JDEM/ADEPT

ADVANCED

DARK

ENERGY

PHYSICS

TELESCOPE

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Dark Energy Overview

Dark energy equation of state: $P = w\,\rho$

Options have **HUGE** implications for fundamental physics

$w = w_0$ (constant) ?

$w = w(z)$ (not constant) ?

w is irrelevant, because GR is wrong ?

Complementary space-based and ground-based measurements are both needed

ADEPT is designed to do from space what needs to be done from space in a cost-controlled manner

What is ADEPT?

A dark energy probe, primarily Baryon Acoustic Oscillations (BAO)

- Redshift survey of 100 million galaxies $1 \le z \le 2$
- Slitless spectroscopy $1.3 - 2.0$ μm Hα
- Nearly cosmic variance limited over nearly the full sky ($28{,}600$ deg^2)
- First and final generation $1 \le z \le 2$ BAO measurement

A dark energy probe, also using Type Ia Supernovae (SNe Ia)

- ~ 1000 SNe Ia $0.8 \le z \le 1.3$ with no additional hardware or operating modes

Products:

- D_A=angular diameter distance $D_A \equiv \ell / \delta\theta$
- D_L = luminosity distance $D_L \equiv \left(L / 4\pi f \right)^{1/2}$
- $H(z)$ expansion rate
- Galaxy redshift survey (power spectrum shape, tests of modified gravity w/CMB)

What is ADEPT?

ADEPT is a dedicated facility in the spirit of WMAP

Cost of WMAP leading to the 2003 papers:

instrument
+ spacecraft
+ launch
+ operations

$145 M

ADEPT cost-control

1.3 m primary (smaller than WMAP)
single instrument / single detector type / single mode of operations (all like WMAP)
predetermined survey mode of operations (like WMAP)
no new technology (like WMAP)
small team (like WMAP)

1998 Discovery of Dark Energy

THE ASTRONOMICAL JOURNAL, 116:1009–1038, 1998 September

OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

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Received 1998 March 13; revised 1998 May 6

ADEPT Team Members

1998 Science Magazine
"Breakthrough of the Year"

2003 WMAP
Baryon Acoustic Oscillations

FIRST-YEAR *WILKINSON MICROWAVE ANISOTROPY PROBE* (*WMAP*)[1] OBSERVATIONS:
PRELIMINARY MAPS AND BASIC RESULTS

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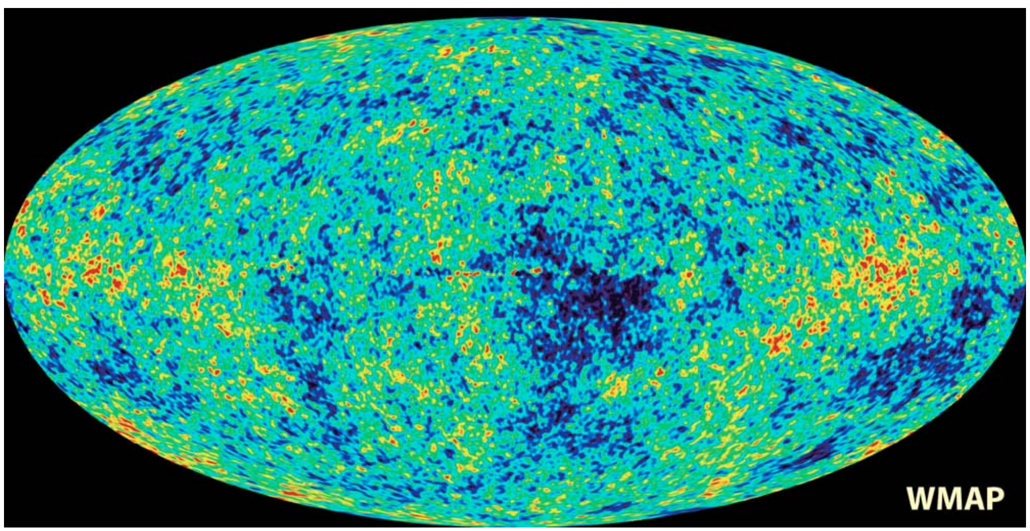
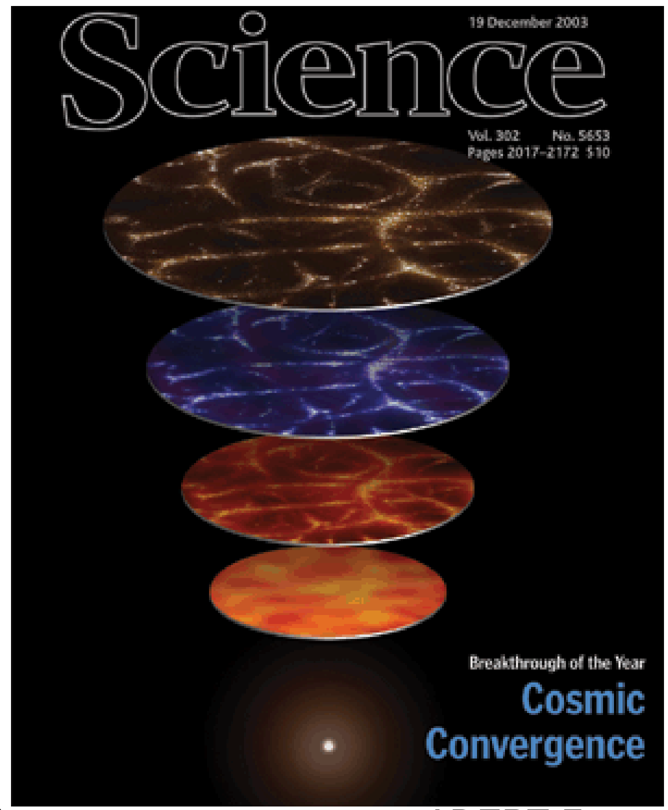
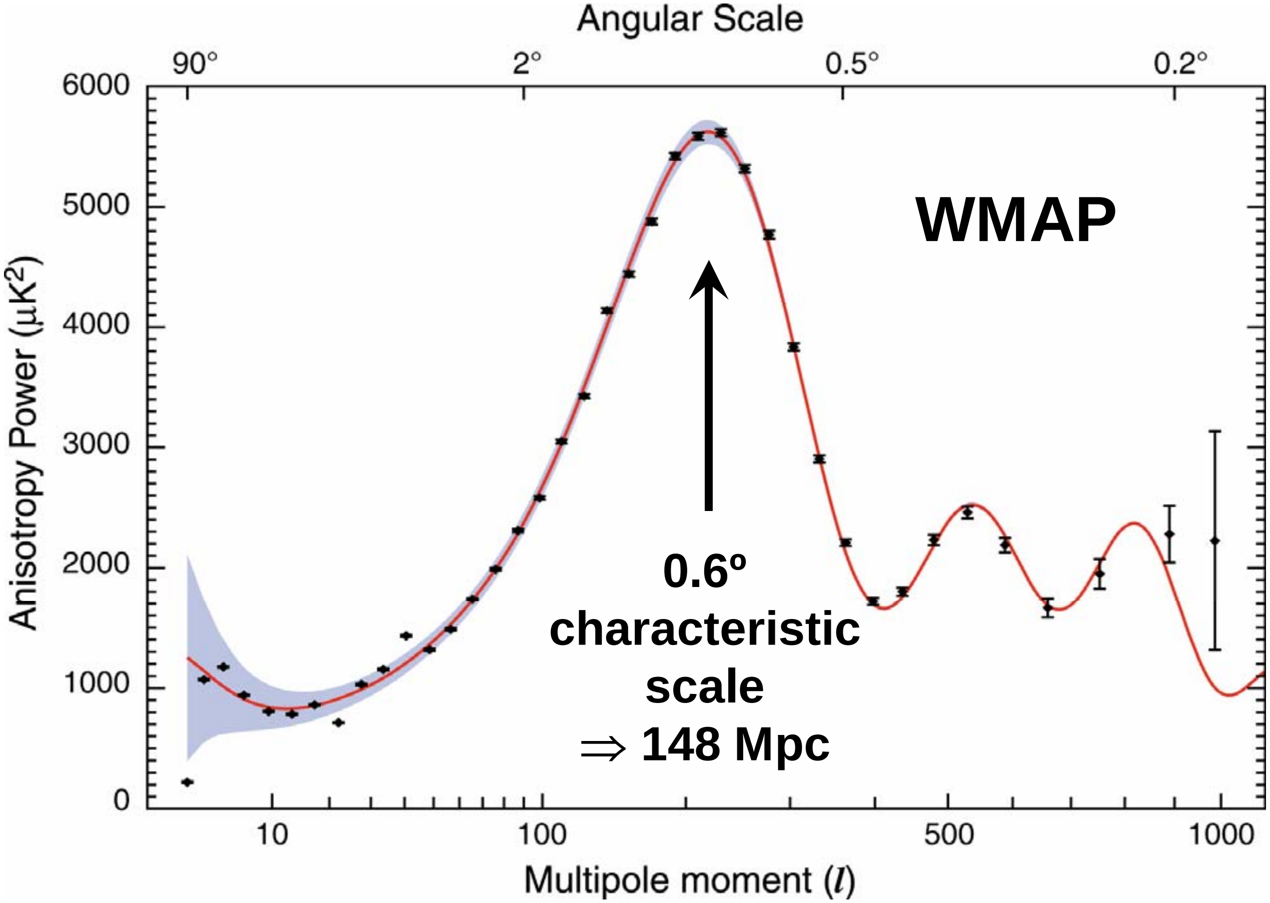
2003 Science Magazine
"Breakthrough of theYear"



