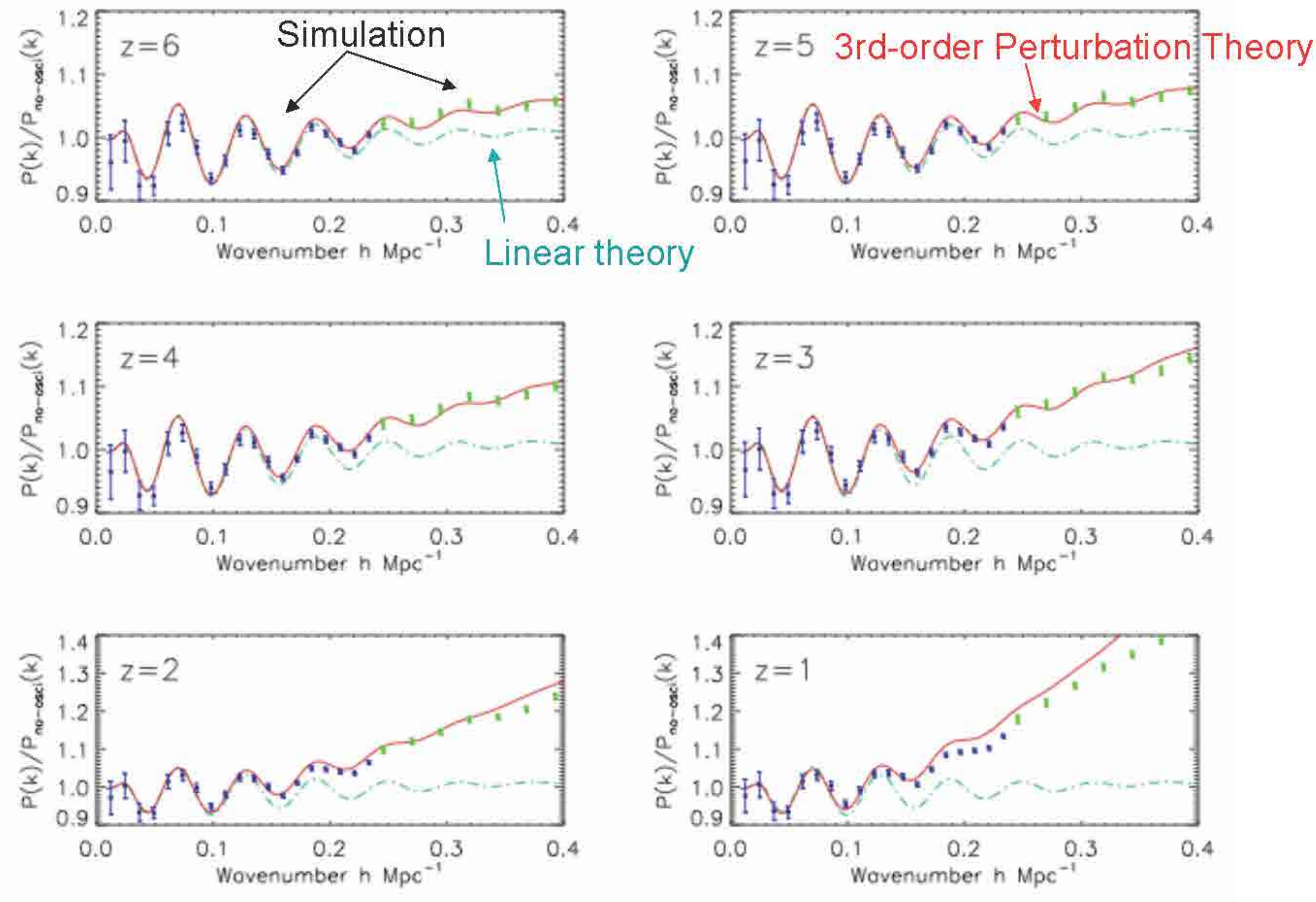

Non-linear bias

- Galaxies not distributed same as matter fluctuations
- Usually, this fact is modeled by a "linear bias", or $P_g(k)=b_1^2\ P(k)$, where b_1 is scale-independent.
- Extending this to a non-linear form, we have to assume something about galaxy formation
- Assumption: galaxy formation is a local process, at least on scales that we care about

- Non-linear bias can be modeled with 3PT (Jeong and Komatsu 2009)
- or constrained by the bi-spectrum (e.g. Sefusatti & Komatsu 2007)

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Non-linear Bias

(Jeong & Komatsu, ApJ 691, 569, 2009)

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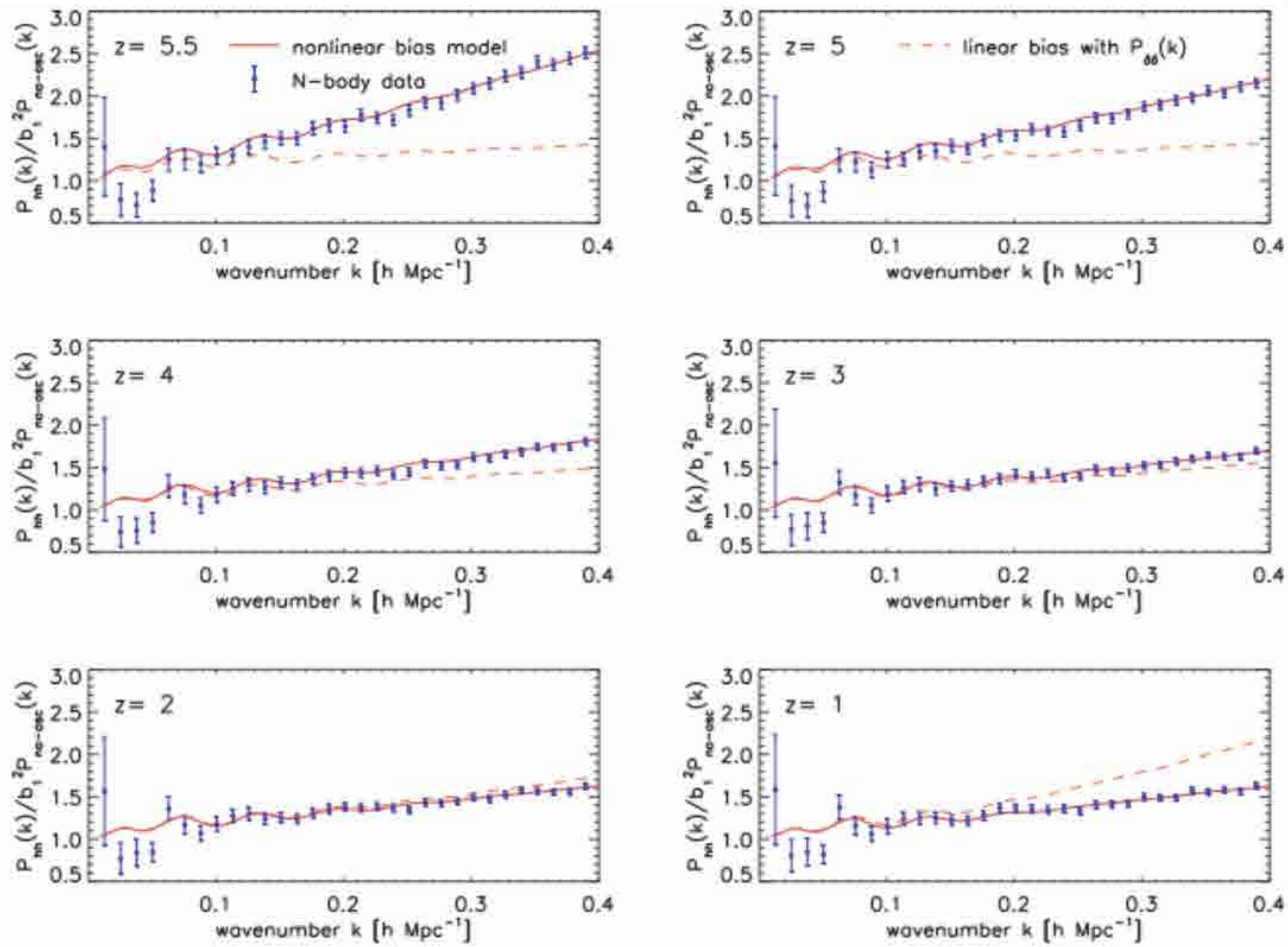

$$\text{Using}: \ \delta_h(x) = b_0 + b_1\delta(x) + \frac{b_2}{2}\delta^2(x) + \frac{b_3}{6}\delta^3(x)$$

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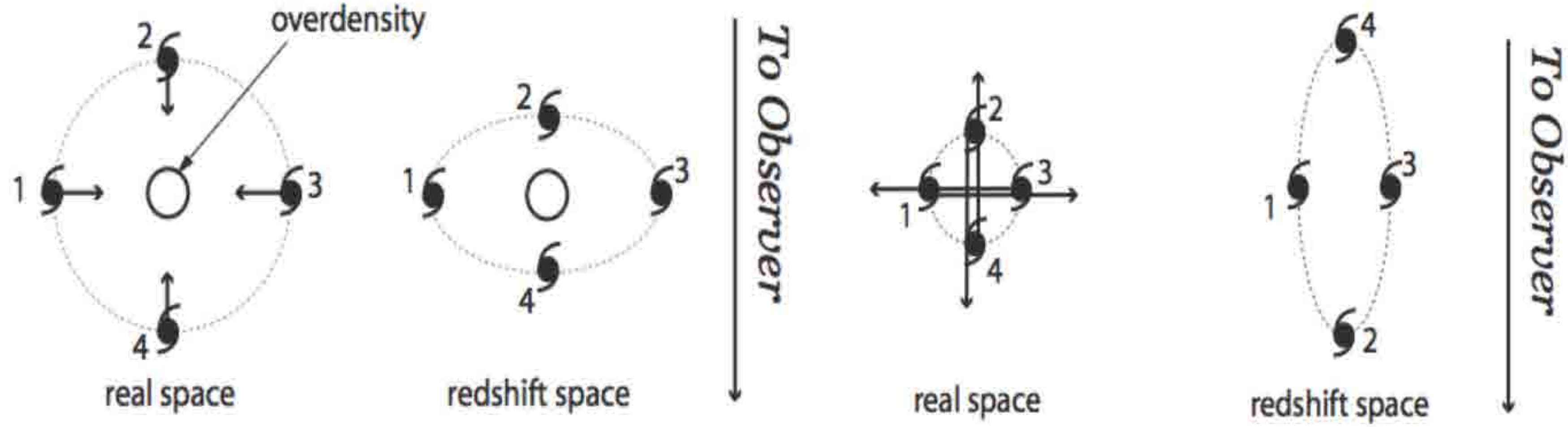
Redshift Space Distortion



