DESI: Dark Energy Spectroscopic Instrument

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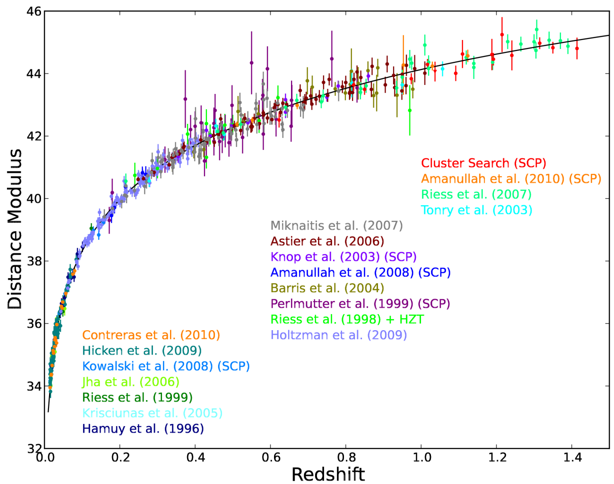
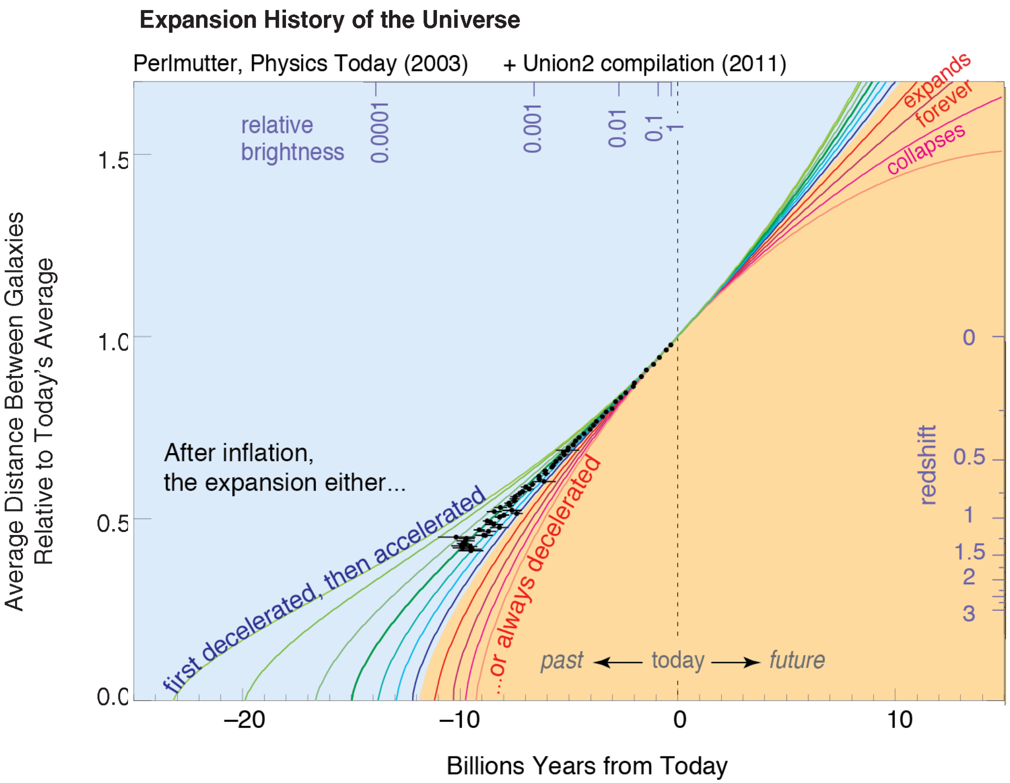
How We Know there is Dark Energy