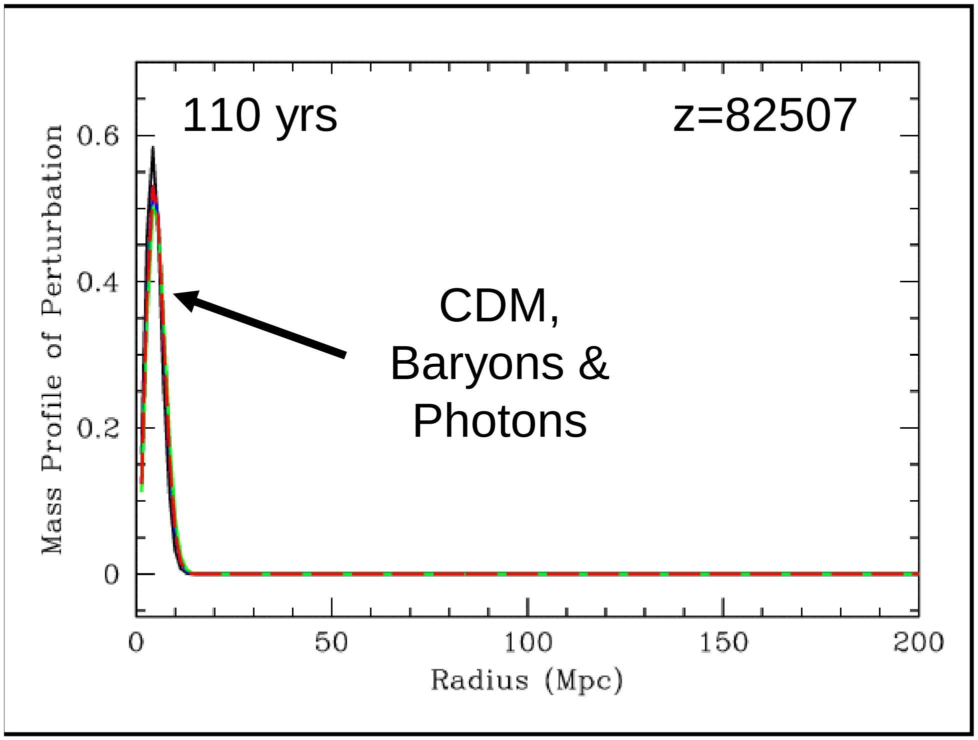


WMAP Baryon Acoustic Oscillations

Although there are fluctuations on all scales,
there is **a characteristic physical & angular scale**.

