Studying Cosmic Acceleration with WFIRST-NRO

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Thanks to the WFIRST SDT Dark Energy Crew:
Charlie Baltay, Rachel Bean, Chris Hirata, Nikhil Padmanabhan, Saul Perlmutter, Jason Rhodes, Yun Wang, DW

For (much) further reference on observational methods:
Observational Probes of Cosmic Acceleration, arXiv:1201.2434 by D. Weinberg, M. Mortonson, D. Eisenstein, C. Hirata, A. Riess, and E. Rozo

Editorial Summary

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Better, Cheaper, Faster

and not drastically worse on the other two.

• At fixed focal plane area and observing time, WFIRST-NRO is a significantly better dark energy mission than DRM1, *provided* SN and WL systematics are adequately controlled.

• At fixed pixel count, the gain over DRM1 is limited, might be outweighed by loss of redder wavelengths.

• At fixed focal plane area, WFIRST-NRO is probably not cheaper than DRM1, though if the price difference is moderate, the funds for WFIRST-NRO *might* be easier to find. Whether it's faster depends on the pace of funding.

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Will it fly?
How soon?

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1. Is this acceleration caused by a breakdown of general relativity or by a new form of energy?
2. If dark energy is causing the acceleration, is its energy density constant in space and time?

The main line of attack:

- Is the cosmic expansion history consistent with Λ?
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Other possible signatures:

- Scale-dependent structure growth.
- Inconsistency of lensing and non-relativistic dynamics.
- Different strength of gravity in different environments.
- Small- or mid-scale deviations from GR.
- Imprint of clustered dark energy on CMB.
- Time- or space-variation of fundamental “constants”.

The WFIRST DRM1 dark energy program

Supernova Survey: 0.45 years of imaging and spectroscopy, spread over 1.8 years, 5-day cadence.
About 2000 Type Ia SNe, $0.2 < z < 1.7$.

High-Latitude Survey: 2.4 years of Y, J, H, K imaging and R=600 slitless spectroscopy, covering 3400 deg^2

- 480 million WL shape measurements (J,H,K) + IR photo-z
- 17 million galaxy redshifts, $1.3 < z < 2.7$

  $D_A(z)$ and $H(z)$ from baryon acoustic oscillations (BAO)
  Growth rate from redshift-space distortions (RSD)
  Other consistency checks (e.g., scale-independent growth)

Quantifying dark energy performance

Quantifying dark energy performance

One approach: Forecast constraints on a parameterized model.

E.g., DETF Figure of Merit, $\text{FoM} = [\ \sigma(w_p) \times \sigma(w_a)\ ]^{-1}$
where $w(a) = w_p + w_a(1\text{-}a)$.

Scales as inverse variance, hence proportional to data volume.

Another approach: Forecast the "aggregate precision" of a method's basic observable, combining redshift bins and accounting for error covariances. E.g. $(\Sigma_i[\Delta \ln D_L(z_i)]^{-2})^{-1/2}$.

Focuses attention on required level of systematics control.
Relatively agnostic about the cosmic acceleration model.