GR & Cosmology in One Slide

Alexander Friedmann

$$\frac{\ddot{a}}{a} = \frac{\Lambda}{3} - \frac{4\pi G_N}{3}\left(\rho + 3p\right)$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N \rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

a is the size-scale of the universe relative to size today

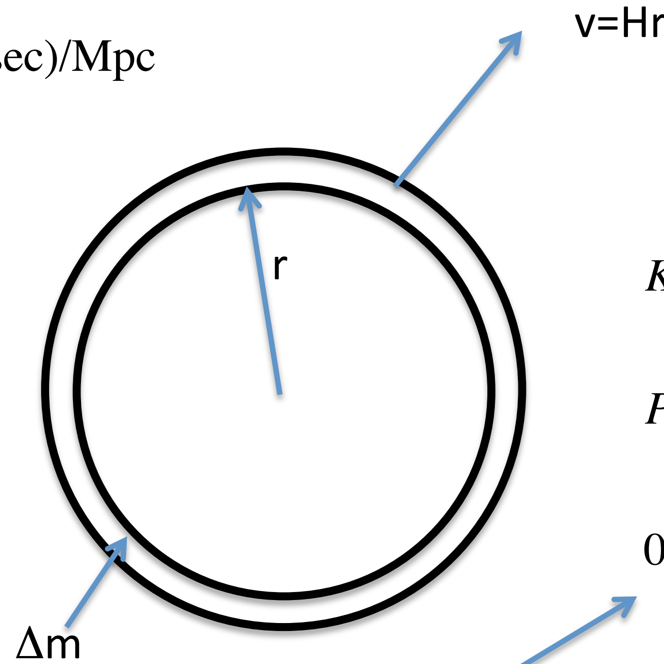
Monseigneur Georges Henri Joseph Édouard Lemaître

Making the Universe Collapse

$\mathrm{v} = Hr$

$H = h \times 100\,(\mathrm{km/sec})/\mathrm{Mpc}$

$\mathrm{h} \approx 0.7$



$$KE = \frac{1}{2}\Delta m \mathrm{v}^2 = \frac{1}{2}\Delta m (Hr)^2$$

$$PE = -\Delta m \left(\frac{4\pi r^3 \rho}{3}\right)\frac{G_N}{r}$$

$$0 = \frac{1}{2}H^2 - \left(\frac{4\pi\rho G_N}{3}\right)$$

$$\rho_{critical} = \frac{3H^2}{8\pi G_N} = 1.05 \times 10^{-5} h^2 \,\mathrm{GeV\ cm^{-3}}$$

Zero total energy. Just enough to stop expansion.

Energy Budget of the Universe

- Re-write Friedmann-Lemaitre equation:

$$\Omega_m + \Omega_{rad} + \Omega_\Lambda + \Omega_k = 1$$

$$\Omega_m = \frac{\rho_m}{\rho_{crit}} \qquad \Omega_{rad} = \frac{\rho_{rad}}{\rho_{crit}} \qquad \Omega_\Lambda = \frac{\rho_\Lambda}{\rho_{crit}} \qquad \Omega_k = -\frac{k}{H_0^2}$$

$$H(a) = \frac{\dot{a}}{a} = H_0 \sqrt{a^{-4}\Omega_{rad} + a^{-3}\Omega_m + a^{-2}\Omega_k + a^{-\varepsilon}\Omega_{DE}}$$