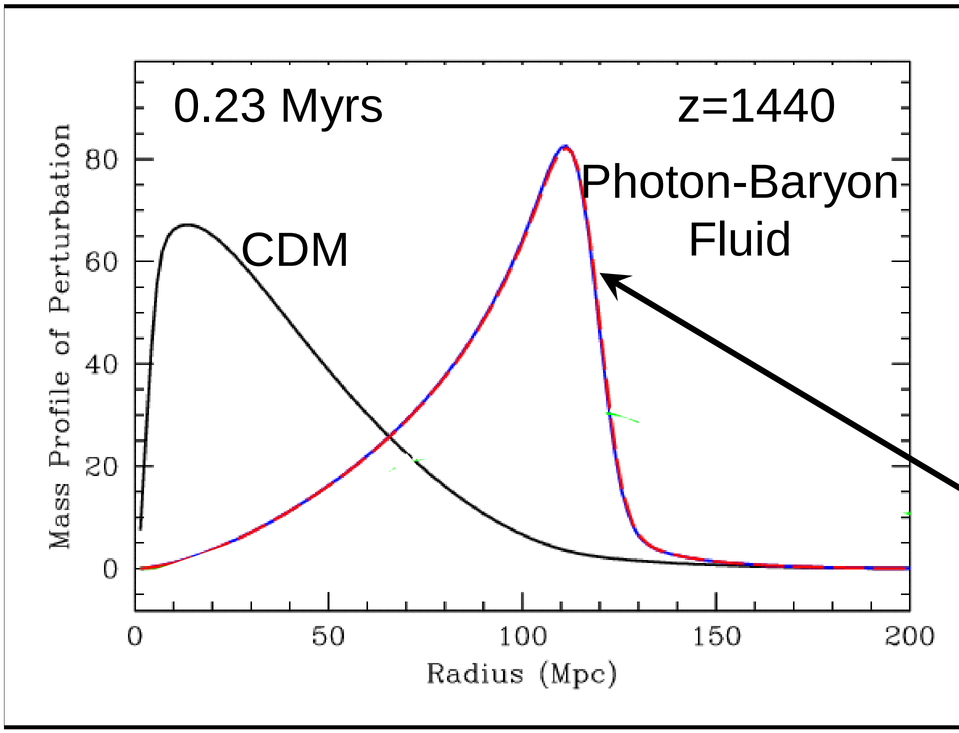


Baryon Acoustic Oscillation Evolution



Initial perturbation in all species

Baryon Acoustic Oscillation Evolution

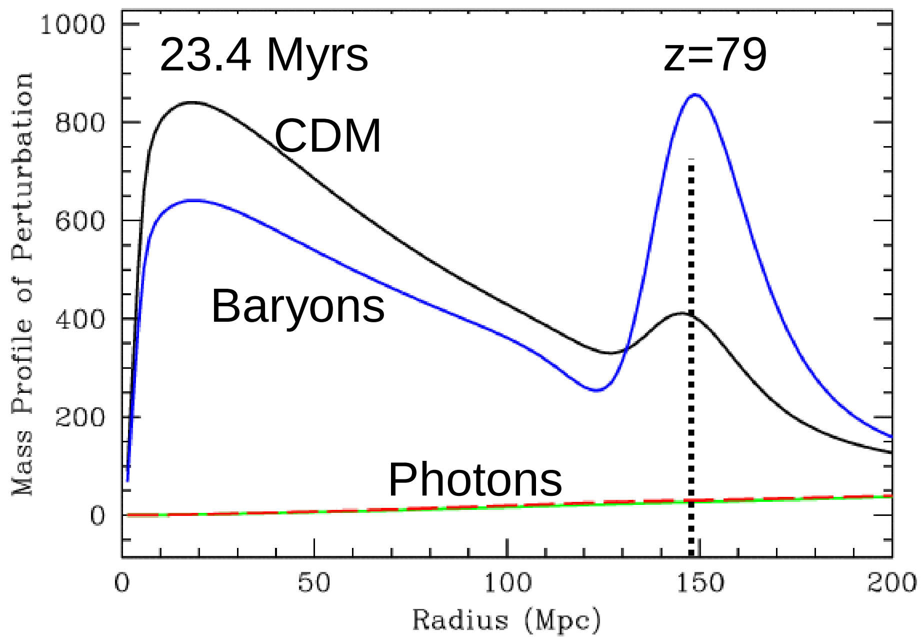


Each initial over-density/over-pressure launches a spherical sound wave

Over-pressure causes the wave to travel outward at the sound speed (57% speed of light)

The photon-baryon fluid remains coupled until z = 1090, so the CMB calibrates the baryon fluctuations

Baryon Acoustic Oscillation Evolution



At z = 1090:

Photon pressure decouples
CMB travels to us
Sound speed plummets
Wave stalls at a radius of 148 Mpc

