Mapping the large-scale structure of the Universe with emission-line galaxies from $z=0.6$ to 3.5: HETDEX and PFS

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Why Large-scale Structure?

• “End-to-end Test of the Universe”

• Cosmology as an initial-value problem
  
  • The initial fluctuation is constrained quite well by the cosmic microwave background data
  
  • We then evolve the initial fluctuation forward, assuming a cosmological model and gravitational theory
  
  • Does the prediction agree with what we see in the data in a late-time Universe?
State-of-the-art

- There is an indication that the E2E test is failing for a flat $\Lambda$CDM model
  - $H_0$
  - Amplitude of matter fluctuations in a low-z universe
- There is also an indication that the current large-scale structure data sets may not be consistent with each other
H0LiCOW XIII. A 2.4% measurement of $H_0$ from lensed quasars: 5.3σ tension between early and late-Universe probes


appeared on July 12

We present a measurement of the Hubble constant ($H_0$) and other cosmological parameters from a joint analysis of six gravitationally lensed quasars with measured time delays. All lenses except the first are analyzed blindly with respect to the cosmological parameters. In a flat $\Lambda$CDM cosmology, we find $H_0 = 73.3^{+1.7}_{-1.8}$, a 2.4% precision measurement, in agreement with local measurements of $H_0$ from type Ia supernovae calibrated by the distance ladder, but in 3.1σ tension with Planck observations of the cosmic microwave background (CMB). This method is completely independent of both the supernovae and CMB analyses. A combination of time-delay cosmography and the distance ladder results is in 5.3σ tension with Planck CMB determinations of $H_0$ in flat $\Lambda$CDM. We compute Bayes factors to verify that all lenses give statistically consistent results, showing that we are not underestimating our uncertainties and are able to control our systematics. We explore extensions to flat $\Lambda$CDM using constraints from time-delay cosmography alone, as well as combinations with other cosmological probes, including CMB observations from Planck, baryon acoustic oscillations, and type Ia supernovae. Time-delay cosmography improves the precision of the other probes, demonstrating the strong complementarity. Using the distance constraints from time-delay cosmography to anchor the type Ia supernova distance scale, we reduce the sensitivity of our $H_0$ inference to cosmological model assumptions. For six different cosmological models, our combined inference on $H_0$ ranges from 73–78 km s$^{-1}$ Mpc$^{-1}$, which is consistent with the local distance ladder constraints.
How do we explain this?

• Insomma, non so come…

• This is the “Early Universe Probe vs Late Universe Probe” tension
  
  • My approach is to “ask the sky”. We keep cross-checking them with more data, until we find new explanation(s)

• In fact, it may not be just $H_0$…

  • The amplitude of matter density fluctuations in the late time Universe measured by the large-scale structure seems low compared to what we infer from CMB

  • Not yet too significant ($\sim 3\sigma$), but it is persistent

• More data on both early and late Universe probes are necessary
I talked about these 4 weeks ago

CMB: Early Universe Probe

CCAT-prime [2021–]

LiteBIRD [JFY 2027–]

HETDEX [2017–2023]

PFS [2022–]

Today’s topic
LSS: Late Universe Probe
The present-day amplitude of the matter fluctuation constrained by the low-z data appears to be smaller than the one predicted by the evolution model given CMB.
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The present-day amplitude of the matter fluctuation constrained by the low-z data appears to be smaller than the one predicted by the evolution model given CMB.
Two known low-z effects

- So, there is some evidence that the end-to-end test is failing. Namely:
  - The locally measured $H_0$ appears to be larger than that predicted by the CMB+
  - The locally measured amplitude of fluctuations appears to be lower than that predicted by the CMB+

- Two effects that are known to influence the low-z evolution:
  - Neutrino mass
  - Dark energy/modified gravity

Large-scale structure!
Hobby-Eberly Telescope
Dark Energy Experiment

Location
McDonald Observatory (West Texas)

Primary Mirror Size
10 m

Wavelength Coverage
350–550 nm ($\Delta \lambda = 6.2 \text{Å}$)

Redshift (Ly$\alpha$)
z = 1.9–3.5

Spectrograph Type
Integral Field Unit (IFU)

Field of View
0.1 deg$^2$ (22’ diam.)

Fiber Diameter
1.5 arcsec

Survey Volume
2.8 (Gpc/h)$^3$

Survey Type
Blind

~20 Mpc in one go!