- (Left) Coherent velocity field => Clustering **enhanced** along the line of sight
    - "Kaiser" effect
- (Right) Virial-like random motion => Clustering **diminished** along the line of sight
    - "Finger-of-God" effect

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Non-Linear Redshift Space Distortion

(Jeong & Komatsu 2009, unpublished)

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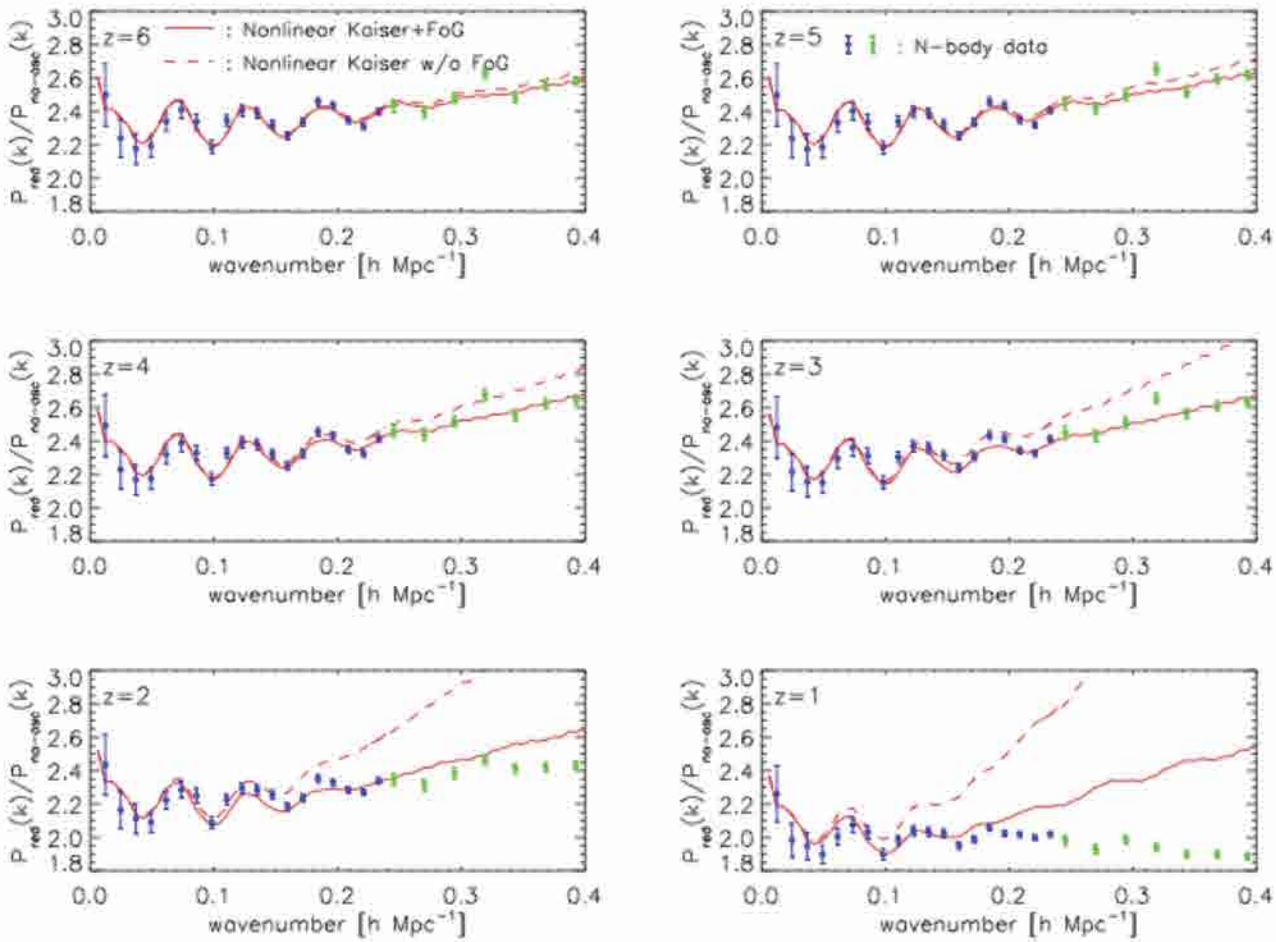
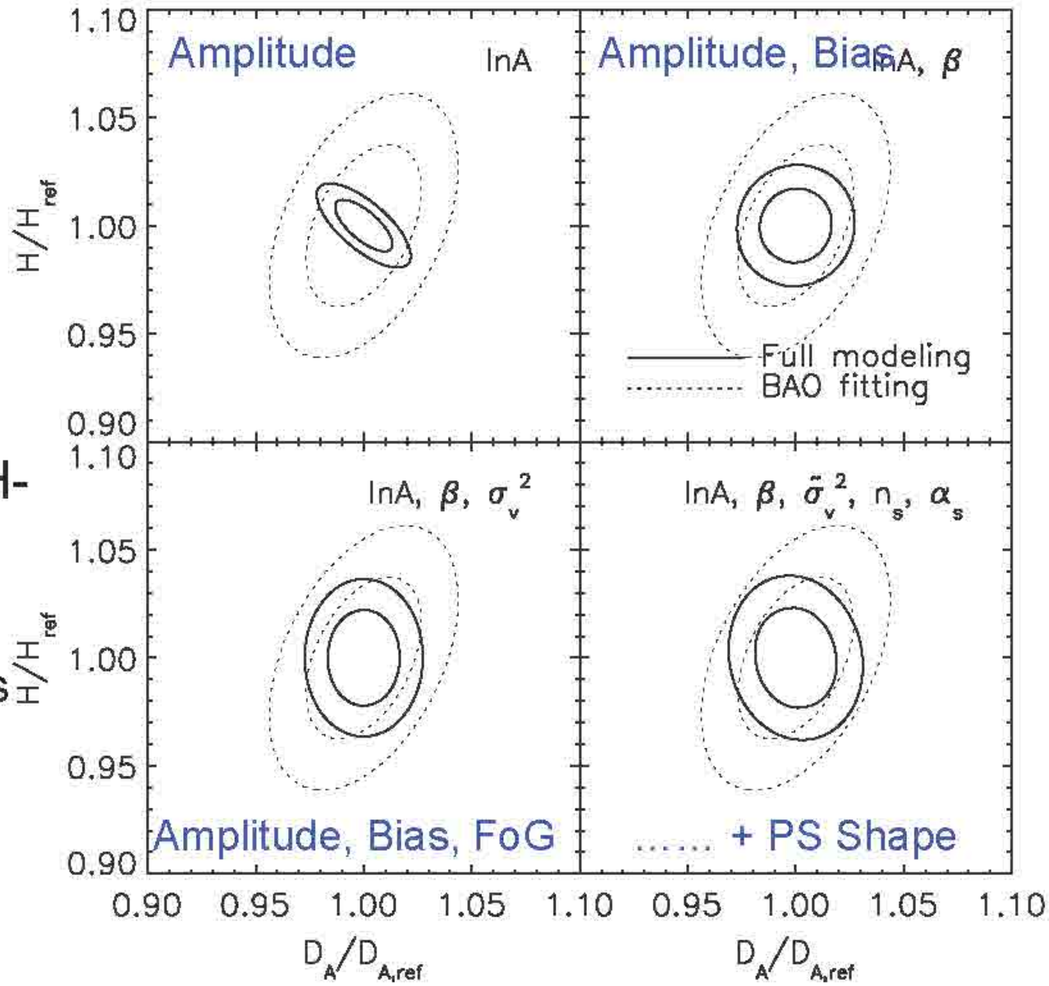


- Virial motion is parameterized by the velocity dispersion, which is included as an unknown free parameter
- We need a better way to model this without any free parameters, or with a parameter that can be measured by other means

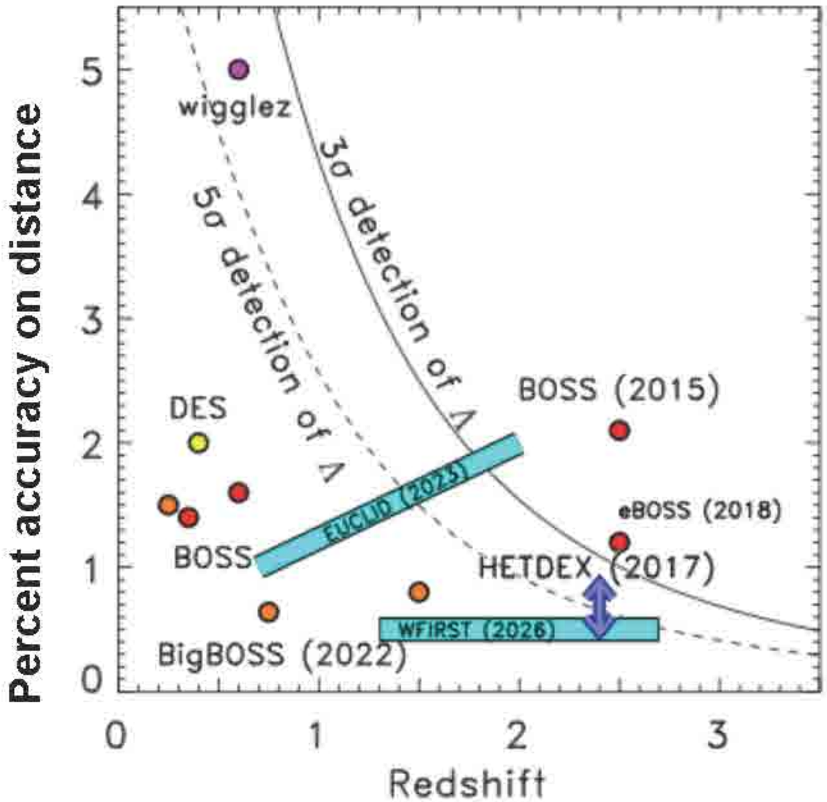
Full power spectrum modeling
(Shoji, Jeong, & Komatsu 2009)