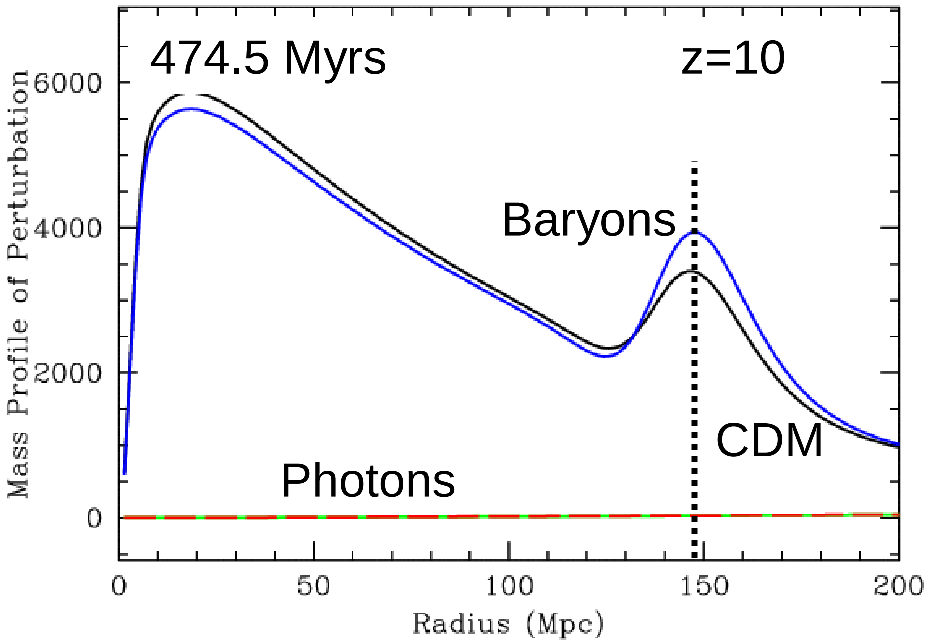
For z < 1090…

Gravity couples dark matter to baryons

Dark matter + baryon shells and centers seed galaxy formation

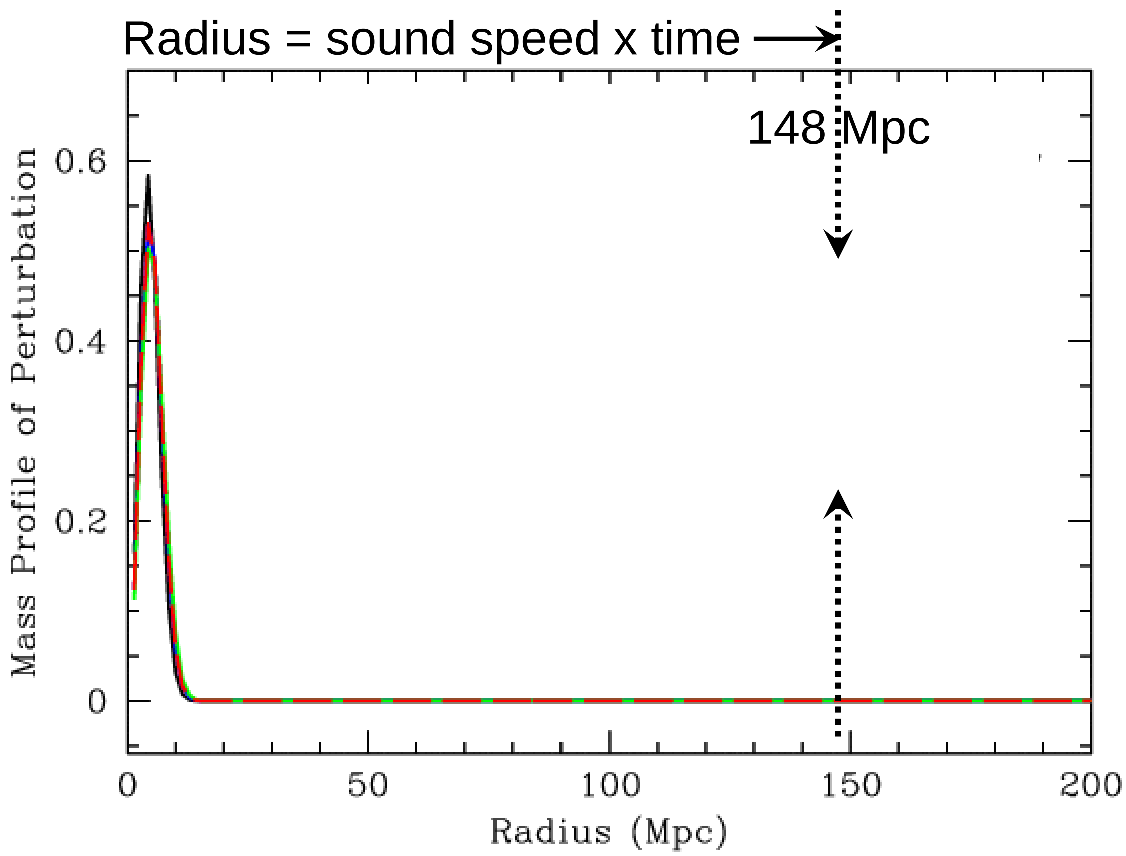
The universe has a super-position of these shells

Baryon Acoustic Oscillation Evolution



BAO generate a 1% bump in the galaxy correlation function at 148 Mpc

Baryon Acoustic Oscillation Evolution



2005 BAO Discovery in z = 0.35 SDSS

The Astrophysical Journal, 633:560–574, 2005 November 10

ADEPT Team Member

DETECTION OF THE BARYON ACOUSTIC PEAK IN THE LARGE-SCALE CORRELATION FUNCTION OF SDSS LUMINOUS RED GALAXIES

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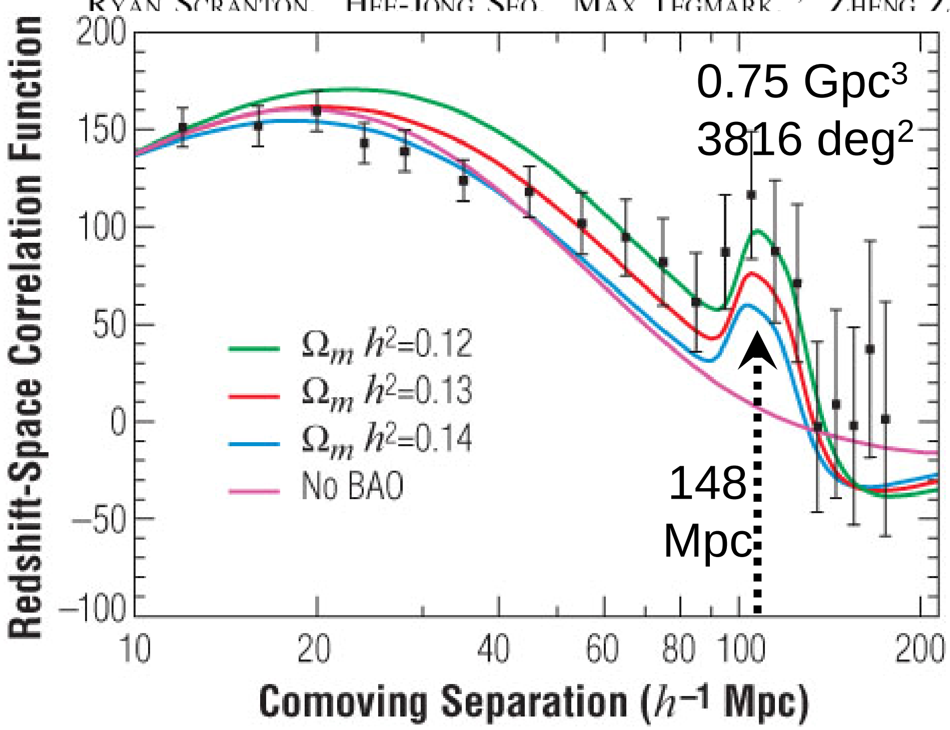


(h^{-1}=1.4)

CDM with baryons is a good fit:
χ^2 = 16.1 with 17 dof.
Pure CDM rejected at
$\Delta\chi^2$ = 11.7 (3.4σ)