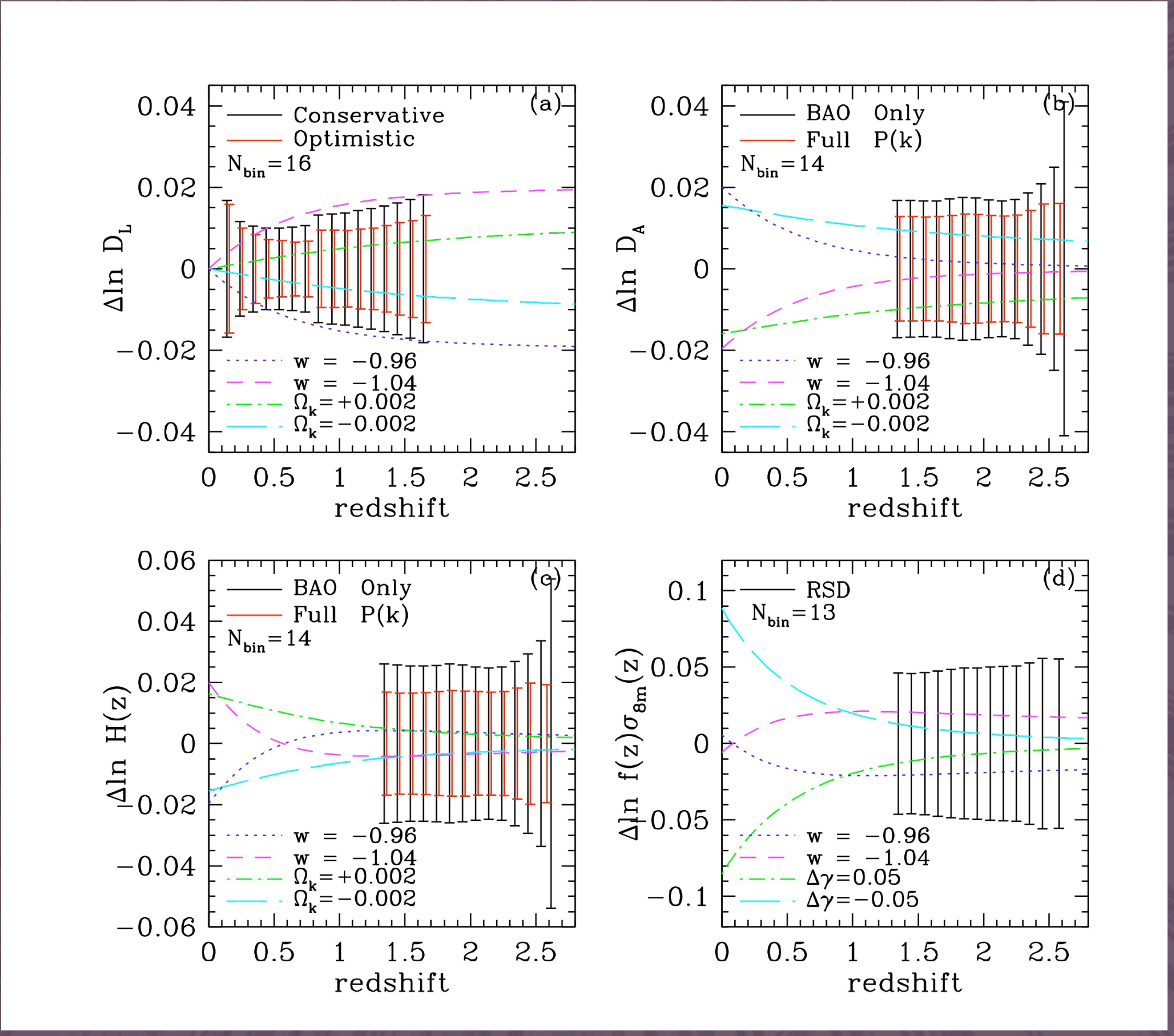
Generically, for fixed aggregate precision:

- Low-z measurements more sensitive to dark energy.
- High-z measurements more sensitive to curvature.
- Wider z-range better for constraints on evolution.
- Want measurements sensitive to expansion and growth.

WFIRST DRM1: Forecast errors on basic observables, SN survey and galaxy redshift survey