distance

$$D(a) = \int_a^1 \frac{da'}{a'^2 H(a')} = \int_0^z \frac{dz'}{H(z')}$$

Dark Energy Equation of State

$$w(a) = p / \rho$$

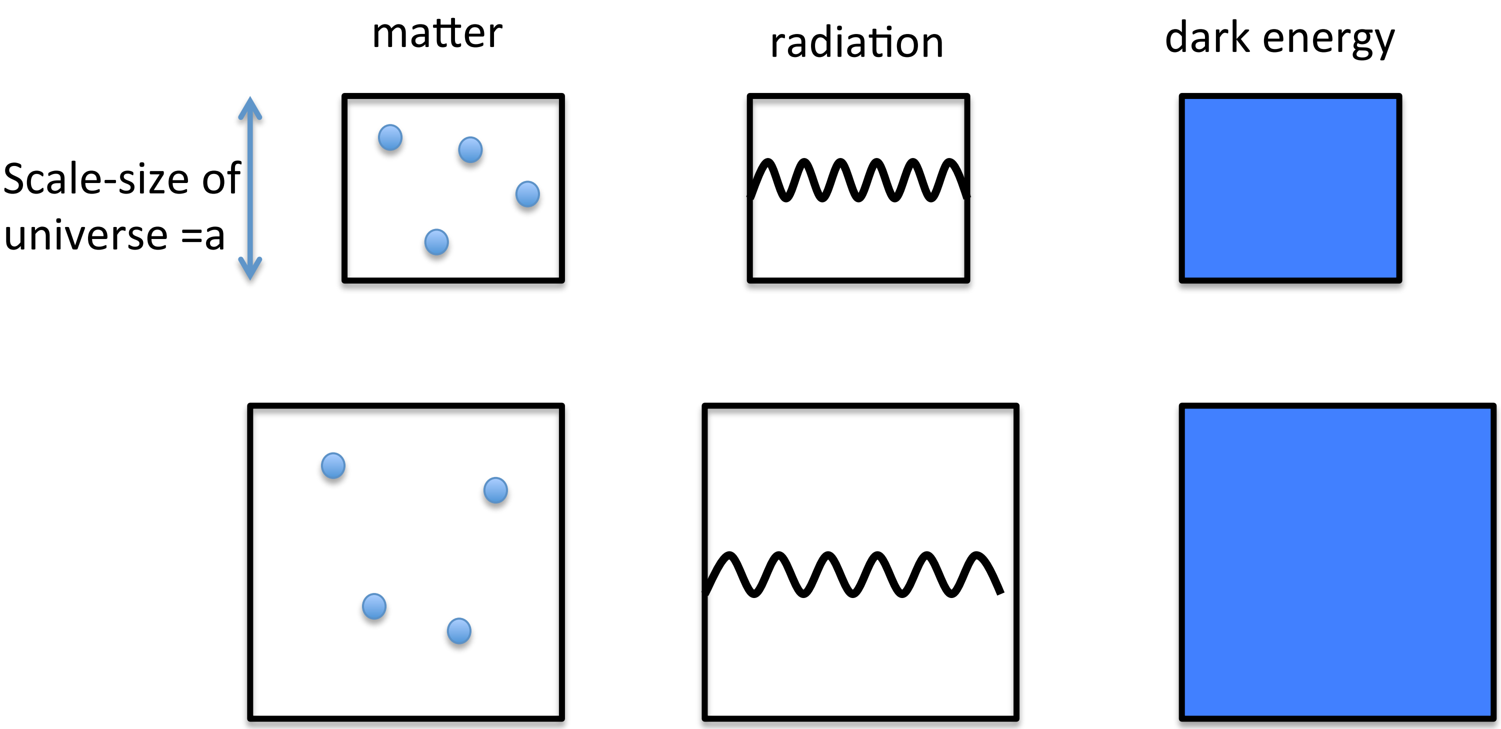
From Friedmann-Lemaitre Equations

$$\frac{d\rho}{dt} = -3(1 + w(a))\rho \frac{da}{dt} \qquad \rho(a) = \rho(a = 1)e^{3\int_a^1 \frac{da}{a}(1+w(a))}$$

Matter: w=0 Radiation: w=1/3 Cosmological constant: w=-1

Accelerating Universe means w < -1/3 or
General Relativity fails.