Ratio of the distances to z =0.35 and z = 1090 to 4% accuracy

Absolute distance to z = 0.35 determined to 5% accuracy

BAO: Radial & Tangential Physics

Galaxy redshifts allow measurement along and across the line of sight

$\Delta r_{\parallel} = \Delta r_{\perp} = r_s = 148$ Mpc

This provides a built-in check on systematic errors

Dark energy properties, e.g. $w(z)$, determines the expansion rate, $H(z)$

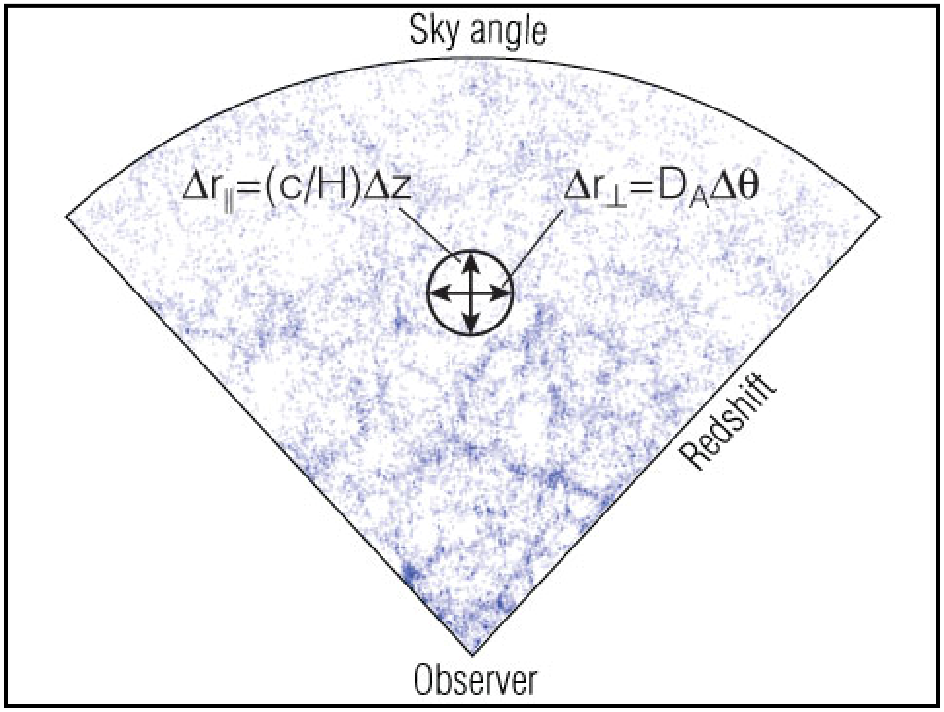
$H(z) = d \ln(a)/dt$ is directly measured

depends on dark energy density

$D_A(z) = \int c / H(z)\, dz$ also measured

for flat, but spatial curvature is parameterized by Ω_k

Measuring H(z) requires accurate redshifts [$\sigma_z/(1+z) \sim 0.003$]



BAO: Well-Established Physics

"The physics of these baryon acoustic oscillations (BAO) is well understood, and their manifestation as wiggles in the CMB fluctuation spectrum is modeled to very high accuracy. The value of r_s is found to be 148±3 Mpc, by the Wilkinson Microwave Anisotropy Probe... The sound horizon scale can thus serve as a standard ruler for distance measurements."

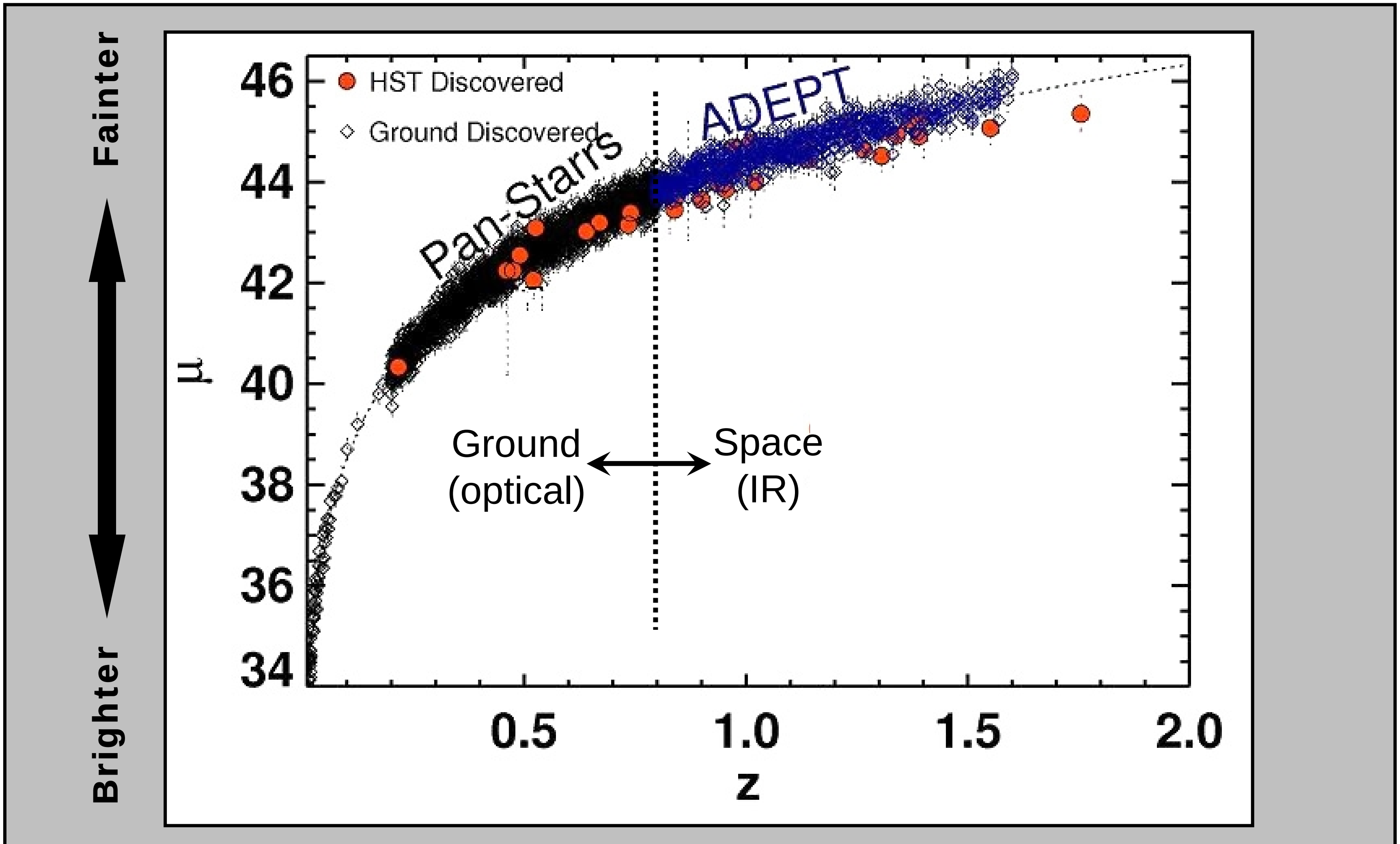
--- DETF

The well-established BAO physics was used to validate SNe dark energy measurements:

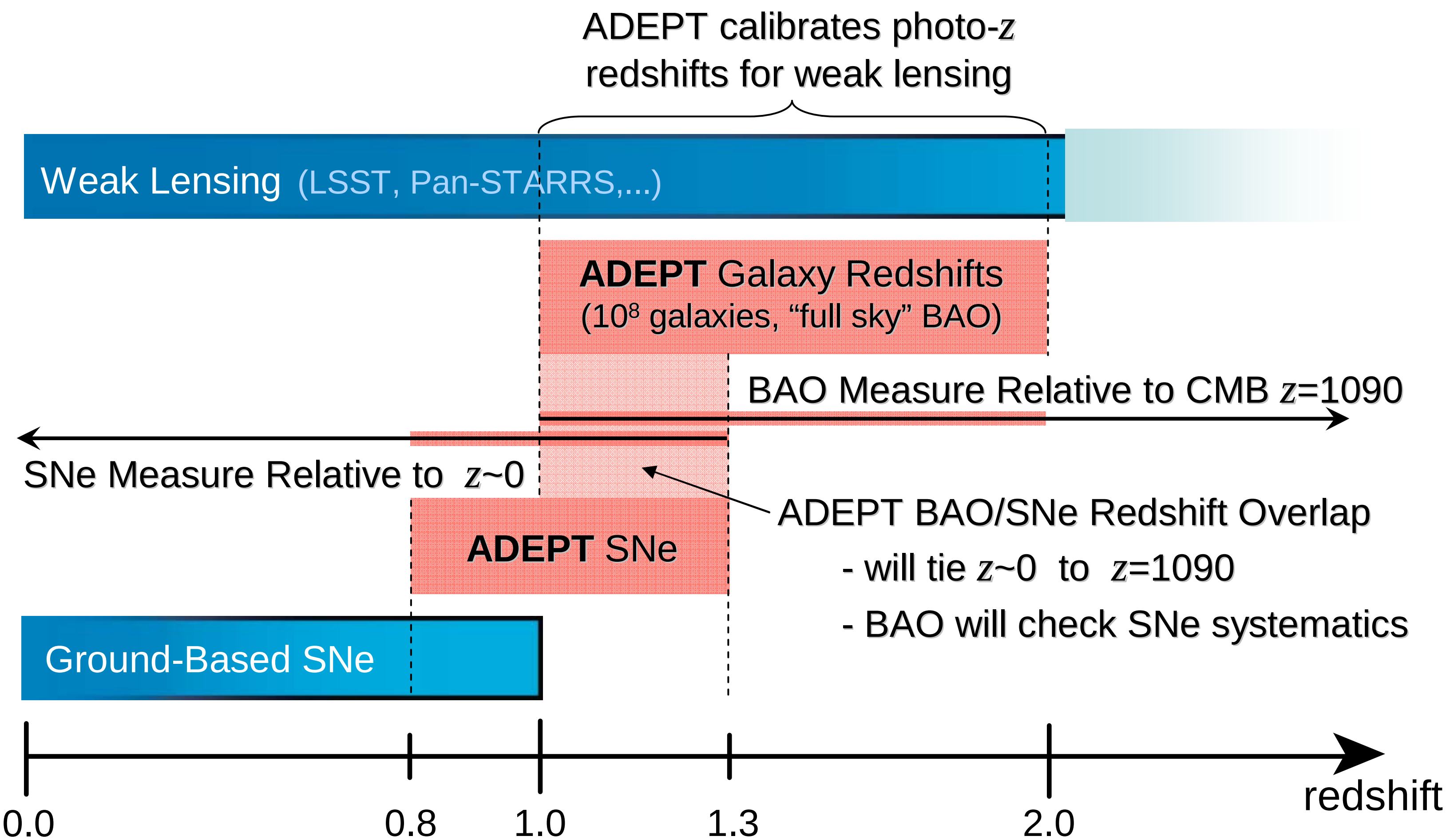
"…Lingering doubts about the existence of dark energy and the composition of the universe dissolved… when the WMAP satellite took the most detailed picture ever of the …CMB."

2003 Science Magazine
BREAKTHROUGH OF THE YEAR:
"Illuminating the Dark Universe"
Charles Seife

ADEPT SNe Complement Anticipated Ground Sample



ADEPT in Context



ADEPT in Context

ADEPT is complementary to LSST

10^8 spectra are fundamentally different than 10^9 galaxy shapes

ADEPT and LSST are a powerful combination

ADEPT and huge numbers of SNe from the ground are also a powerful combination

BAO Systematic Errors

Nonlinearities

Non-linear gravitational collapse occurs on small scales (3-10 Mpc)
Large-scale features are unaffected
BAO technique improves with redshift – especially good for $z > 1$

Bias and Redshift Distortions

Redshift distortions arise from a halo's peculiar motion relative to the Hubble flow

Clustering bias arises when two overdense regions fall toward each other & two underdense regions fall away from each other
This cancels to first-order *unless* galaxy bias causes us to mis-weight the over- and under-dense regions

Clustering bias and redshift distortions don't create features at preferred scales of 148 Mpc

Simulations verify BAO at 1% accuracy level
We are now running 0.1% accuracy level simulations
Any small errors will be correctable using such simulations based on known gravity physics

Conclusion

Acoustic peaks are robust

DETF on BAO Systematics

“This is the method least affected by systematic uncertainties, and for which we have the most reliable forecasts of resources required to accomplish a survey of chosen accuracy. This method uses a standard ruler understood from first principles and calibrated with CMB observations.” --- DETF

“An advantage of BAO is that it does not require precision measurements of galaxy magnitudes, though if photo-z’s are used then precision in galaxy colors is important. In contrast to weak lensing, BAO does not require that galaxy images be resolved; only their three-dimensional positions need be determined.” --- DETF

ADEPT SNe Ia Systematic Errors

Intrinsic SN luminosity distribution unknowns

(Physics of explosions not fully understood)

- Distance accuracy ~10% per SN (distribution width)
- ~5% of SNe Ia are oddballs (distribution tails)
- Evolution (time-dependent change in distribution)

Photon propagation interactions

- dust absorption, scattering

Calibration accuracy limited, now >1%

- 0.3% (optimistic calibration) = 10% / $\sqrt{N_{SNe}}$
- $\Rightarrow$N=1000 required to reach systematic limit

We use BAO to provide a high-quality check whether SNe extend another order of magnitude before reaching systematic limits

Tests of Modified Gravity

Small-scale lab experiments & Solar system tests

CMB – galaxy cross-correlation / Growth of Structure

modified gravity changes "the correlations between the CMB and galaxy surveys. All of these phenomena are accessible with current and future data and provide stringent tests of general relativity on cosmological scales."