Aggregate precision ~ 0.3%

Aggregate precision ~0.5%

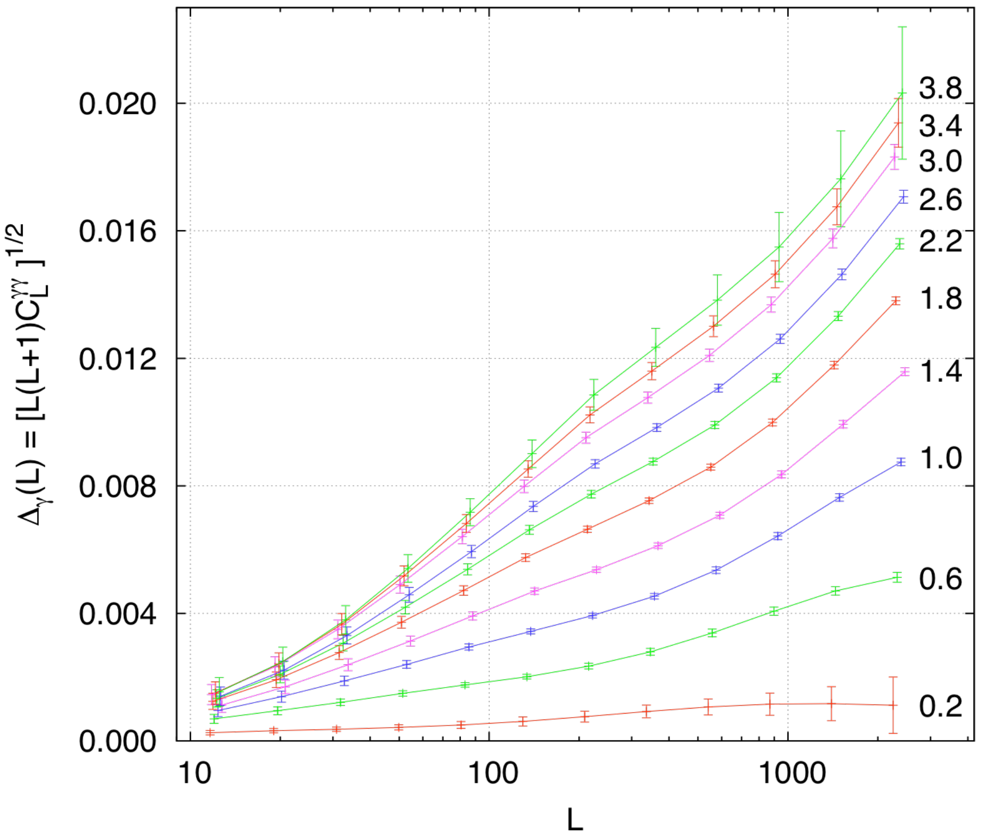


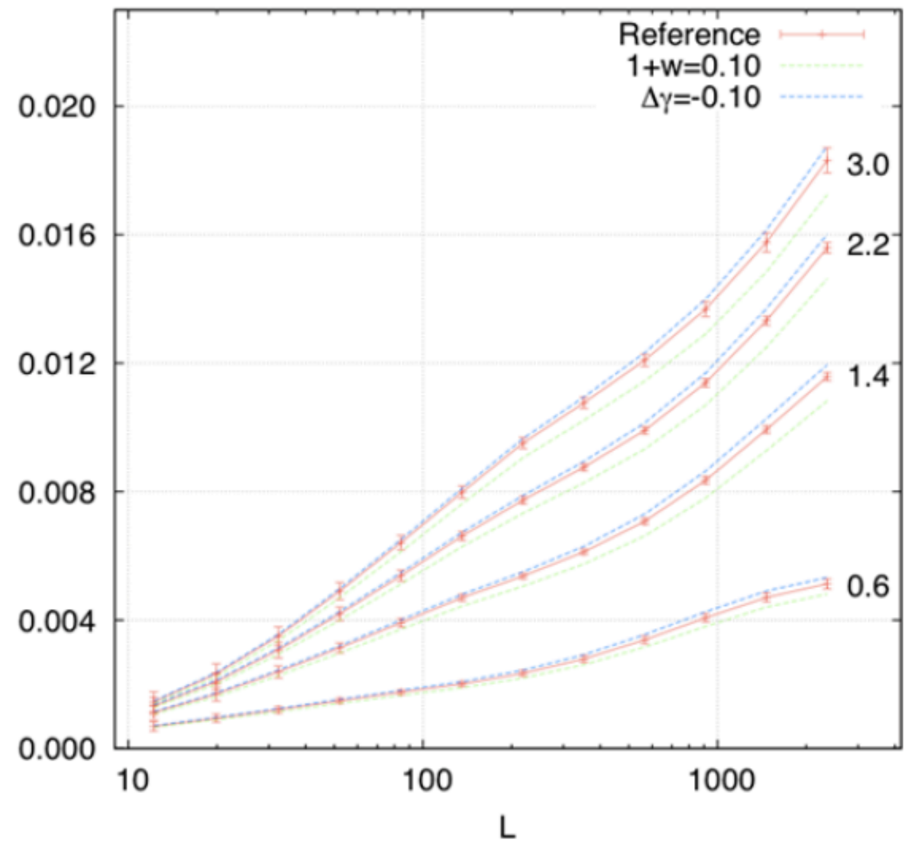
Aggregate precision ~0.7%

Aggregate precision ~1.4%

WFIRST SDT Report

WFIRST DRM1: Forecast errors on WL shear power spectrum in 10 photo-z bins





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WFIRST SDT Report

Assumptions for comparing WFIRST-NRO to DRM1

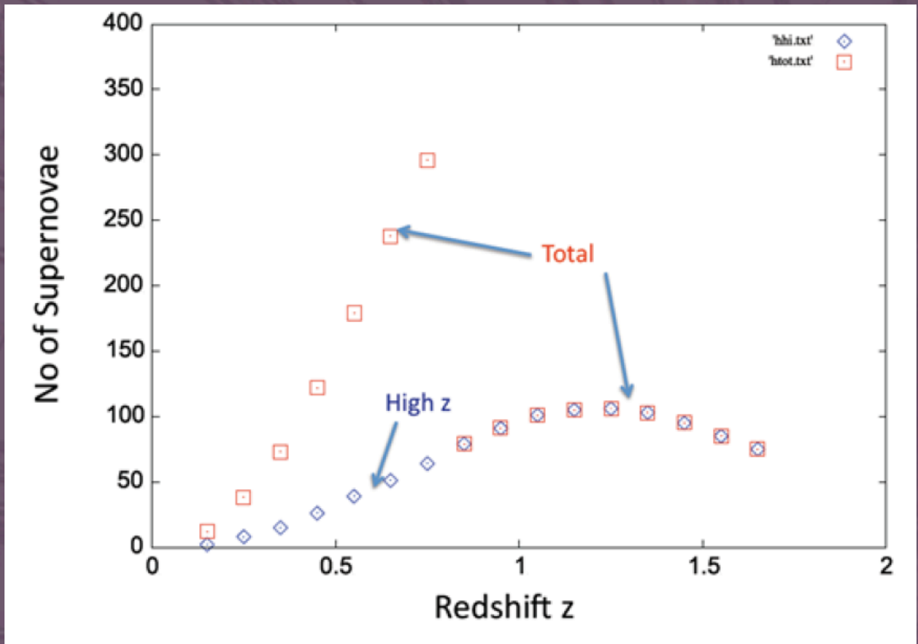
To compare these implementations, I will assume:

- Aperture ratio $0.85 \times (2.4/1.3)^2 \approx 3$.
- Same instrumented focal plane area, 0.375 deg^2.
- Long wavelength cutoff 2.0μm (vs. 2.4μm). No K-band.
- Pixel scale adequately samples J and H band for weak lensing, but not Y band. (Same as DRM1, except loss of K.)
- Same observing time for dark energy program (0.45 yrs of SN, 2.4 yrs of HLS).