Dark Matter vs Dark Energy

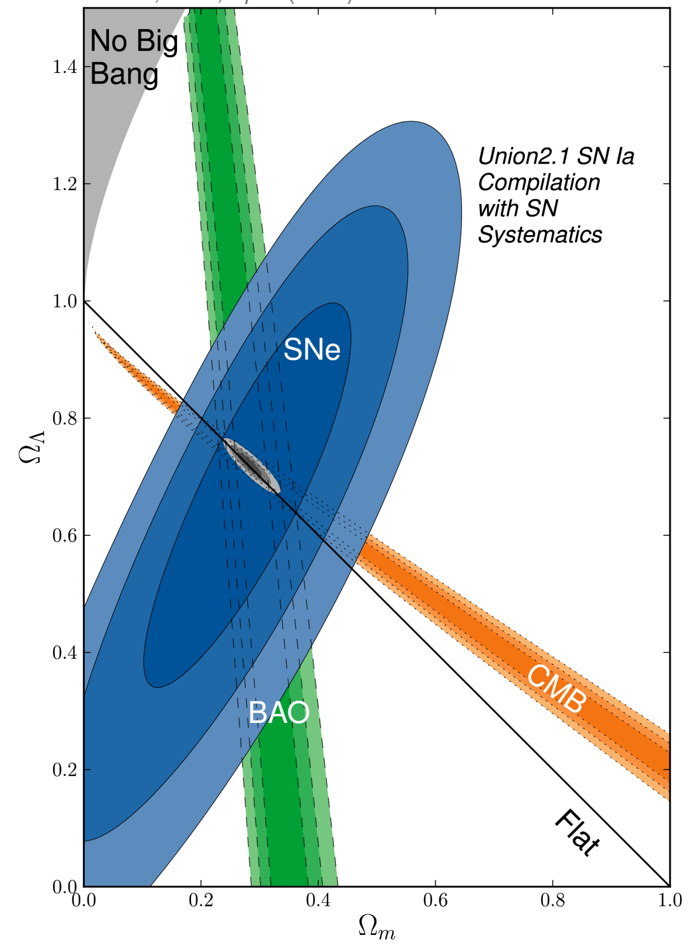


$\rho \propto a^{-3}$ $\rho \propto a^{-4}$ $\rho \propto a^{0}$

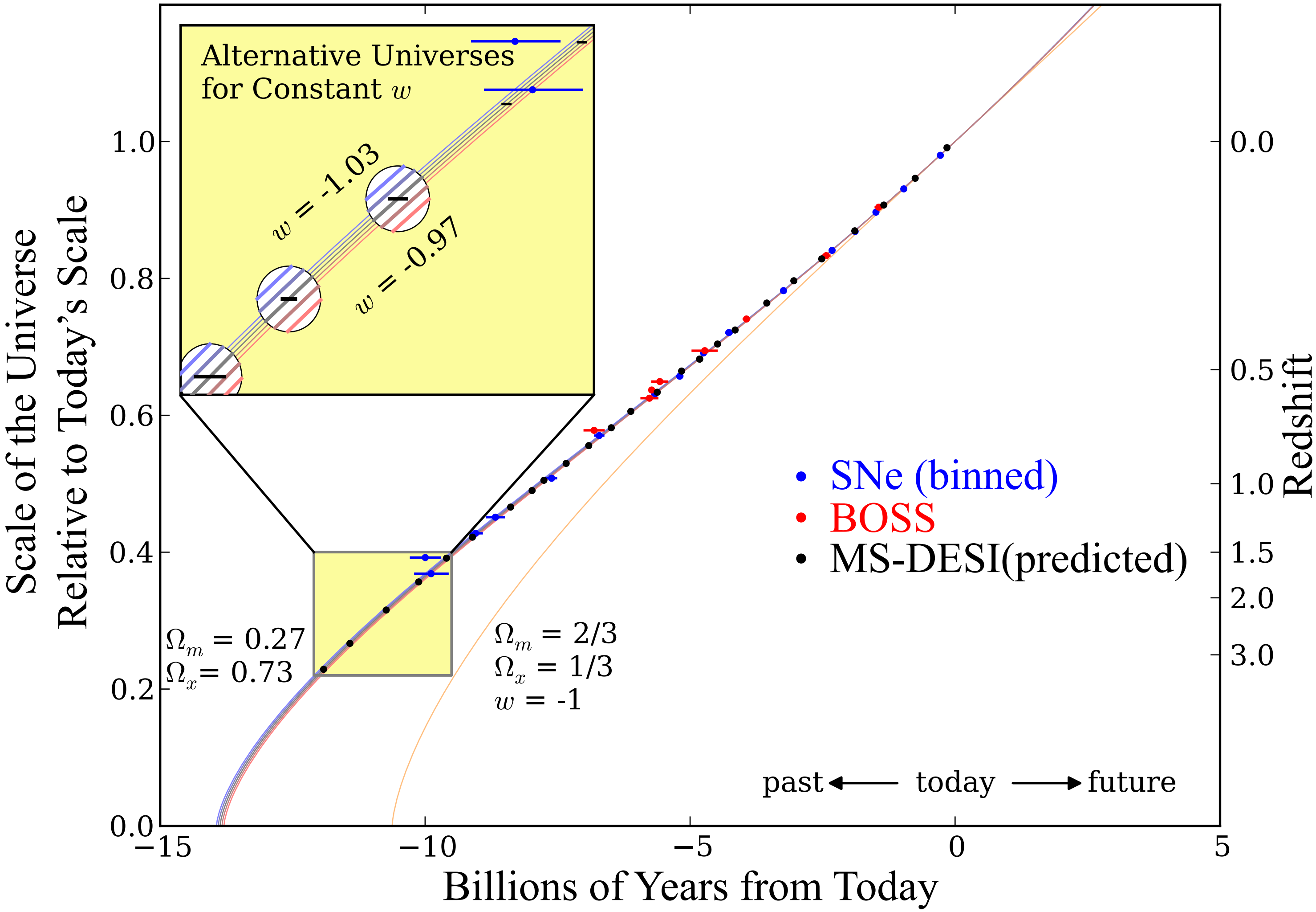
Energy Budget of Universe

- Combining three kinds of measurements we learn that
  - The Universe is flat.
  - 32% of energy is matter.