Y.-S. Song, W. Hu & I. Sawicki,
"The Large Scale Structure of f(R) Gravity,"
Phys.Rev., D75, 044004, 2007

galaxy – CMB fine-scale B-mode (weak lensing) correlation ⇒ growth of structure
galaxy – CMB temp. correlation ⇒ corr. ISW & project out kinetic-SZ for lensing

Weak Lensing / Growth of Structure

ADEPT's 3-D positions of 10^8 galaxies will calibrate ground photo-z's for Pan-STARRS, LSST, etc. (growth of structure mostly at $z < 1$ for Λ)

Beyond the DETF Figure-of Merit

Improvements to DETF "Figure of Merit"

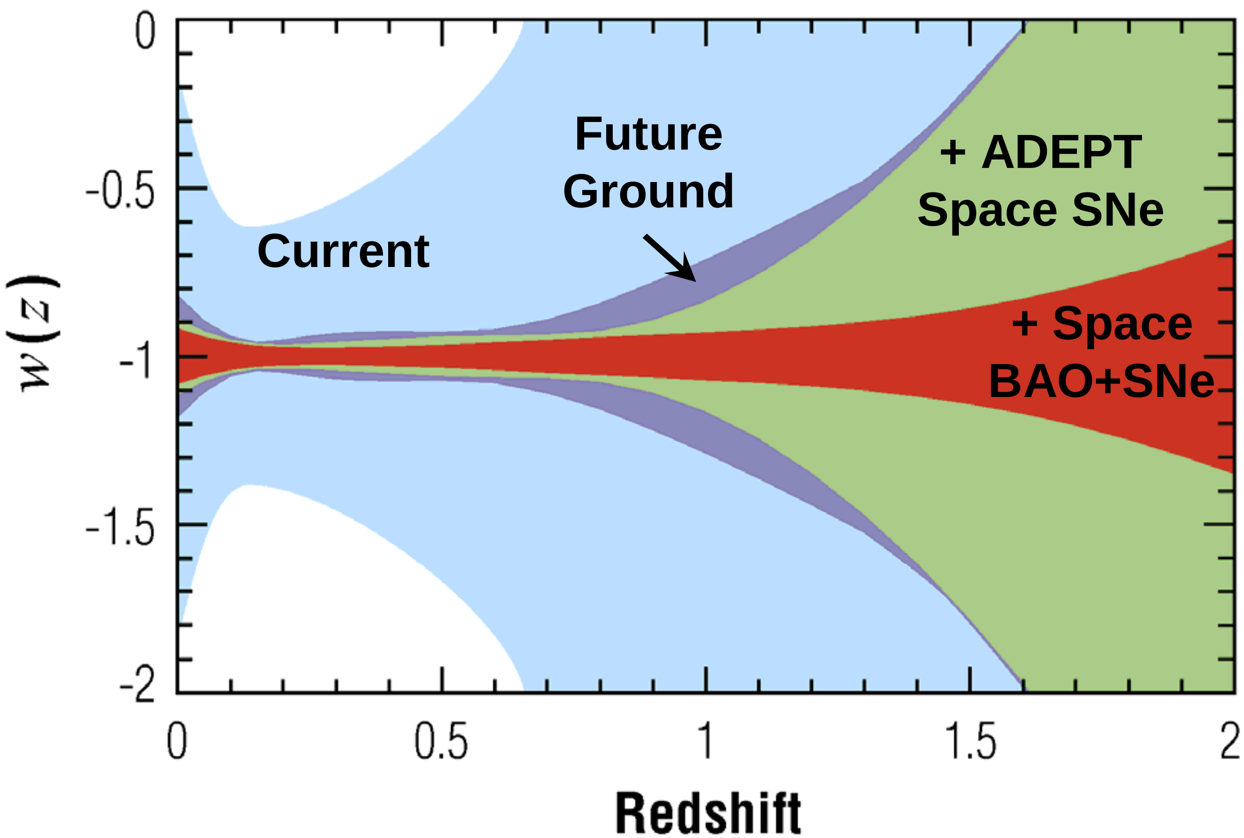
Must model *w(z)* with many DOFs

A. Albrecht & G. Bernstein
"A Dark Energy Figure of Merit in Higher Dimensions"
astro-ph/0608269

Must account for the combination of space data with anticipated ground data

Must estimate appropriate future systematic error limits

Limits on *w(z)*



- Markov chains are run with w(z) represented in a 5 parameter quartic polynomial in ln(1 + z).

- Ω_m, h, Ω_k, and *w(z)* free to vary, with priors set on $\Omega_m h^2$ (1% precision) and the CMB angular size of the acoustic scale at z = 1100.

- Assumes 0.5% SNe distance calibration per Δz = 0.1 redshift bin.

Why Space?