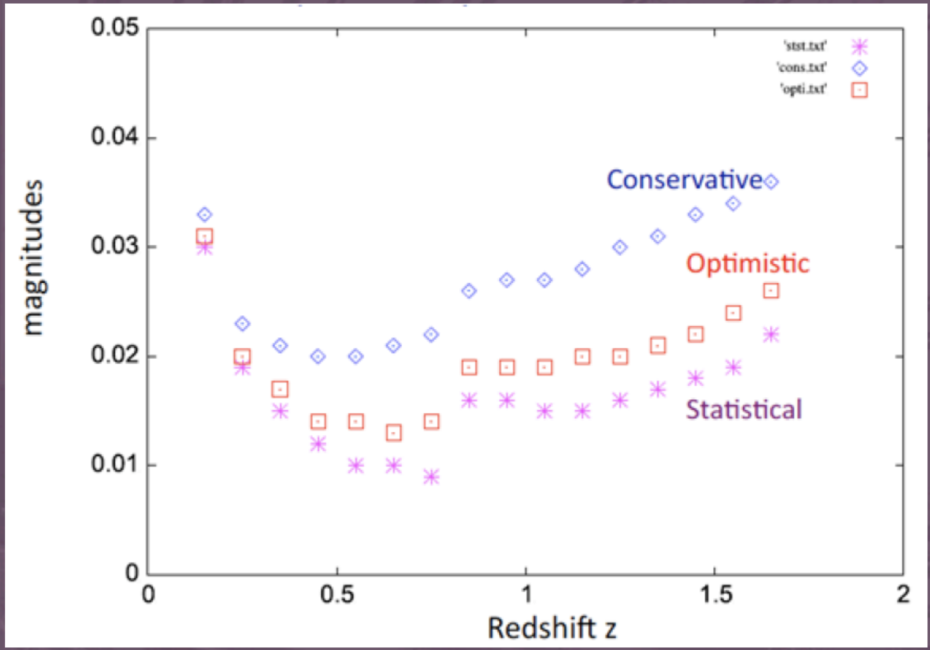
Same sampling requires pixel scale 0.18” × (1.3/2.4) = 0.0975”, hence $(2.4/1.3)^2 = 3.4$. *Might* get away with 0.11”, 2.7× pixel count, with more dithers. (DRM1 has 8-9.)

Gain in EE50 of PSF is only ~ 1.3 (not 2.4/1.3 ~ 1.6) because of central obscuration.

DRM1: Type Ia SN counts



DRM1: distance modulus errors



DRM1 SN forecasts assume $\sigma_{int} = 0.10 + 0.033z$ mag and *uncorrelated* systematic errors per $\Delta z = 0.1$ bin that are either $\sigma_{sys} = 0.02(1+z)/1.8$ (cons.) or $\sigma_{sys} = 0.01(1+z)/1.8$ (opt.)

Critical systematics are

- flux calibration and k-corrections
- reddening/extinction
- possible evolution of Type Ia SN population with redshift

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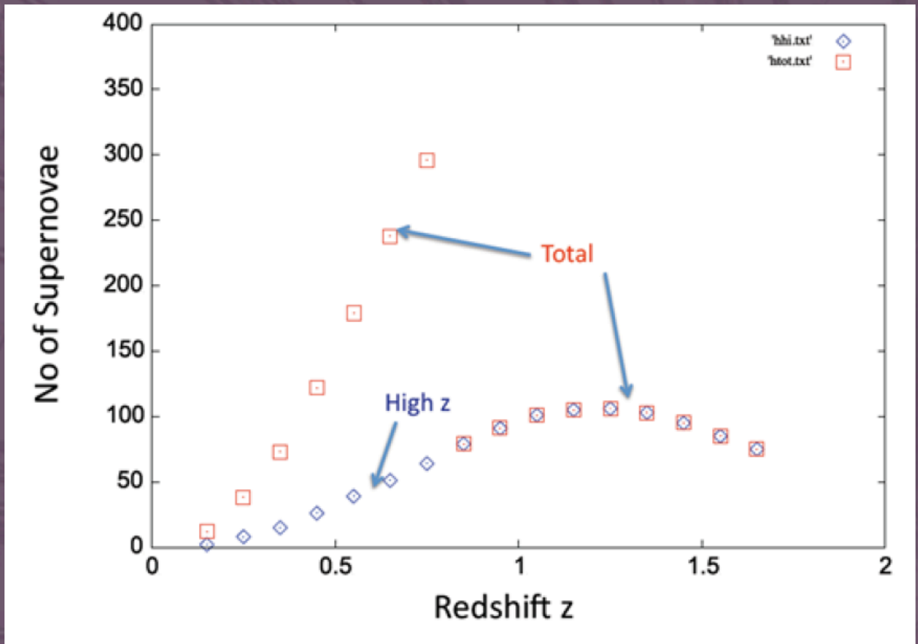