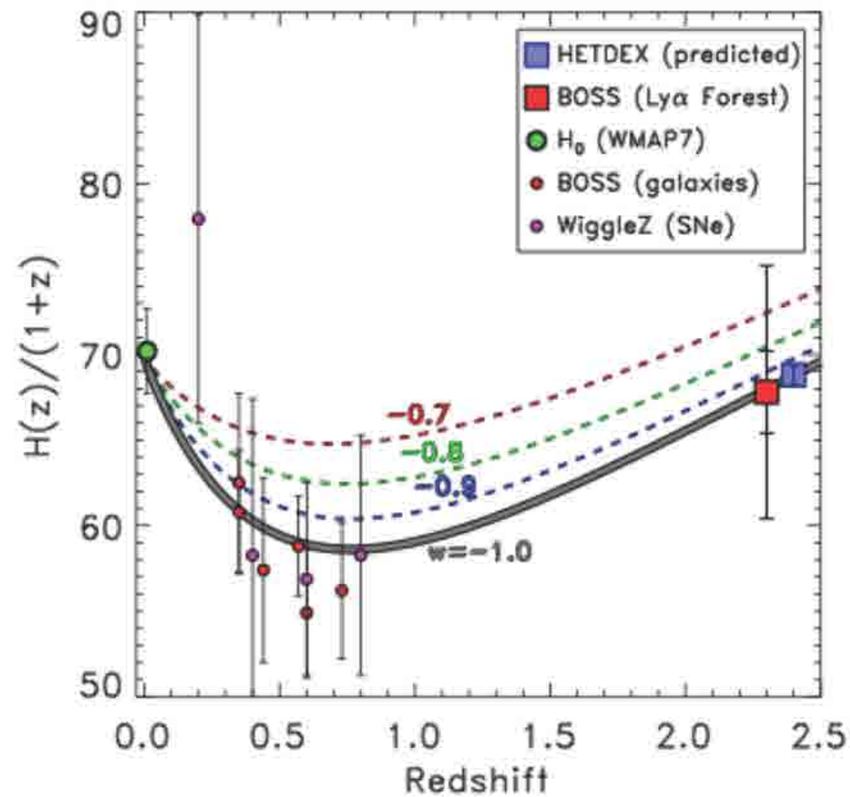
- 2-D power spectrum modeling including the effects of
  - structure growth
  - non-linear bias
  - redshift-space distortions
  - shape of PS
  - 0.8 M tracers b=2.5
- Comparison of constraints on H-D_A for BAO vs. full PS
  - Up to factor of 4 improvement
  - depending on what parameters are marginalized over
- Technique recovers H-D_A for Millennium simulation



Shoji, Jeong & Komatsu, ApJ 693, 1404, 2009

Ongoing and proposed efforts



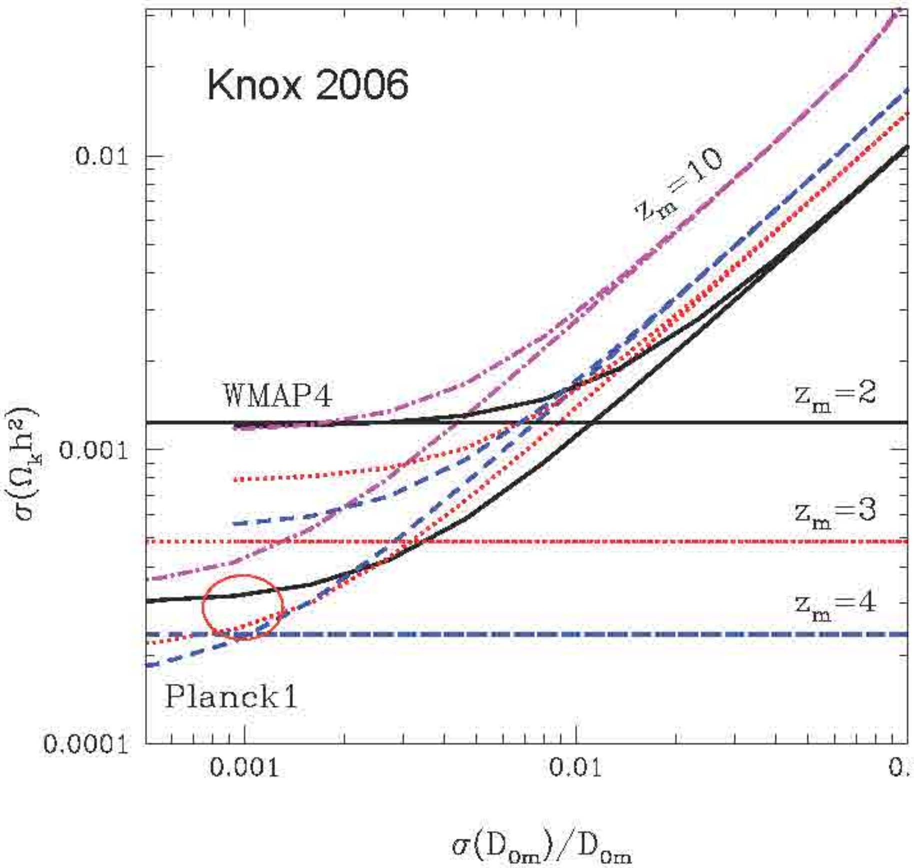


- HETDEX: 2014-2017, $1.9 < z < 3.5$
- BOSS: 2009-2014, $z = 0.35, 0.6, 2.5$
- WIGGLEZ: done, $0.5 < z < 0.8$
- DES: 2012-2016, $0.3 < z < 1.0$
- eBOSS: 2015-2018, $z \leq 2.5$
- EUCLID: 2019-2025, $0.8 < z < 2.0$
- WFIRST: > 2020

Curvature

$$\left(\frac{H(z)}{H_{100}}\right)^2 = \omega_r(1+z)^4 + \omega_m(1+z)^3 + \omega_k(1+z)^2 + \omega_\Lambda(z)$$

- Expect curvature very close to flat (10^{-5}) in inflationary universe
  - Often assumed flat, but currently only known to 1-2%
  - Can become a dominant unknown in high precision dark energy experiments at low z
- Comparison of d_A between z~2-3 and recombination can measure $k=\Omega_k h^2$ to ~0.2% (Knox 2006)
  - Which depends mainly on k in the matter dominated era
  - Due to the much smaller contribution of dark energy between z~2-3 and recombination, compared to lower redshift



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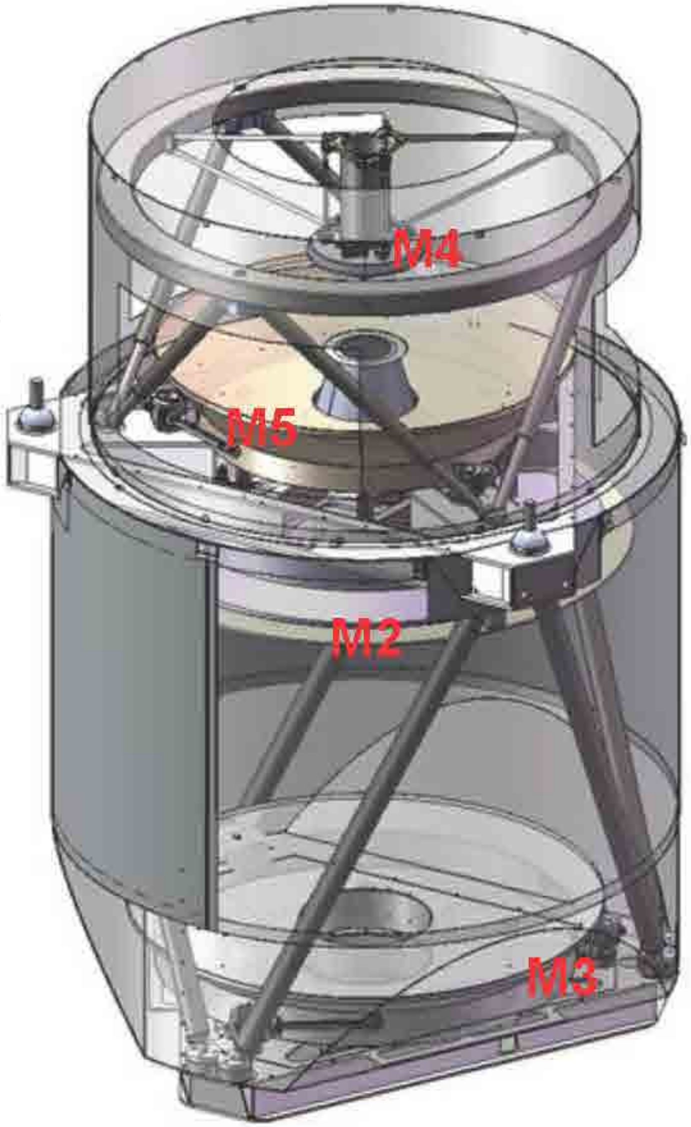
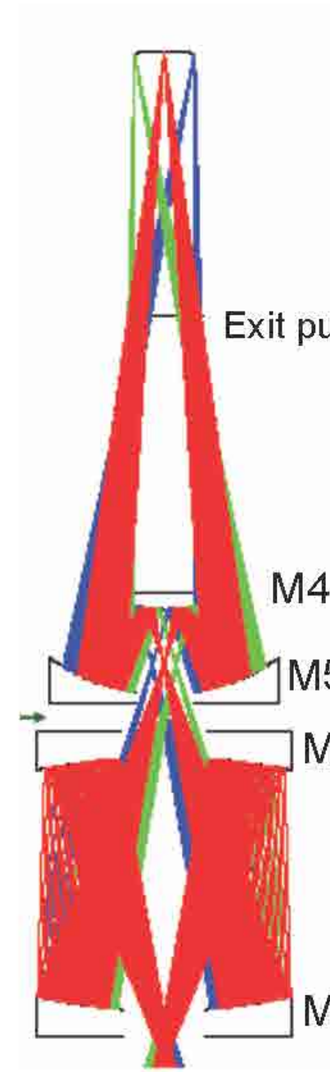
The HET Wide Field Upgrade and VIRUS

Wide Field Corrector

- Four mirror corrector with meter-sized optics and large aspheric departures
  - 22 arcmin diameter field of view
  - 10 m pupil diameter
- Subcontracted to the University of Arizona College of Optical Sciences
- Challenge for polishing, testing, mounting, and alignment
- Reflective coatings cover 350 to1800 nm
- Unit is sealed and purged with nitrogen to protect coatings