  - 68% of energy is “dark” .
- Distribution of elements tells us only 5% of energy is ordinary matter.
  - 27% of energy is due to “dark matter”

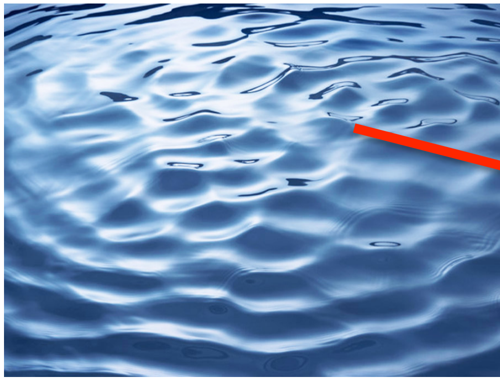
Supernova Cosmology Project
Suzuki, et al., *Ap.J.* (2011)



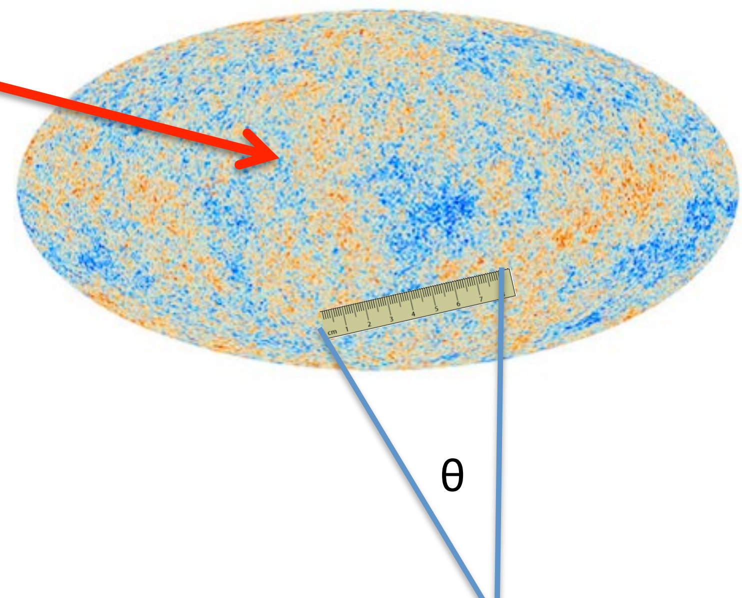
How Hard is it to Rule out Cosmological Constant?