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Subaru Telescope

Location
Subaru Telescope (Hawaii)

Primary Mirror Size
8.2 m

Wavelength Coverage

- Blue: 380–650 nm ($\Delta \lambda = 2.1 \text{Å}$)
- Red(LR): 630–970 nm ($\Delta \lambda = 2.7 \text{Å}$)
- Red(HR): 710–885 nm ($\Delta \lambda = 1.6 \text{Å}$)
- NIR: 940–1260 nm ($\Delta \lambda = 2.4 \text{Å}$)

Redshift ([OII])
z = 0.02–0.74

z = 0.69–1.60

z = 0.90–1.37

z = 1.52–2.38

Spectrograph Type
Robotic Multi Object Fiber-fed

Field of View
1.25 deg$^2$ (1.38 deg diam.)

Fiber Diameter
1.2 arcsec

Survey Volume
8.2 (Gpc/h)$^3$

Survey Type
Traditional

PFS

# of fibers
34,944

# of fibers
2,394 + 96
Main Objective:
Cosmology

But, we can do:
- Properties of Lyman-alpha emitting galaxies
- Blind survey: Unbiased survey of everything

Three major science programs:
- Cosmology
- Galaxy Evolution
- Galactic Archeology

Main Objective:
Spectroscopic follow-up of targets detected by the imaging survey of Hyper Suprime Cam
• We want **accurate** and **robust** cosmology! (not just precision)
Science Cases (Cosmology)

- Not just testing tensions in $H_0$ and the amplitude of fluctuations!

- **To rule out the standard ΛCDM model** (or to put the tightest limits on deviations)
  - If ΛCDM, HETDEX can detect Λ at $z>2$ for the first time

- **To rule out the inverted hierarchy of the neutrino mass** (or to discover it)

- And, we do a lot of non-cosmological projects too!

- I would love to discuss other ideas with you today. These instruments are really amazing
Experimental Landscape

- HETDEX
- DESI: 500 nights
- PFS: 300 nights
- Euclid (launch sometime in Jan-June 2022?)
Experimental Landscape

• We are the only players at $z>2$. Lasting impacts well beyond Euclid (~a billion dollar mission)
• We are the only players at $z>2$
• Lasting impacts well beyond Euclid (~a billion dollar mission)
IFUs fabricated at AIP

Long fibers!
(Each fiber sees 1.5")

Put into cables...

448 fibers per IFU

One IFU feeds two spectrographs

A test IFU being lit
Current VIRUS

- 47 IFUs (out of 78) are active now. More IFUs will be installed as they are built (at the rate of 3 units per month)

- $47 \times 448 = 21,056$ fibers! And this is the open-use instrument

*VIRUS = Visible Integral-field Replicable Unit Spectrograph
Example of full field on M3. Green boxes are the IFU locations.

~1 arcmin, completely filled by fibers (after 3 dither)
Prime Focus Instrument (2 tons!)

Fibers

Detectors / Cryogenic system

One VIRUS Detector Unit

cameras

Fibers

Hobby-Eberly Telescope with VIRUS
Tracker
("An eye ball")

Strongback

Hexapod

Lower hexapod frame

Y-axis actuator

Upper hex

Tracker bridge

X-axis actuators
This is the real one!
HETDEX Foot-print (in RA-DEC coordinates)

Volume = 2.8 (Gpc/h)^3
Survey Strategy

4000 shots in the northern region ("spring field")
• Each “shot” in the sky contains 78 IFUs
• Spending 20 minutes per shot ~ 200 LAEs
• We do not completely fill the focal plane
• This is the “sparse sampling” technique
What do we detect?

- $\lambda=350$–550nm with the resolving power of $R\sim700$ down to a flux sensitivity of a few $10^{-17}$ erg/cm$^2$/s will give us:
  - $\sim1$M Lyman-alpha emitting galaxies at $1.9<z<3.5$
  - $1/10$ of them would be AGNs
  - $\sim1$M [OII] emitting galaxies at $z<0.47$
  - ...and lots of other stuff, like white dwarfs, **blindly** selected/discovered
Current HETDEX Data
(~10% of the full survey data)

• **64 million** calibrated spectra!
  
  • 47,880 IFUs on the sky
  
  • 47,880 x 448 (# of fibers per IFU) x 3 (dither) = 64M
  
  • And this is only 10% of the full survey data!
  
  • Goal: 468,000 IFUs on the sky
  
• **629M calibrated spectra. This is the big data!**
A typical hetdex field

Reconstructed image of the 21k fibers. Filled squares are active IFUs, open squares are those remaining.