New HET tracker

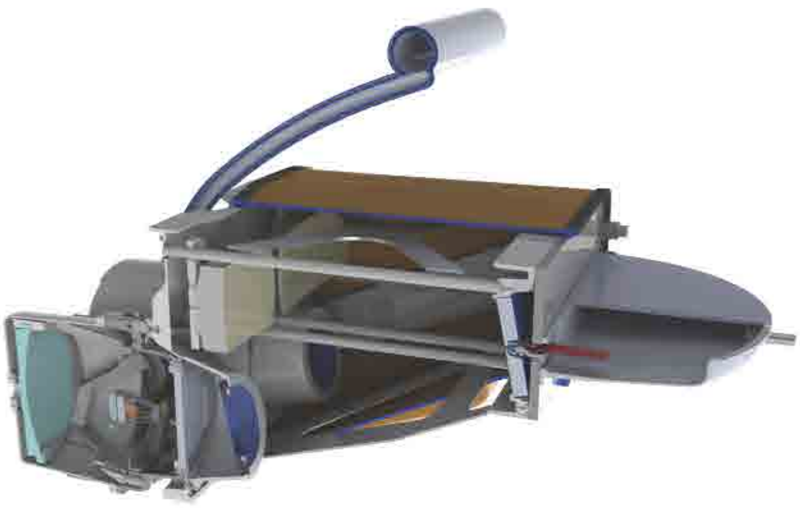
UT Austin Center for Electromechanics and McDonald Observatory

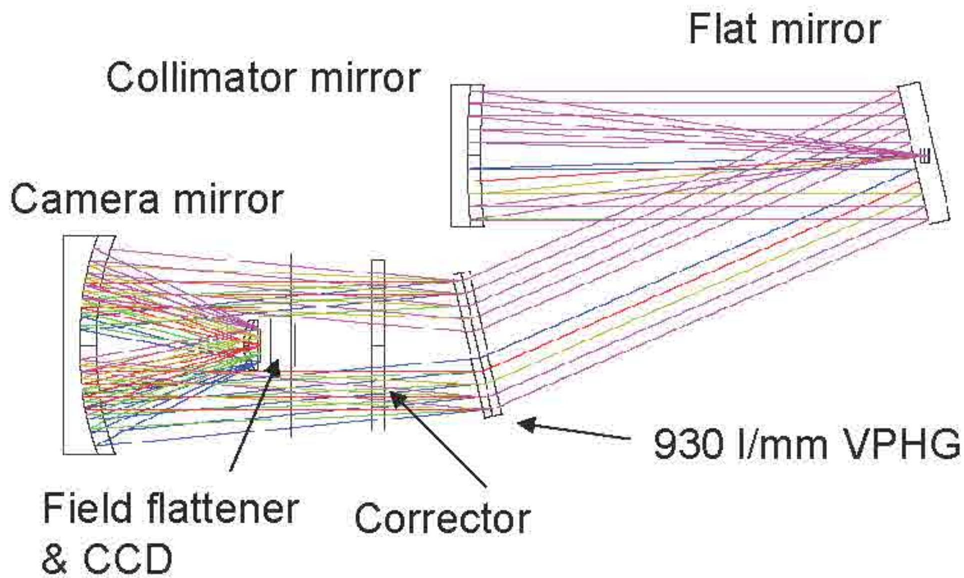
Tracker assembled in CEM high bay in Austin

- Need to increase tracker payload 4-fold
- Tracker locates payload to 5 μm accuracy within a 7x7x4 m^3 volume
- X,Y linear axes
- Hexapod for other degrees of motion
- We are now testing the tracker meets its requirements
- Effort will be complete in late July
- Tracker will be packed and shipped by end of September

VIRUS

- VIRUS is a simple spectrograph replicated on large scale
  - 150 channel fiber-fed IFS placing >33,600 1.5" dia fibers on sky
  - 350-550 nm coverage and R~700
  - Optimized to detect LAEs via blind integral field spectroscopy
- VIRUS protoype has been used at McDonald 2.7 m for 5 years
  - Used for HETDEX Pilot Survey (Adams et al 2010, Blanc et al 2010)
  - Proved the optical design, principles of the mechanical design, and the data reduction software





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VIRUS hardware components

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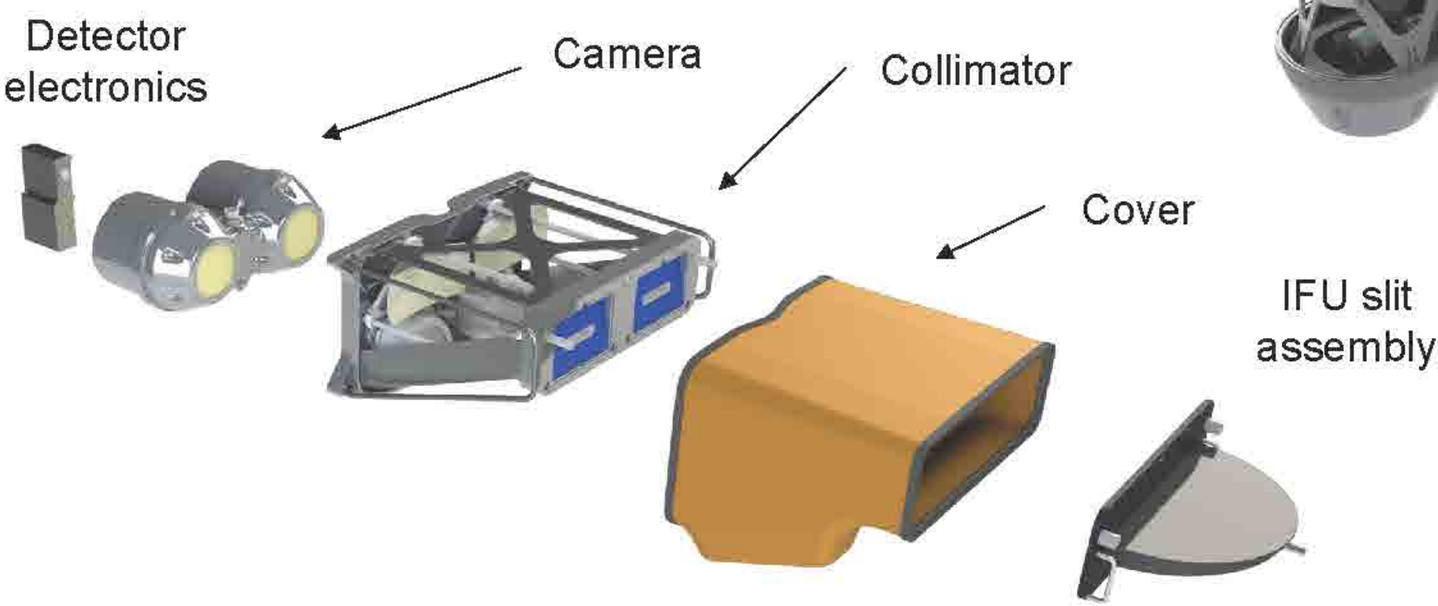
- Fiber IFU production led by AIP
- Collimator production led by TAMU
- Camera production led by UT Austin
- Data pipeline lead by MPE
- Many mechanical parts produced by Oxford and IAG

- Three fiducial spectrographs used to ensure interchangeability of parts



IFU Production @ AIP

- Leibniz Institut Potsdam (AIP)
- 18 m average length; 448 fibers per IFU (1.5 arcsec diameter on sky)
- Production IFU cables are being assembled at two vendors plus at AIP

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Collimator Production @ TAMU

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- Collimators being assembled at TAMU
  - Many parts supplied by Oxford

Complete Collimator assemblies

VPH gratings being assembled into cells

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VIRUS camera assembly @ UT

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Camera mirror in mount

Complete Camera Mirror Assembly

x 150
Thousands of parts in hand

Detectors and CMA integrated into housing

Invar "spider" support with CCD and field flattener installed

Units undergoing testing in lab

AIP Potsdam

UT Austin

VIRUS production unit in lab

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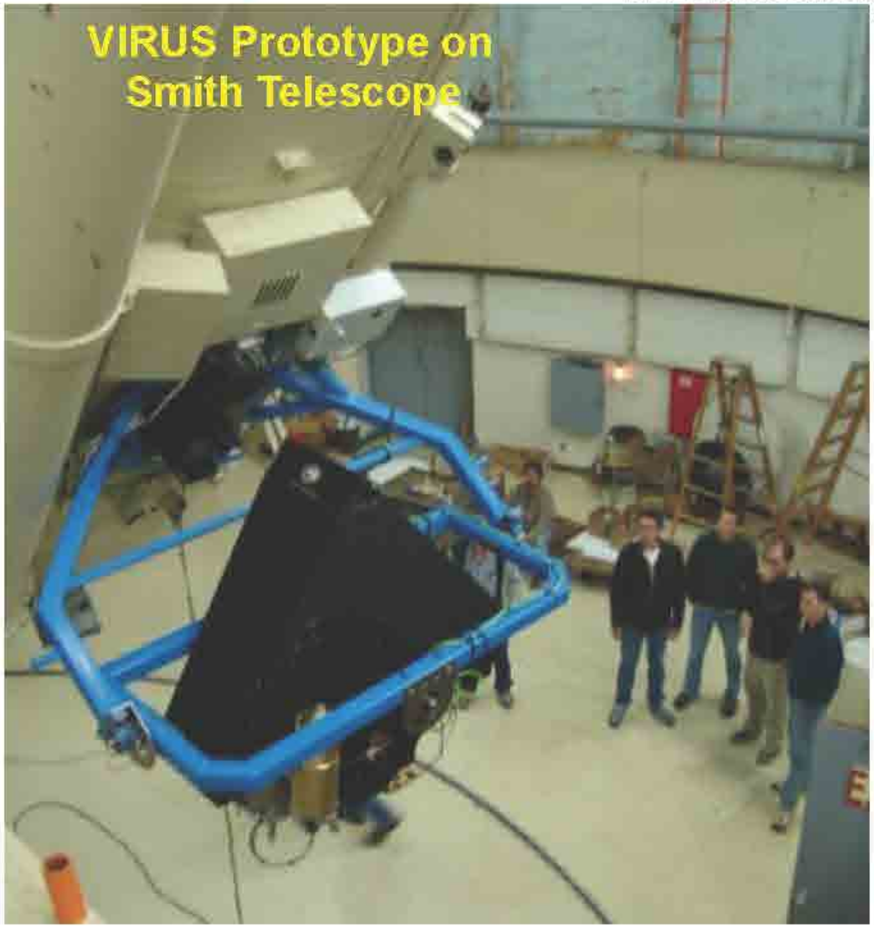
Proving HETDEX: the VIRUS Prototype

HETDEX Pilot Survey (HPS)