Tiny Ripples in Early Universe

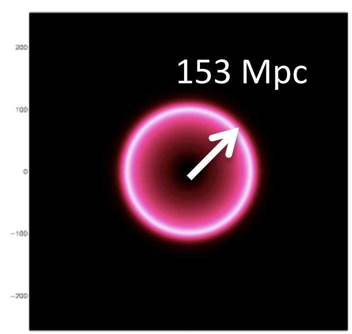


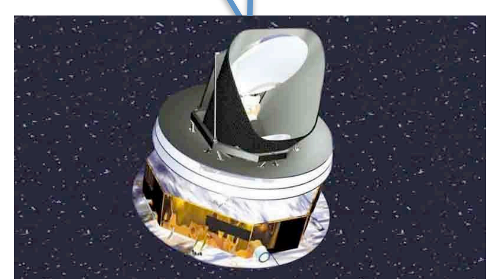
Cosmic Microwave Background



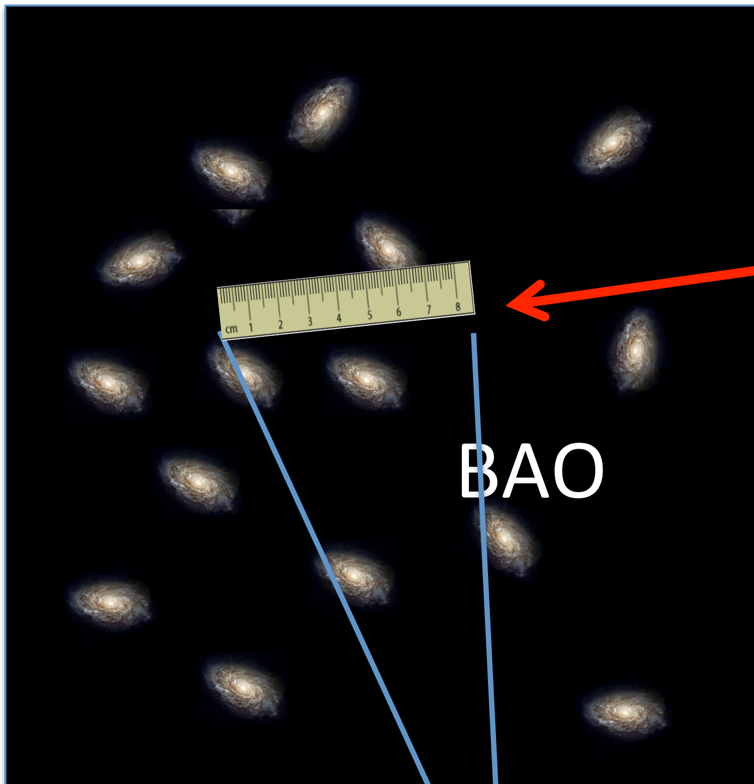
Ripples in early universe imprint standard ruler in cosmic microwave background.

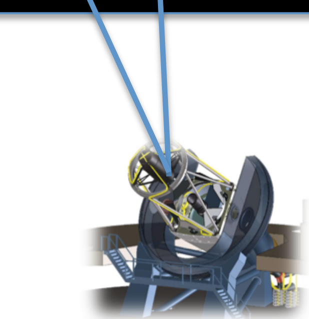
Waves emanate from high density regions. Using data from Planck we know these waves go 153 Mpc (comoving) before stopping after 380,000 years when the plasma becomes neutral.