Need IR to measure *z* > 1 to the experimental/cosmic limits

- This can not be done from the ground

Sensitivity: ground IR sky 1000x brighter than in space

- SNe z > 0.8 & Large spectroscopic high-z galaxy survey must be in space

Systematics: Full sky sample homogeneity (as with WMAP)

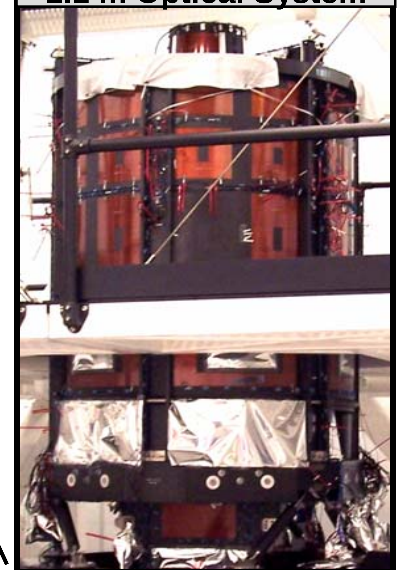
- Same hardware / same approach, avoid mosaic & calibration artifacts

These factors enable ADEPT to reach cosmic variance limit

- Open the investigation of dark energy at *z* > 1
- Harvest full BAO info in important 1 < z < 2 range

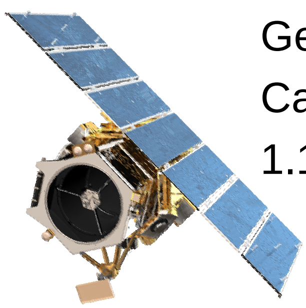
Instrument & Spacecraft

1.1 m Optical System



ITT

- One instrument
  - Components have TRL ≥ 6
  - No moving parts (1-time aperture cover & focus)
- One detector type
- 1.3 m scaled from current Geo-Eye I Payload
- One observing mode
- GeoEye-1 heritage
  - Slews multiple times per orbit (680 km circular polar)
  - 8 low-noise reaction wheels (105º slew in 60 sec)
  - 1800 kg Observatory
  - Due to launch on a Delta 7420-10 this year
  - Fully redundant; 7-year lifetime
  - General Dynamics contract award for S/C + telescope/camera = $209 M
  - Camera and optical telescope assembly developed by ITT Corp.
  - 1.1 m clear aperture 3-mirror anastigmat telescope



GENERAL DYNAMICS

Technology Development Requirements

No technology breakthroughs required

- All components flight-proven
- Ready for the normal design, fabrication, qualification, acceptance, integration, verification process

2 μm Hawaii HgCdTe 2k x 2k Sensor Chip Assembly (SCA)

- Development driven by HST & JWST
- 1.7 μm (WFC3/HST) and 2.5 μm (NIRCam/JWST) cutoffs
- **In-family.**

Read noise and dark current performance acceptable for ADEPT application

Conclusions

Dark energy is a fundamental scientific mystery

Need to measure *w(z),* or determine that GR is wrong

Physicists require reliable results.

DETF says of BAO:

"This is the method least affected by systematic uncertainties"

physics "is well understood"

"uses a standard ruler understood from first principles and calibrated with CMB observations"

"the most reliable forecasts of resources required"

THE END

A Sampling of the Rich Set of Ancillary Science Data from ADEPT

- Largest effective volume survey of universe, by far
- Get 100 million galaxy redshifts in epoch of last vigorous period of star formation – can not be done from the ground
- P(k) power spectrum of density fluctuations
  - 20 million linear modes
  - 0.03% measurement of linear theory
  - Scales <1 Mpc will accurately constrain galaxy positions in halos
  - Probes a different volume than LSST
- Improved determination of matter density ($\Omega_m h^2$) & neutrino mass
- Best data for high n-point correlation functions
- Star formation rates vs. environments
- 2 million broad-line QSOs/AGN

BAO Spectroscopic Surveys: Current Results and Future Prospects

Survey[a]	Redshift Range	Sky Area (deg^2)	Millions Galaxies	Volume (h^{-3} Gpc^3)	Volume (Gpc^3)[c]	Effective Volume (h^{-3} Gpc^3)	Effective Volume[b] (Gpc^3)[c]
ADEPT	$1 < z < 2$	28,600	~100	100	390	60	180
SDSS DR4 Main+2dF	$z < 0.3$	7,000	0.7	0.4	1.2	0.17	0.50
SDSS LRG	$0.16 < z < 0.47$	3,800	0.047	0.75	2.2	0.18	0.52
SDSS-II 8-yr LRG	$0.16 < z < 0.47$	7,600	0.094	1.5	4.4	0.36	1.0
WiggleZ/AAT (220 nights)	$0.5 < z < 1.0$	1,000	0.4	1.0	2.9	0.22	0.64
APO-LSS	$0.2 < z < 0.8$	10,000	1.5	7.3	21	3.5	10
FMOS/Subaru (200 nights)	$1.4 < z < 1.7$	300	0.6	0.3	1.0	0.24	0.7
HETDEX	$1.8 < z < 3.8$	250	1.0	2.0	5.8	0.7	2.0
WFMOS/Subaru (150 nights)	$0.5 < z < 1.3$	2,000	2.	4.	12	1.3	3.8
WFMOS/Subaru (150 nights)	$2.3 < z < 3.3$	300	0.6	1.2	3.5	0.4	1.2

Notes to the Table: a. The SDSS surveys in the 2nd and 3rd rows are the only ones completed; the rest are planned or proposed. They are all spectral line surveys. LSST plans a large (~10,000 deg^2) photometric redshift survey, perhaps observing $>10^8$ galaxies at $0.5 < z < 3.5$. The photometric redshift errors would degrade the equivalent effective volume of the LSST survey to $<5h^{-3}$ Gpc^3. **b.** Effective volume accounts for the limited sampling of the survey volume due to the discrete number of galaxies as a function of redshift. It is evaluated at the scale of the BAO, $k = 0.15h$ Mpc^{-1}. **c.** Assumes $h = 0.7$.

Number Density Considerations

An Optimal Number Density

- Statistical errors on large-scale correlations are a competition between sample variance and Poisson noise.
  - Sample variance: How many independent samples of a given scale one has.
  - Poisson noise: How many objects per sample one has.

- Given a fixed number of objects, the optimal choice for measuring the power spectrum is an intermediate density.

Basic Cosmology

$$f = \frac{L}{4\pi S_\kappa(r)^2(1+z)^2} \equiv \frac{L}{4\pi D_L^2} \quad \text{flux}$$

$$\mathrm{S}_\kappa(\mathrm{r}) \equiv \begin{cases} R_0 \sin(r/R_0) & \kappa = +1 \quad \text{closed} \\ r & \kappa = 0 \quad \text{"flat"} \\ R_0 \sinh(r/R_0) & \kappa = -1 \quad \text{open} \end{cases}$$

$$D_L \equiv \mathrm{S}_\kappa(r)(1+z)$$

$$D_A = \frac{\ell}{\delta\theta} = \frac{\mathrm{S}_\kappa(r)}{1+z}$$