- Mitchell Spectrograph (VIRUS-P) observations on the McDonald 2.7 m Smith Telescope
  - 200 nights
  - 166 sq. arcmin.
  - 350-580 nm R~900
- Executed by Graduate students Josh Adams and Guillermo Blanc
- Tests the fundamentals of HETDEX
- First "wide field" integral field spectroscopic survey
  - Blind spectroscopy complements narrow band imaging
  - Much larger volume probed than NB imaging
- Mitchell Spectrograph has been used for many other investigations, especially where low surface brightness sensitivity is required

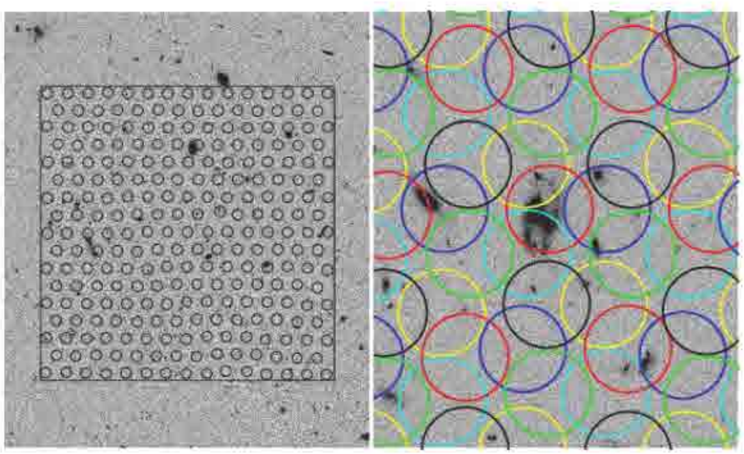


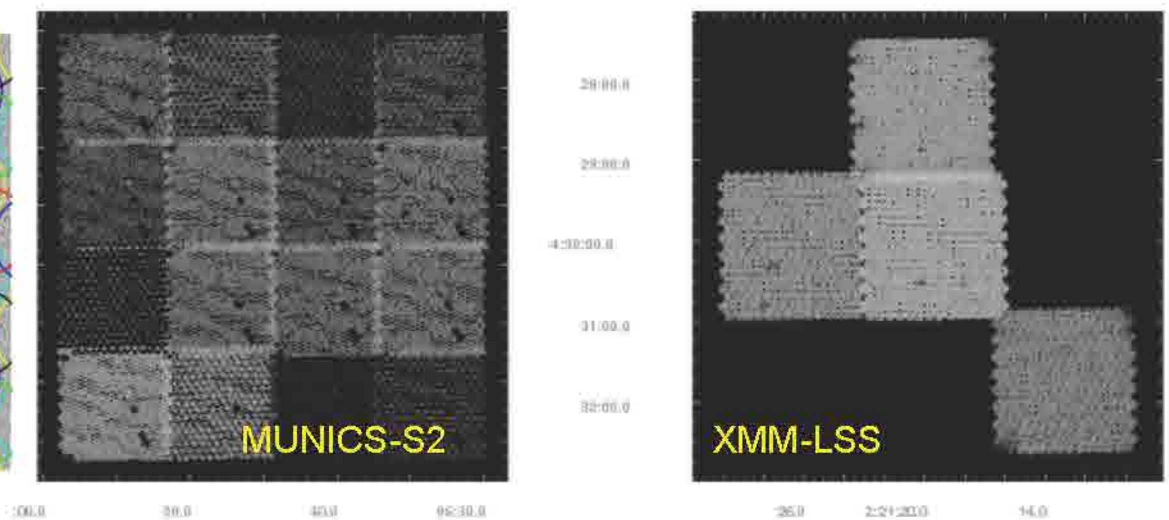
Adams, et al., 2011, ApJS, 192, 5
Blanc, et al., 2011, ApJ, 736, 31
Finkelstein et al., 2011, ApJ, 729,140
Ciardullo et al., 2013, ApJ, in press

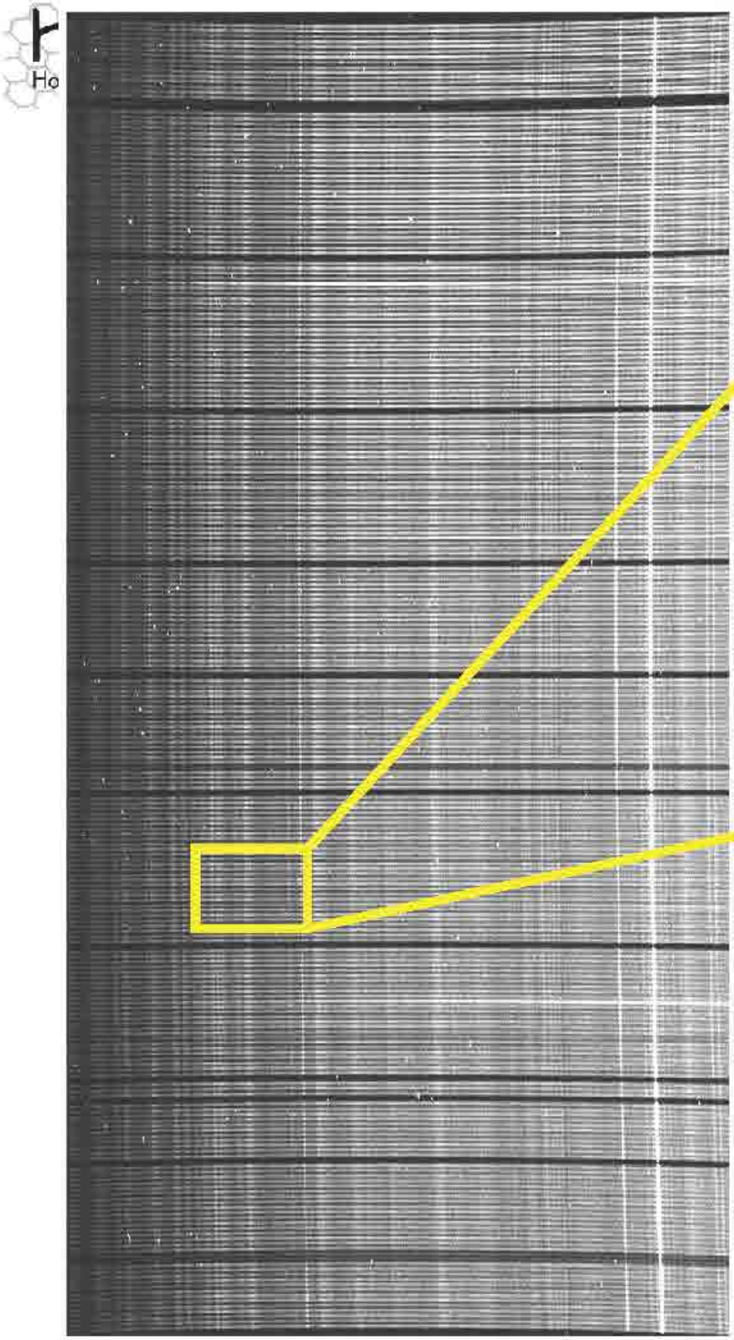
HETDEX Pilot Survey

- Survey volumes
  - 1.03×10^6 Mpc^3 for Ly-α
  - 4.24×10^4 Mpc^3 for [OII]
- 104 bright LAEs and 293 [OII] emitters detected to 6e-17 erg/cm^2/s
- LAEs and [OII] cleanly separated by observed line equivalent width
- 6 AGN among Ly-α detections
- Fields selected to have deep multi-wavelength broad-band imaging

Adams, et al., 2011 ApJS, 192, 5







Example Data

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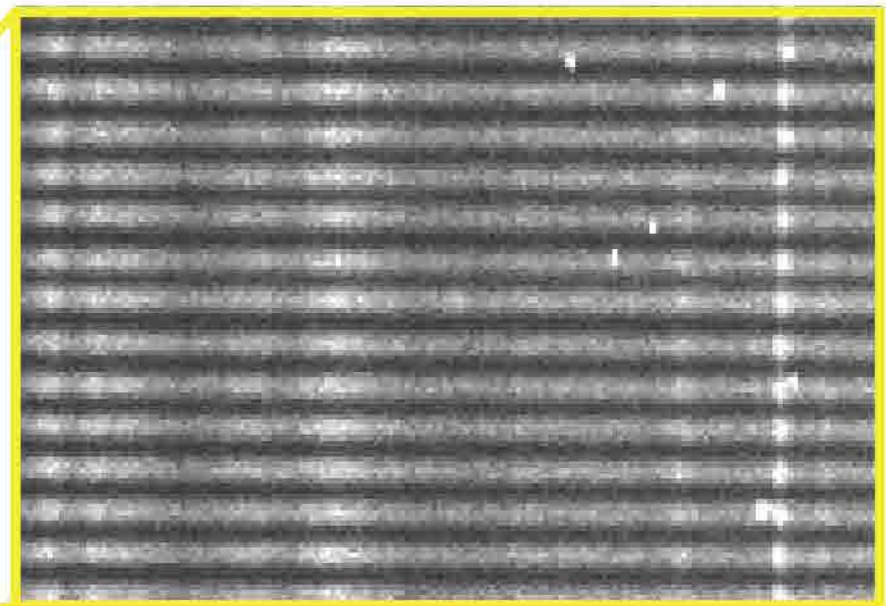

- 6 position dither pattern ensures good field coverage
  - 4.1 arcsec dia fibers on 2.7 m
- Three 20 min exposures at each position cover 3 sq. arcmin
- 2 hr of effective exposure time