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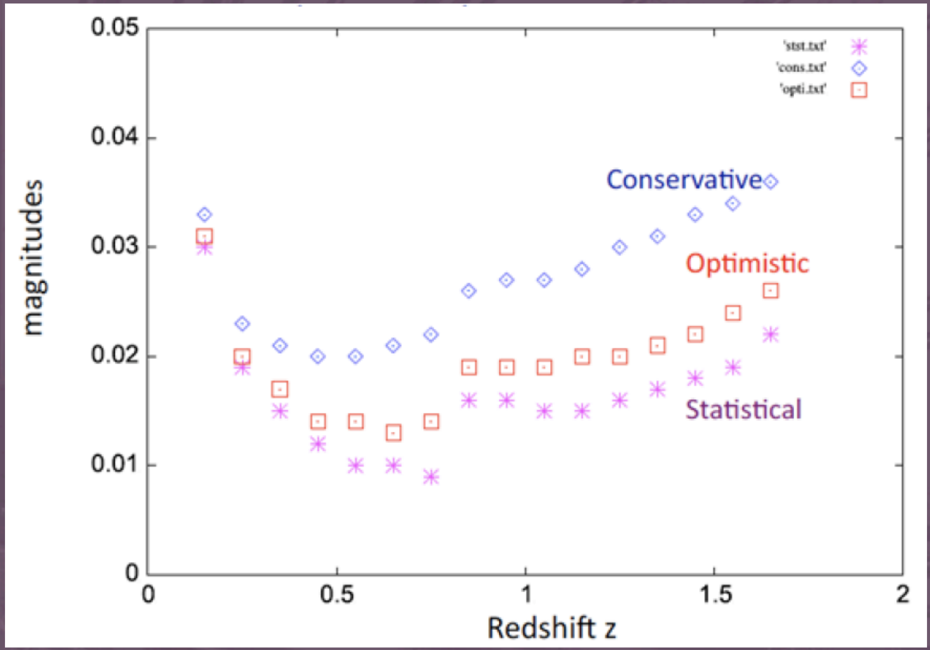


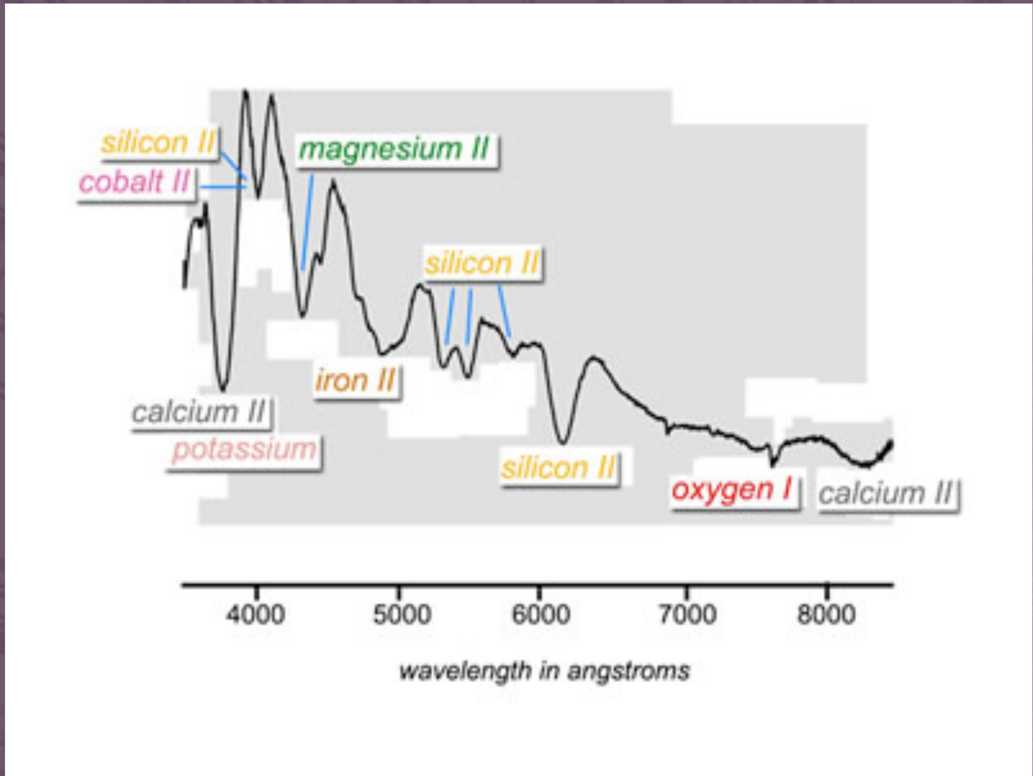
With same survey strategy, WFIRST-NRO could cover ~3× area, reducing statistical errors by ~√3 per bin.