In this frame, we would use about 15 of the stars for astrometry and throughput measures.
Example calibration check, using 2 white dwarfs from SDSS (virus in red, SDSS in black)
Examples from one field

20180123v089 1269.pdf
Obs: 20180123v09.1
Entry# (1269), Detect ID (1)
Primary IFU Slot 074
RA,Dec (150.638250,2.127700)
λ = 5174.44Å  FWHM = 9.447Å
EstFlux = 4.58e-16
EstCont = 5e-19
EW r(LyA) = 215Å
S/N = 20.82
P(LAE)/P(OII) = 999
LyA z = 3.2553  OII z = 0.3884

STACK_COSMOS: Possible Matches = 0 (within +/- 2.5") No continuum floor baseline defined.

Fiber Positions  Subaru HSC g  u  g  r  i  z
SDSS-III/BOSS (z=0.6)  

Full survey expectation for HETDEX (z=2.5)
One of the “Red” Spectrograph Modules being tested at LAM
One of the “Red” Spectrograph Modules being tested at LAM
S/N for $5 \times 10^{-17}$ (erg cm$^{-2}$ s$^{-1}$) [OII] doublet

by K. Yabe
Robotic Fiber Positioner “Cobra”

Prime Focus Instrument (PFI)

The hexagonal focal plane: 2394 fiber positioners are assembled in the 42 modules.

“Cobra” actuators (production batch)

“Top” view

“Cobra” optical bench

“Cobra” eng. model module
HSC Image of M31 (HSC FoV=1.8 sq. degrees)

reduced by HSC pipeline (Princeton, Kavli IPMU, NAOJ)
PFS will populate 2394 individual fibers for simultaneous spectroscopy over this hexagonal field.

\[ \sim 1.5 \text{ deg} \]
PFS Foot-print (in RA-DEC coordinates)

1400 deg$^2$
Volume = 8.2 (Gpc/h)$^3$
PFS Foot-print (in RA-DEC coordinates)

Great region for cross-checks: LAE and [OII] in $z=1.9-2.4$
Target Selection

Number of emission-line galaxies predicted by “COSMOS Mock Catalog (CMC)”

Goal: To select objects in $0.6 < z_{\text{photo}} < 2.4$ from the galaxies detected by HSC.
Target Selection

Number of emission-line galaxies predicted by "COSMOS Mock Catalog (CMC)"

Goal: To select objects in $0.6 < z_{\text{photo}} < 2.4$ from the galaxies detected by HSC.

Updated CMC: $0.6 < z_{\text{photo}} < 2.4$

$23.2 \leq g \leq 24.1$ AND $0 < g - r < 0.35$

mod T14 (S/N>6)

t14
Example Deliverables: Galaxy Power Spectra

- There are six more redshift bins
PFSxHSC: Galaxy-weak lensing

Cross Spectra

$S/N=19$

$S/N=26$

$S/N=23$

$S/N=19$

$S/N=12$

$S/N=8$

$S/N=6$

$z = 0.7$

$z = 0.9$

$z = 1.1$

$z = 1.3$

$z = 1.5$

$z = 1.8$

$z = 2.2$

$l^2C_l$

Multipole $l$
PFSxHSC: Testing gravity

Galaxy-shear correlation divided by galaxy clustering

$E_g(z)$

$z$

Pengjie Zhang

PFS X HSC ($z > z_{PFS}$)

PFS X ACTpol

General Relativity

“DGP” braneworld

PFS’s unique territory

Prime Focus Spectrograph
Neutrino Mass
Two major goals

• To rule out the inverted mass hierarchy of neutrino masses by measuring $\sum m_\nu < 0.1$ eV (95% CL)

• or, to determine the total mass if $\sum m_\nu > 0.1$ eV

• To rule out the $\Lambda$CDM model by finding time evolution of dark energy density, $\rho_{DE} = \rho_{DE}(t) \neq \Lambda$

• or, to confirm it with unprecedented precision to $z=3.5$
Why Neutrino Mass Hierarchy?

• We know that neutrinos have masses, but we do not know the absolute value of the mass

  • Only mass differences between three mass eigenstates are known from the neutrino oscillation experiments

• Knowing the mass would be nice, but what appears to be more fundamental is the mass hierarchy

  • “Normal” vs “Inverted”
Mass Hierarchy

• Do we have two heavy states (inverted), or just one (normal)? $\sum m_\nu = 0.1$ eV is the key level

From Patterson (1506.07917)
Are neutrinos Dirac or Majorana?

- Deciding the mass hierarchy sets a concrete target for the neutrino-less double beta decay experiments

- Dirac or Majorana? Fundamental importance!