Example Data

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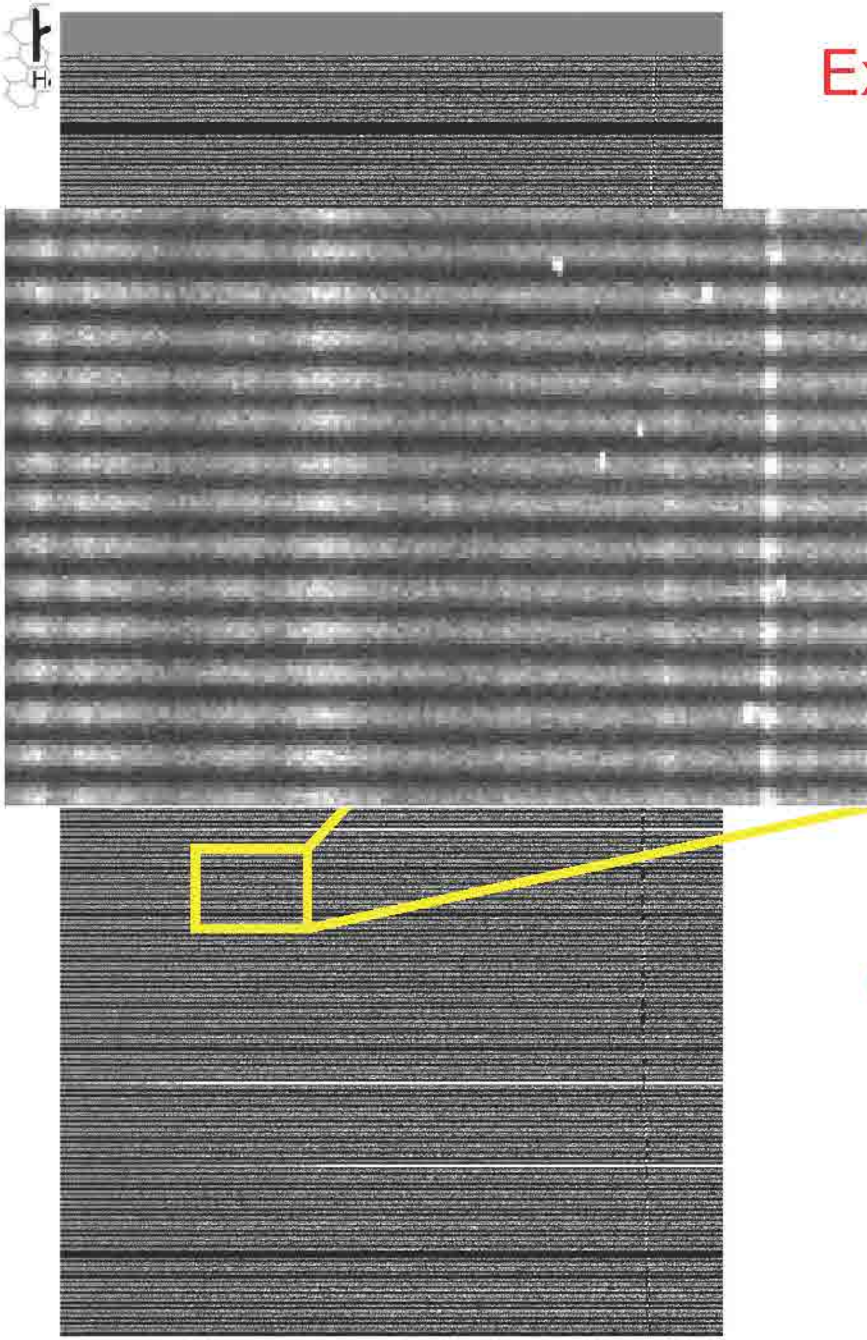

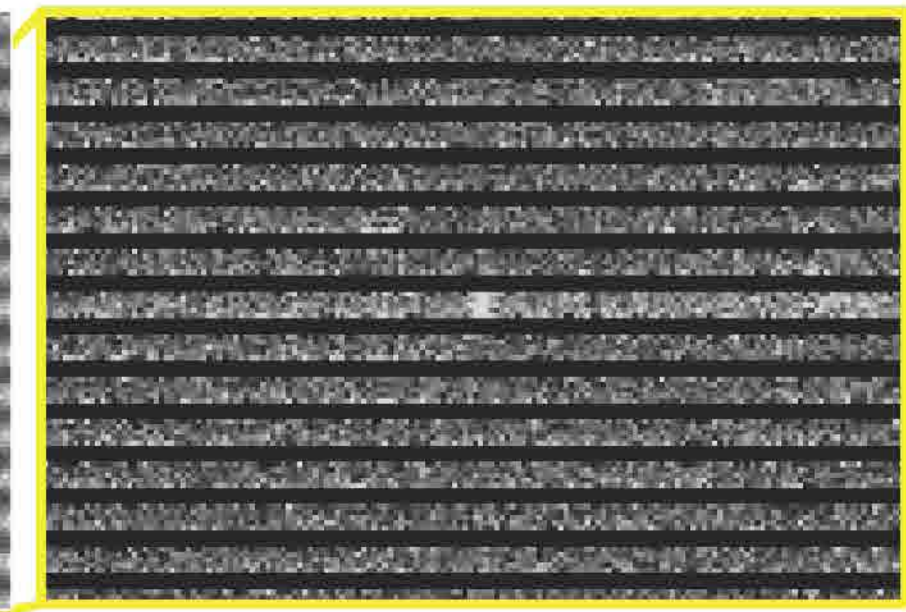

- VIRUS data reduced with two independent pipelines
- Vaccine (U. Texas) and Cure (USM/MPE Munich)
- 5σ flux limit of ~6×10^{-17} erg/s/cm^2 for a point-source and unresolved line

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Lyα Luminosity Function

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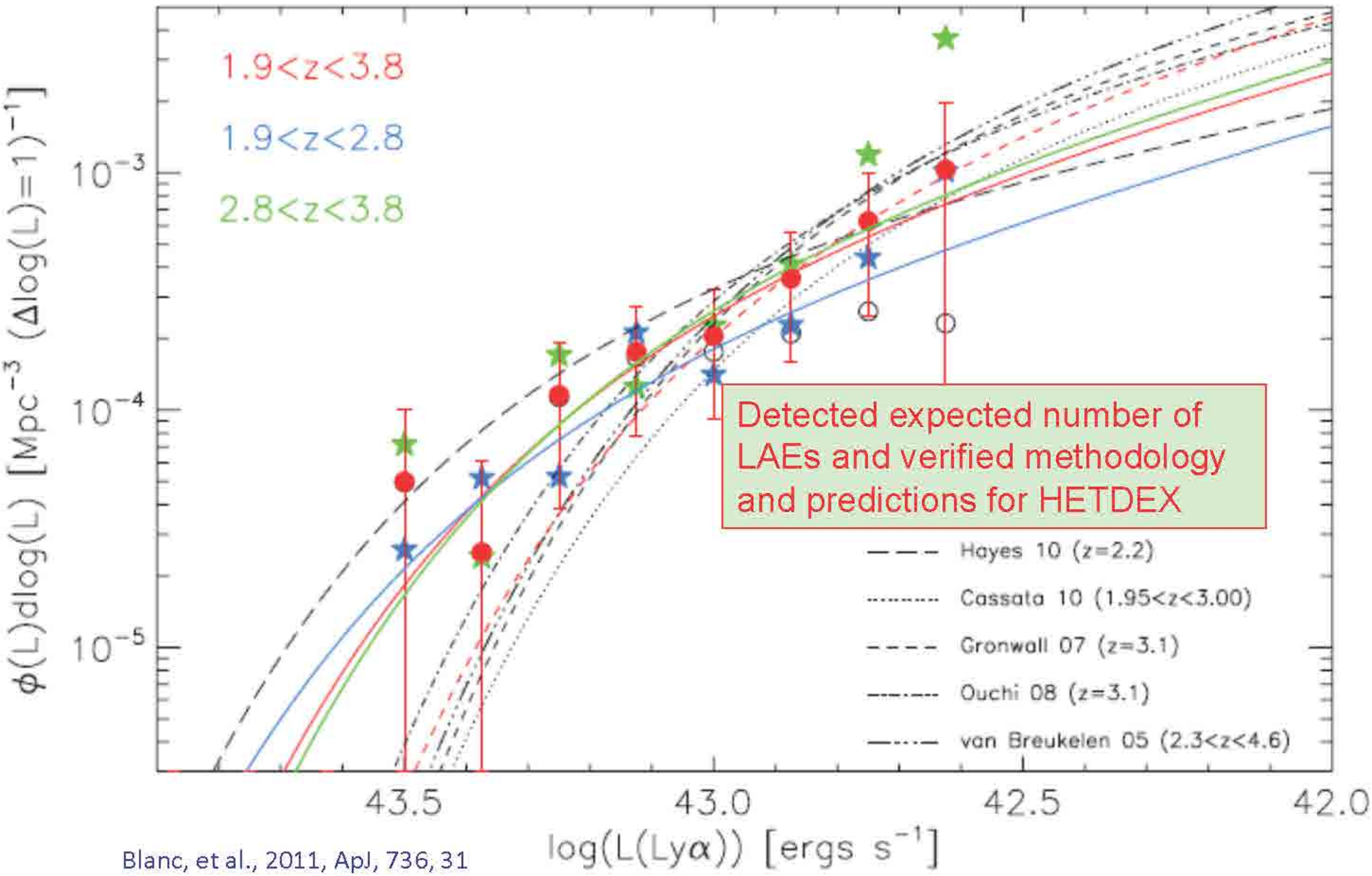

Blanc, et al., 2011, ApJ, 736, 31

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HETDEX Survey – geometry and example science

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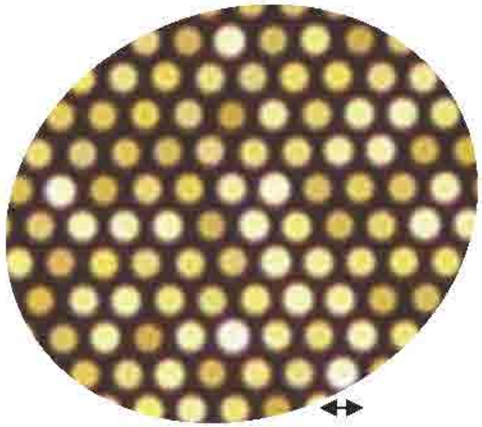
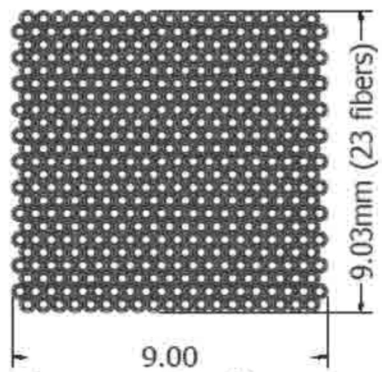
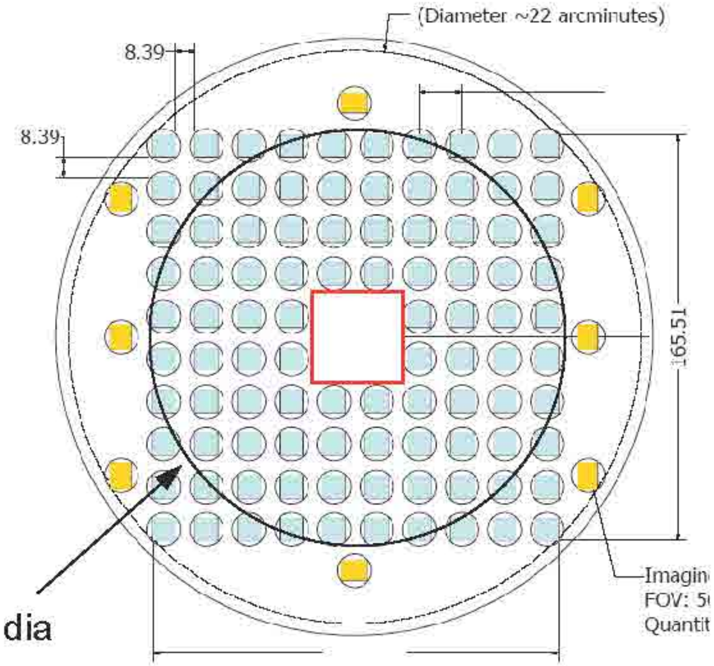
Observing footprint of VIRUS