For optimistic systematics, significant improvement.

For conservative systematics, not much improvement.

Strategy optimization might favor more high-z.

Controlling systematics is the key to improved performance, harder with loss of K band.



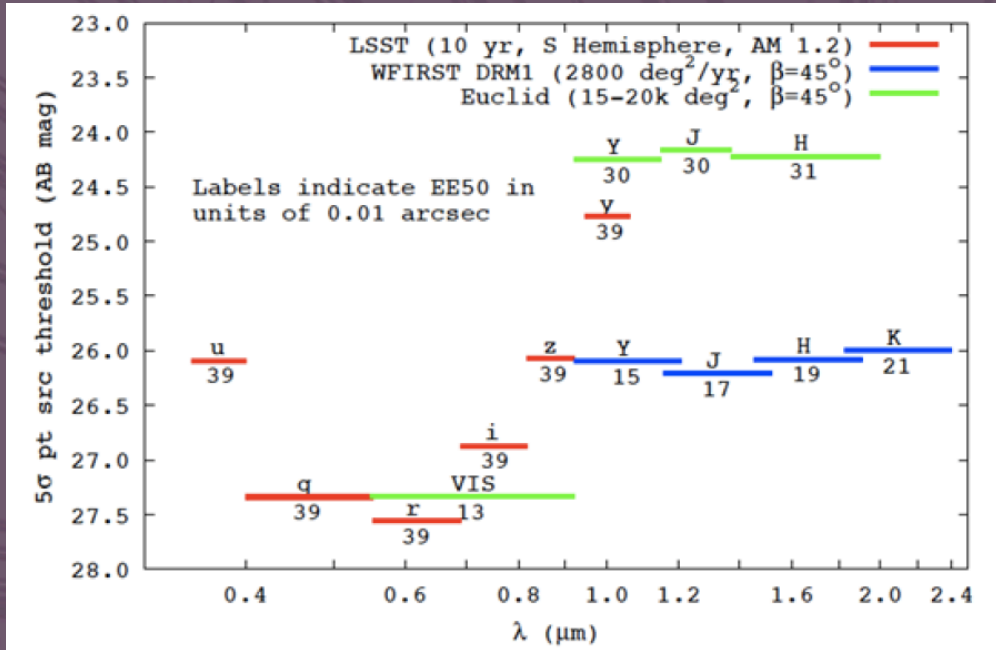
DRM1 uses slitless spectroscopy, R = 75.

SDT report also investigates an IFU hardware option, which would address systematics by allowing

• peak fluxes measured from spectra, no k-corrections

• matching low- and high-z SNe with similar spectra.

For WFIRST-NRO, need for extraordinary systematics control and capability from larger aperture make IFU even more attractive.



Imaging depth of DRM1 HLS is reasonable match to LSST.
2 mags deeper than Euclid-IR, and ~ double the resolution.

Effective surface density for WL shapes ~ 30 arcmin^{-2} in J, H, K, 40 arcmin^{-2} in union.
3400 deg^2, 480 million shape measurements.
Shape measurements systematics requirements set to keep survey statistics limited even at 10^4 deg^2:
- multiplicative shear error < 1×10^{-3}
- additive shear error < 3×10^{-4}
- requires knowing PSF size and shape to ~ 5×10^{-4} rms

WFIRST-NRO could survey ~3× area in same time, 10^4 deg^2.

Higher resolution => higher effective source density (~30%?).