Capozzi et al. (2016)
Neutrino Mass Target in Landscape

- The current upper bound from cosmology (Planck+BOSS): $\sum m_\nu < 0.16 \text{ eV} \ (95\% \ CL; \ Alam \ et \ al. \ 2017)$

- Planned laboratory (i.e., non-cosmological) neutrino experiments would yield:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Hierarchy sensitivity</th>
<th>Approximate timescale</th>
<th>Comments and concerns</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO$\nu$A+T2K</td>
<td>1–3$\sigma$</td>
<td>2020</td>
<td>currently operating below designed beam power</td>
</tr>
<tr>
<td>DUNE</td>
<td>3–6$\sigma$</td>
<td>2030</td>
<td>funding, timeline</td>
</tr>
<tr>
<td></td>
<td>5–10$\sigma$</td>
<td>2035</td>
<td></td>
</tr>
<tr>
<td>PINGU</td>
<td>3–6$\sigma$</td>
<td>2025</td>
<td>funding; past systematics and resolution concerns largely addressed</td>
</tr>
<tr>
<td>ORCA</td>
<td>3–6$\sigma$</td>
<td>–</td>
<td>insufficiently developed at present</td>
</tr>
<tr>
<td>Hyper-K</td>
<td>3–6$\sigma$</td>
<td>2030</td>
<td>funding, timeline</td>
</tr>
<tr>
<td>ICAL@INO</td>
<td>2–4$\sigma$</td>
<td>2030</td>
<td>timeline</td>
</tr>
<tr>
<td>JUNO</td>
<td>$\sim 4\sigma$</td>
<td>2027</td>
<td>detector performance not yet demonstrated</td>
</tr>
<tr>
<td>RENO-50</td>
<td>$\sim 3\sigma$</td>
<td>–</td>
<td>insufficiently developed at present</td>
</tr>
<tr>
<td>Cosmology</td>
<td>0–4$\sigma$</td>
<td>2027</td>
<td>0$\sigma$ for most of allowed mass range; requires minimal NH spectrum</td>
</tr>
</tbody>
</table>
Effects of Massive Neutrinos in Cosmology

- Neutrinos do two things:
  1. Change the expansion history of the Universe
  2. Slow down the structure formation

![Graphs showing monopole and quadrupole wavenumber k (h/Mpc) vs. kP_x(k) [Mpc^2/h^2] with best-fit, \(\Sigma m_\nu = 0.2 \text{ eV}\), and sim. curves.](image)
If the total neutrino mass is

$$\sum m_\nu = 0.06 \pm 0.02 \text{ eV} \quad [68\% \text{CL}]$$

$$0.02 < \sum m_\nu < 0.10 \text{ eV} \quad [95\% \text{CL}]$$

If the total neutrino mass is

$$\sum m_\nu = 0.06 \text{ eV}$$
But, what about cosmological model-dependence?
Neutrino mass from cosmology: Model dependence!

• A typical thing you see at conferences:
  
  • A cosmologist: “So, this is our measurement of the total neutrino mass from cosmology. This is much better than the laboratory experiments!”
  
  • A particle physicist: “Nice, but how dependent is your constraint on the assumed cosmological models”
  
  • A cosmologist: “Ah… Um…”
  
  • Let’s settle this!
Deconstructing the neutrino mass constraint from galaxy surveys

- Neutrino mass changes:
  - Expansion rate (hence distances)
  - Overall growth of matter fluctuations
  - But, these effects can be mimicked by other effects in cosmology

- The scale-dependent suppression of the power spectrum is not!
  - *This is unique to neutrino masses* (in General Relativity)
Distance Effect

[Forecast for Euclid]

Strong dependence on the assumed cosmological models!
Overall Growth Effect

[Forecast for Euclid]

Strong dependence on the assumed cosmological models!
Free-streaming Shape Only

[Forecast for Euclid]

Free-Streaming Signal in $P_m(k)$

Model dependence disappears!
Everything Combined

[Forecast for Euclid]

Constraints tighten, but
the model dependence re-appears
Precision vs Robustness

- If we want precision, we may combine all the information and report the neutrino mass constraint

- But, we must be honest and admit the cosmological model dependence!

- If we want robustness, we can get a model-independent constraint on the neutrino mass from the free-streaming signature in the power spectrum

- Particle physicists would be happier?
Summary

- Galaxy surveys are going to high redshifts
  - PFS: 0.6<z<2.4; HETDEX: 1.9<z<3.5
- Blind nature of HETDEX is very exciting for new discoveries
- Checking for the internal consistency of \( \Lambda \)CDM over a wide redshift range. Is the \( H_0 \) tension due to low-z effect?
- Measurement of the neutrino mass may be “just around the corner”
  - But beware the cosmological model dependence. The free-streaming signature is a promising way to remove the model dependence
Final Message

• Both instruments are open-use!
  • VIRUS (IFU used by HETDEX) is publicly available
  • PFS will be publicly available also after ~2022
• Use them! I would be very happy to talk with you about new ideas