1.5" dia fibers in 1/3 fill hexagonal close pack

IFU Layout





IFUs arrayed on a basic 50 arcsec pitch square grid

50"x50" field covered in 3 dithers in 20 minutes exposure

This shows the layout for 96 IFUs. We expect to deploy 75 and will concentrate them within 16 arcmin field diameter in a roughly hexagonal shape

HETDEX Survey

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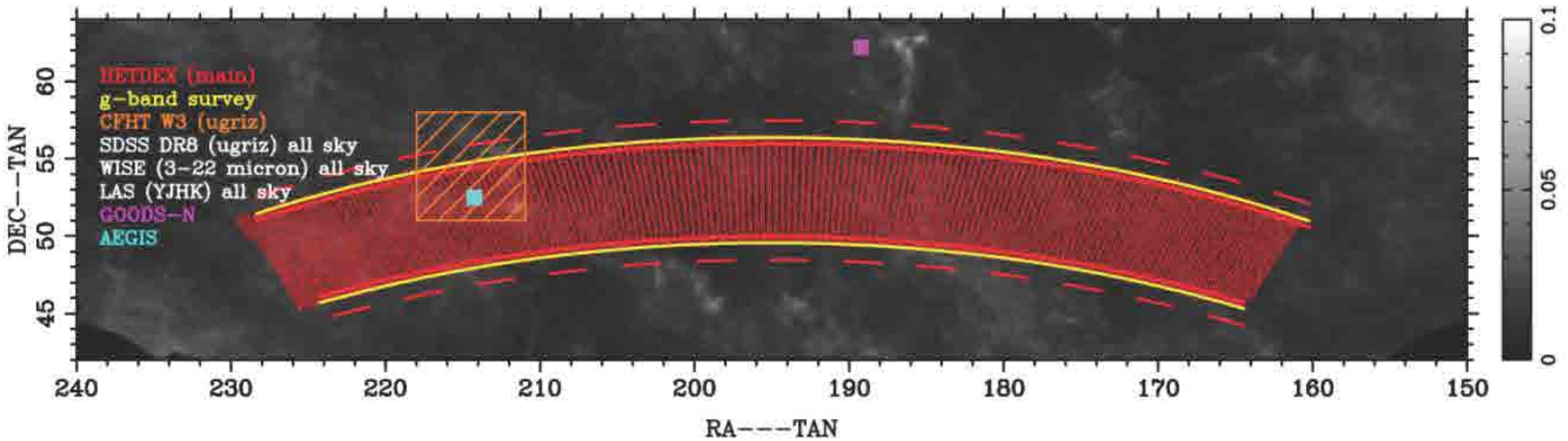
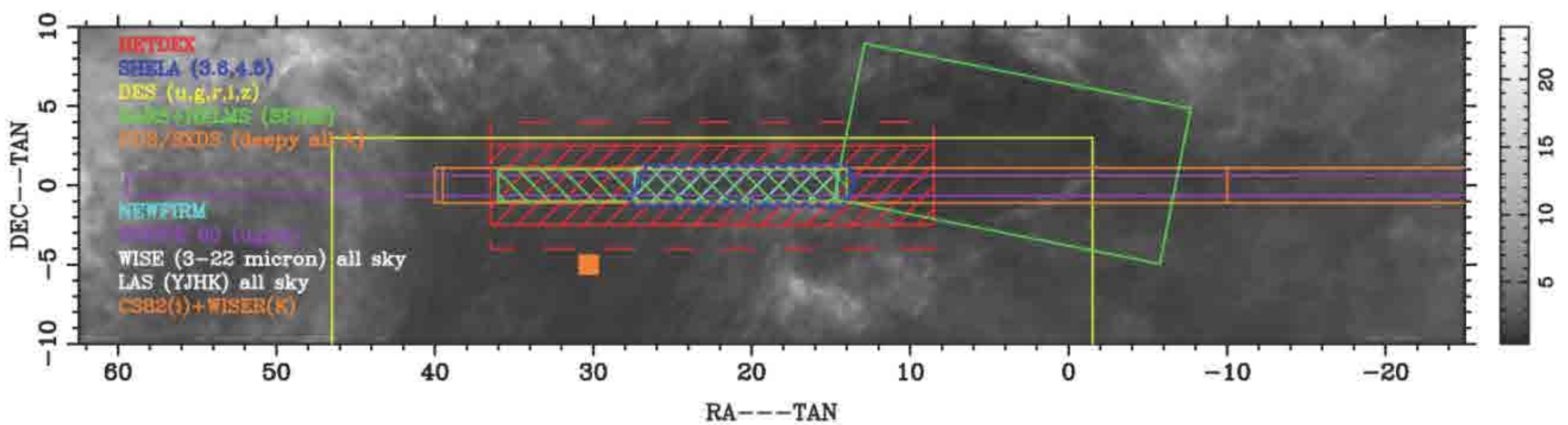
- Spring field - 300 deg^2 with 1/4.5 fill factor; 600k LAEs ≈ 0.5 LAE arcmin^{-2}.

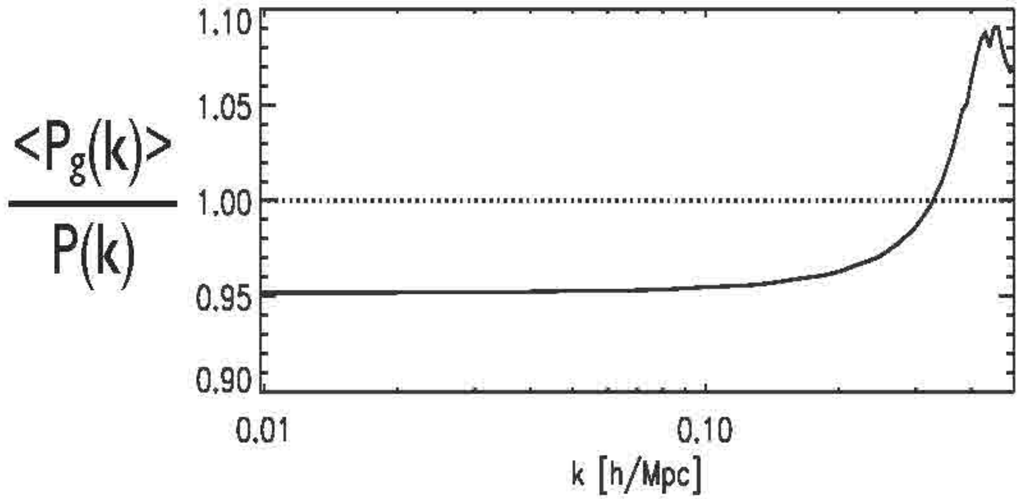


- Fall field - 150 deg^2 with 1/4.5 fill factor; 300k LAEs ≈ 0.5 LAE arcmin^{-2}.



Window function

- Sparse sampling is a central feature of HETDEX observing strategy
  - Mean density of LAEs is ~4x higher than needed
  - Inefficient to expose shorter due to read noise and overhead
- Separation of IFUs is ~1 Mpc
  - Causes feature in window function at k~π [h/Mpc)
  - No effect on scales of interest (k < 0.3)



- Hole in center of IFUs for other instruments is on a scale that causes a 5% depression of the power spectrum
  - Can be modeled & corrected
- Extensive modeling of WF
  - C-T Chiang et al, in prep

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Example science from HETDEX

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Cosmology and Galaxy Evolution

- Detection of dark energy at an early epoch
- Curvature of Universe to 0.2%
- Shape of matter distribution early in the Universe
- Total neutrino mass
- Detection of cosmic web in emission
- Nature of early galaxies

Nearby Galaxies

- Star formation at late times ([OII])
- Dark matter in nearby galaxies
- Stellar populations at large radii
- Galactic structure from stellar kinematics
- Map nearby galaxy clusters
- Study of the first stars in our Galaxy
- White dwarfs

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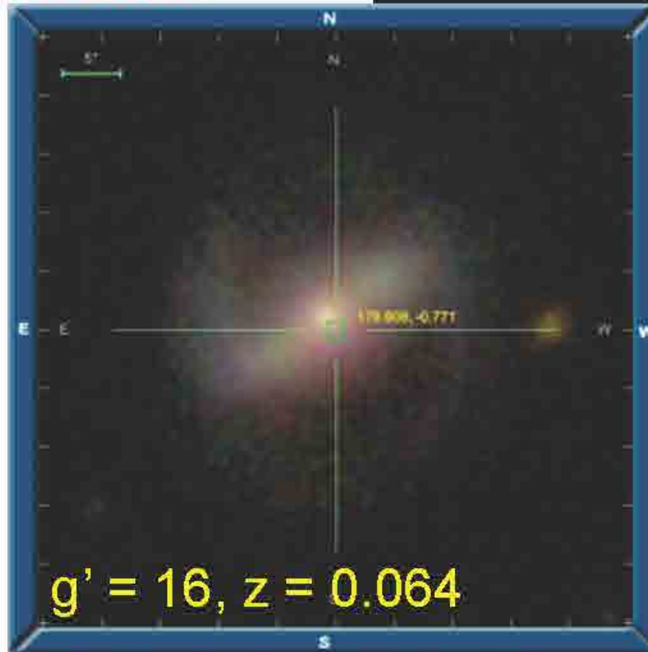
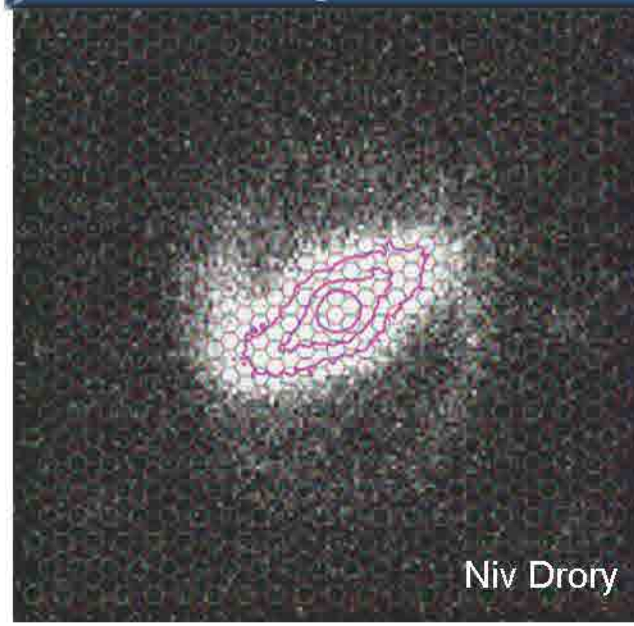
Nearby stars, galaxies, & clusters