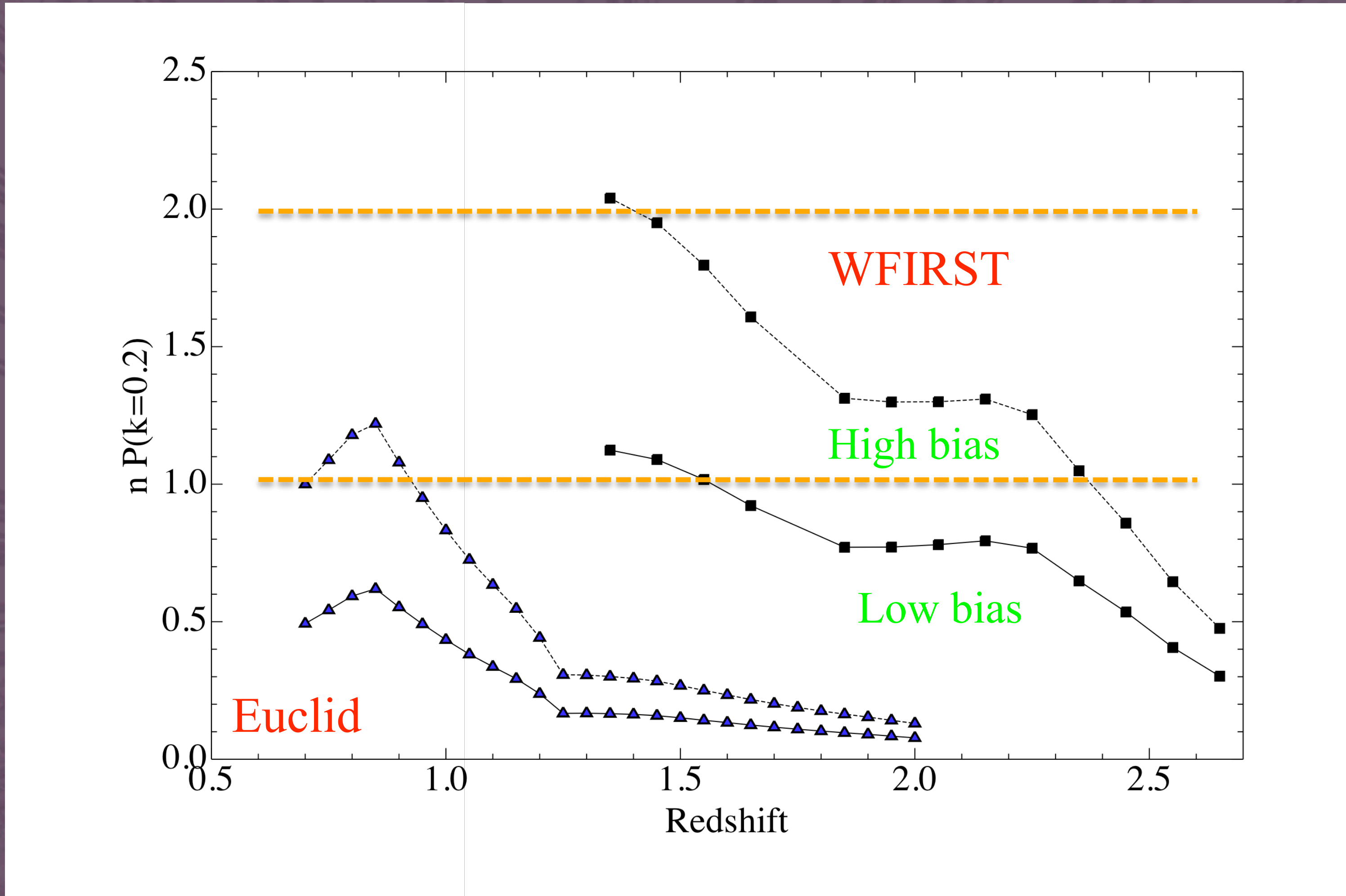
PSF more compact, but uglier, with more degrees of freedom.

Loss of K-band => less redundancy, 2 auto-correlations and 1 cross-correlation instead of 3 and 3.

Statistically, should gain by factor 3-4 in inverse variance (proportional to number of shape measurements).

Meeting systematics requirements is harder, but no obvious show-stoppers. Larger aperture helps spectroscopy for photo-z calibration.

For dark matter studies, opportunity to reach source surface density 100-200 $arcmin^{-2}$ in deep exposures over large fields could be very powerful.



Transition from sample variance limited BAO measurements to shot-noise limited at nP ~ 1.
WFIRST should have nP > 1 at z < 2.3.
Euclid should have nP > 1 only at z < 1.

WFIRST-NRO w/ 2.0-micron cutoff would lose $z > 2.0$, but it could survey ~ 3× area in same time, 10^4 deg^2.

Probably reduce lower redshift cutoff below $z=1.3$, depending on what's been done from the ground.

Large gain for BAO precision. Also for RSD, unless limited by theoretical modeling systematics.

Redshift range no longer complements Euclid, but measurement is much more precise and non-redundant because it is limited by sample variance, not shot noise.

Focus on redshifts $1 < z < 2$ that seem hardest from ground.

Factor 3 gain in comoving volume should produce similar gain in BAO inverse variance.

Summary of Dark Energy Performance: NRO vs. DRM1

Given the assumptions made here:

SN: NRO could outperform DRM1, but only with tight control of systematics. Loss of K-band significant because systematics get better in rest-frame IR. Might regain this ground with IFU spectroscopy and spectrophotometry, better matching of spectroscopic cohorts. Potential gain ~ 1.8 (inverse variance).

WL: Better statistics from larger area, higher source density. Need to control shape measurement systematics from uglier PSF. Potential gain ~ 3-4 (inverse variance).

BAO/RSD: Better statistics from larger comoving volume. Loses the high redshift range of SDT DRMs, so less complementary to Euclid, but much better sampling. Potential gain ~ 3 (inverse variance).

But fixed pixel count, instead of fixed focal plane area, would give back most of these gains.

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The solution to the cosmic acceleration puzzle could be around the corner, or it could be decades away, or more.


MANIFEST
DESTINY
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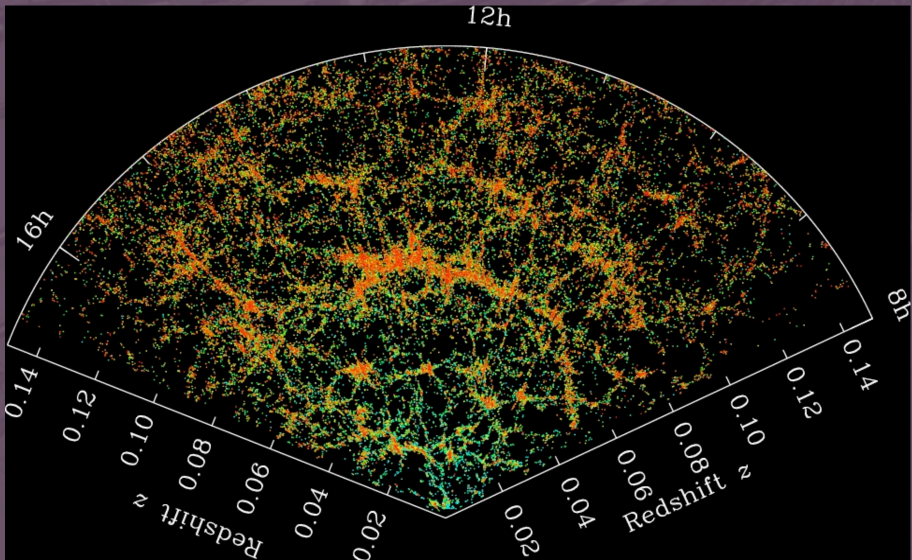
12h
16h
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Redshift z
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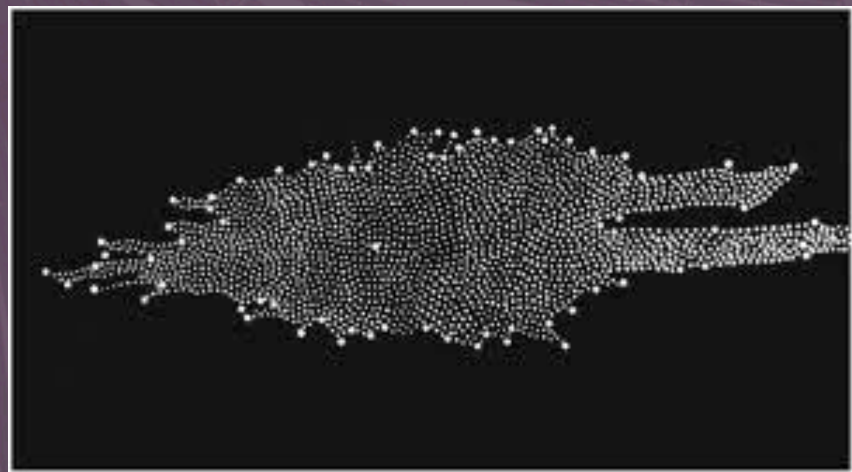
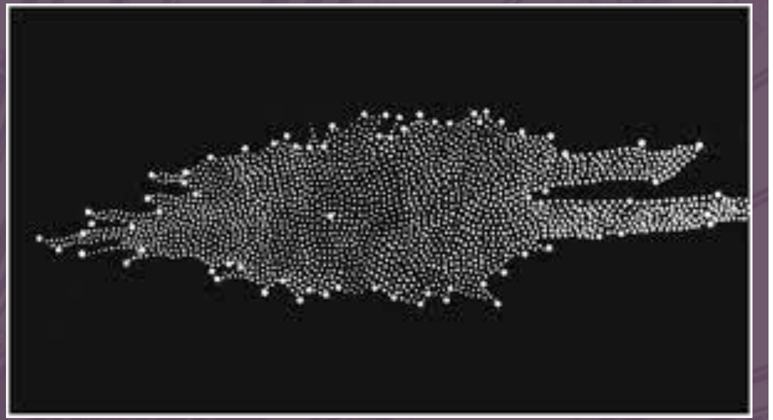
0.04
0.06
0.08
0.10
0.12
0.14



Manifest destiny



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A crucial part of the rationale for studying cosmic acceleration is that the data sets needed to do so are rich, supporting a wide range of astronomical discovery.

These data sets fall within the "manifest destiny" of astronomy: to map the observable universe with the greatest achievable sensitivity and resolution.

When a major next step on this path is feasible (technologically, financially), it makes sense to take it.

WFIRST-SDT and WFIRST-NRO both offer good opportunities.

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