HETDEX ∩ SDSS (survey realization)

44714	stars with g<22 (S/N ≈ 3)
50579	galaxies with g<22 (S/N ≈ 3)
789	stars with SDSS spectrum in IFUs
4204	galaxies g<17 (rotation curves)
9101	galaxies g<19 & D>5"

- VIRUS probes stars deeper and bluer than other galactic structure surveys
  - Will include tens of extremely metal poor stars
- Large sample of resolved galaxies (z<0.1)
  - Rotation curves and dark matter distributions to SDSS surface brightness limit
  - Spatially-resolved star formation rates
  - Cross with new Westerbork APERTIF HI survey
- Continuum spectra of stars and galaxies to ~SDSS photometric limit (at >5σ per resolution element)
- 2000 Abell richness clusters covered (z<0.45)
  - Selected by spectroscopic signature
  - Complements eROSITA X-ray and HSC weak lensing

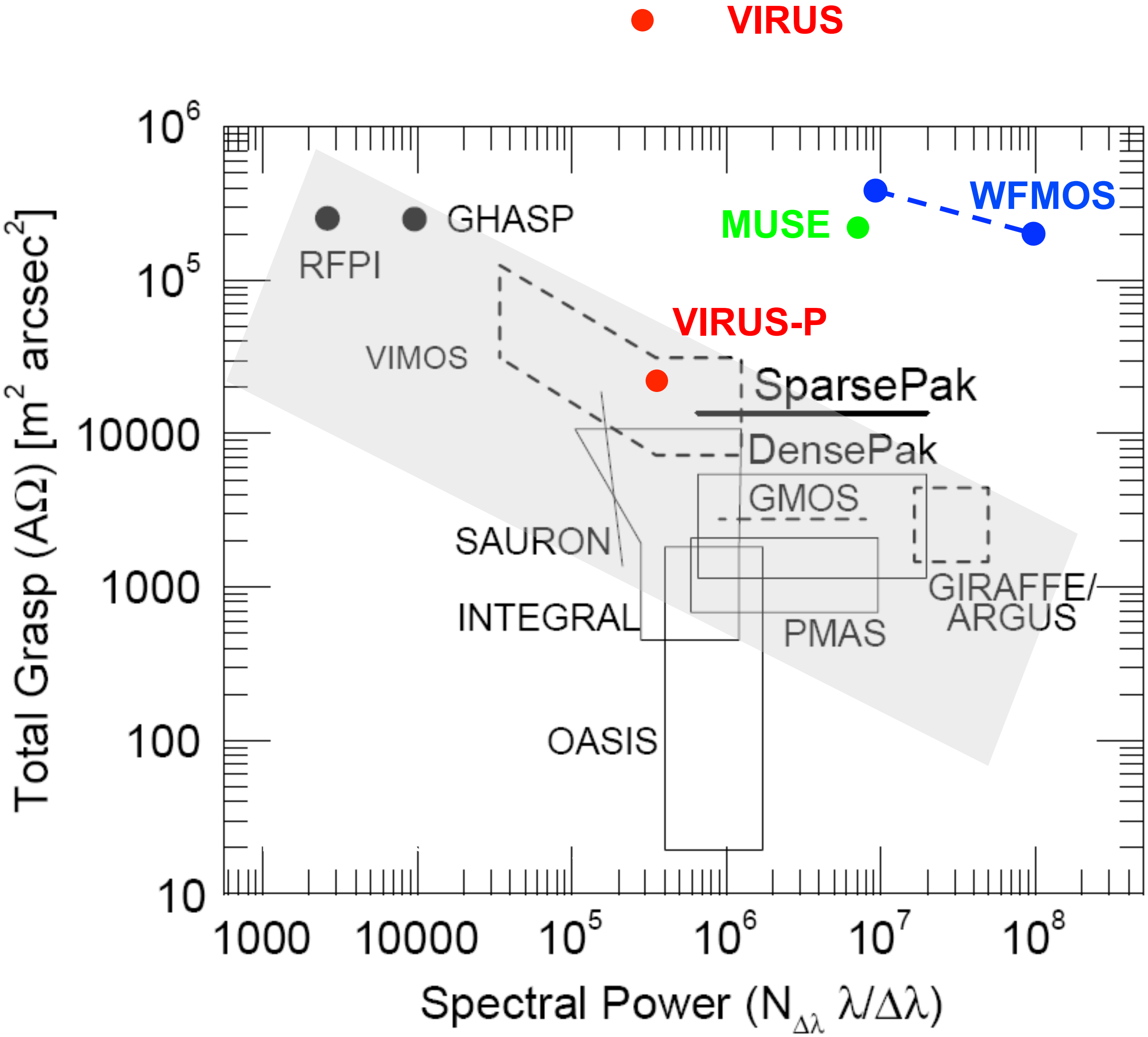




Hobby-Eberly Telescope Dark Energy Experiment

The power of VIRUS

McDonald Observatory
THE UNIVERSITY OF TEXAS AT AUSTIN



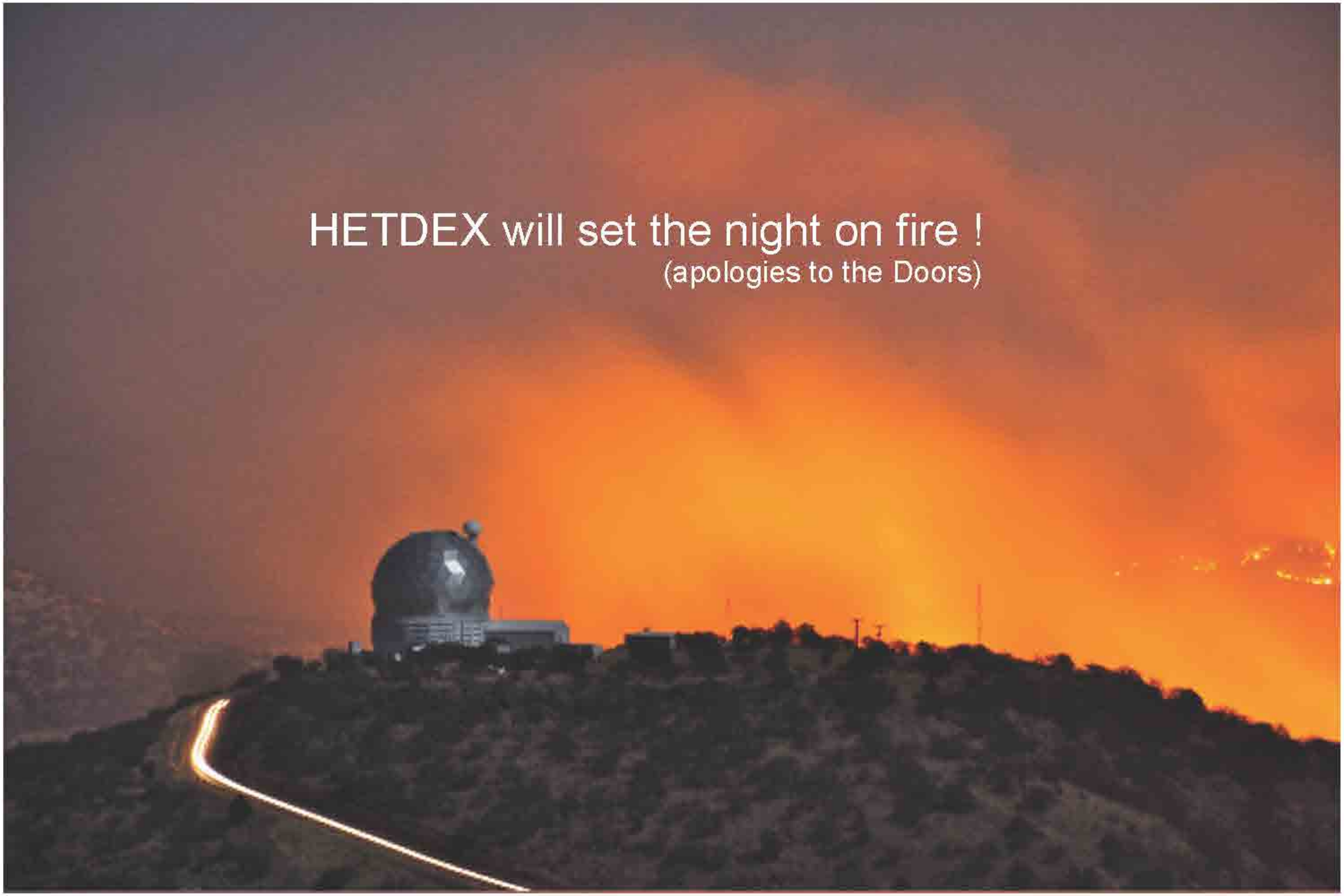
Bershady et al. 2004

Summary

- VIRUS is in full production
  - Production will extend through 2013 and be complete in 2014
  - Majority of units will be deployed in time for HETDEX survey in Q2 2014
- HET Wide Field Upgrade is expected to be deployed by early 2014
- The combination of the upgraded 10 m HET and VIRUS will create a unique survey facility
  - Opens up new parameter space in wide-field blind spectroscopy
  - >33,000 fibers each 1.5 arcsec on sky gives huge grasp – 60 sq. arcmin. per exposure
  - Incredible grasp for low surface brightness measurements

New HET tracker

Expect 150 LAEs in the first 20 minute observation with VIRUS on HET – more than we detected in 100 nights in the HETDEX Pilot Survey !


HETDEX will set the night on fire !
(apologies to the Doors)