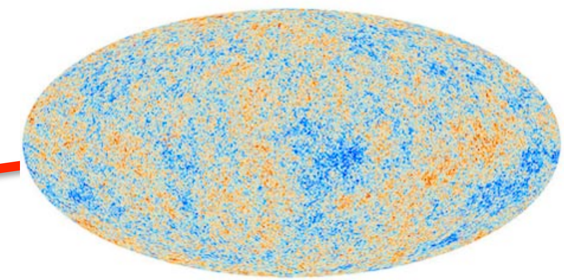




BAO gives Ruler

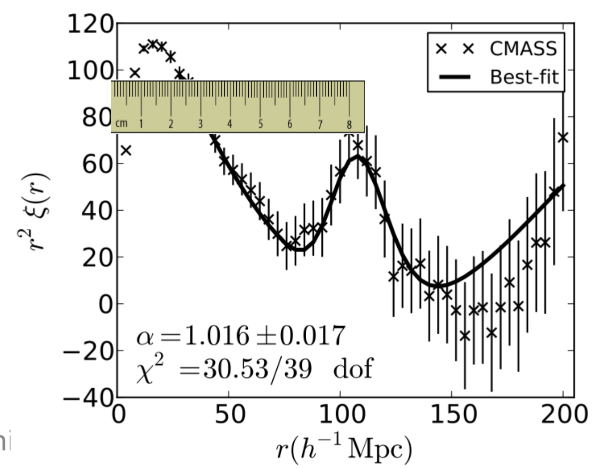






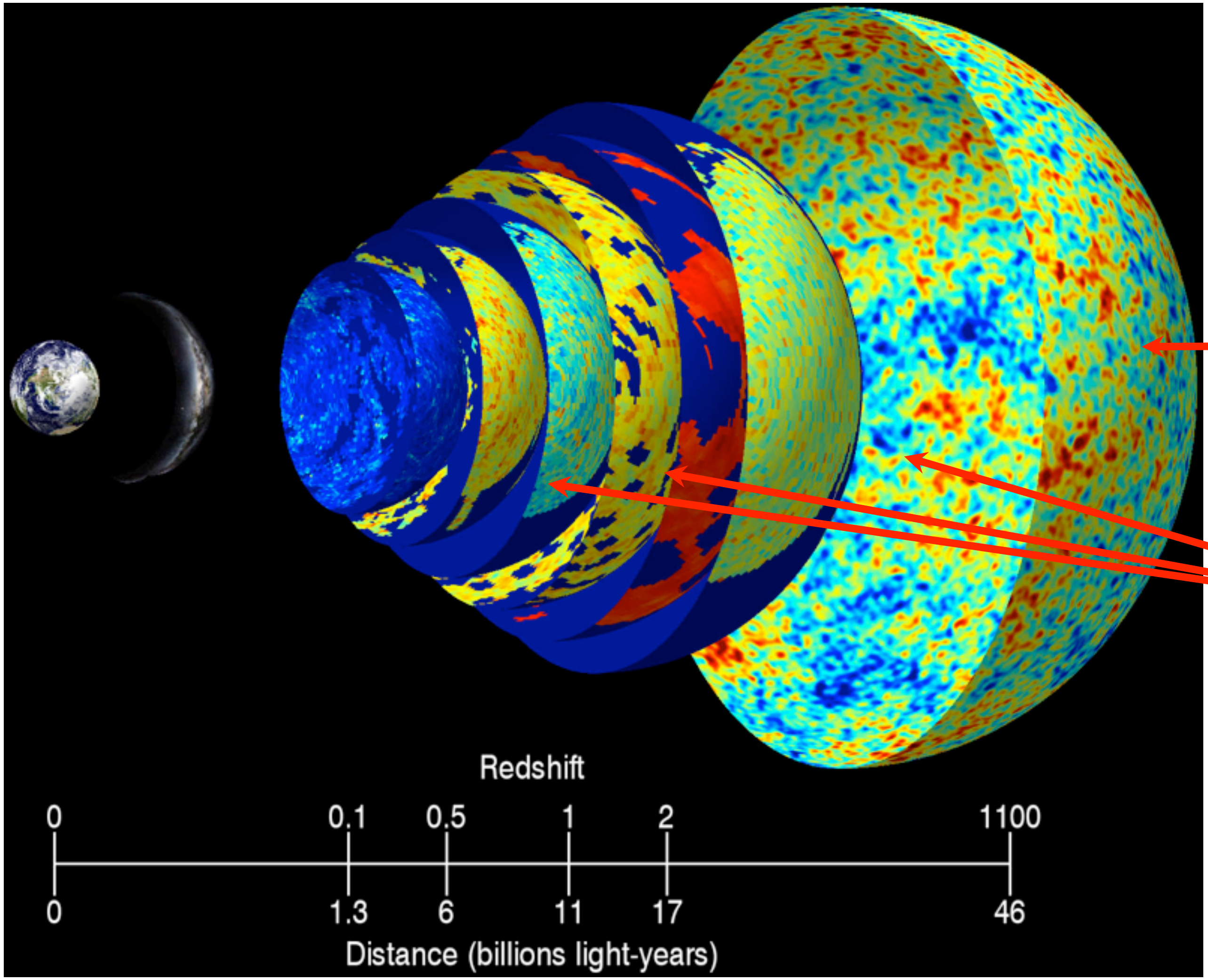
That pattern is preserved in the distribution of the galaxies.

By measuring the pattern looking back billions of years we can deduce the expansion history of the universe.



BAO at z=0.57
Anderson et al (2012)

CMB is 2-d   BAO is 3-d

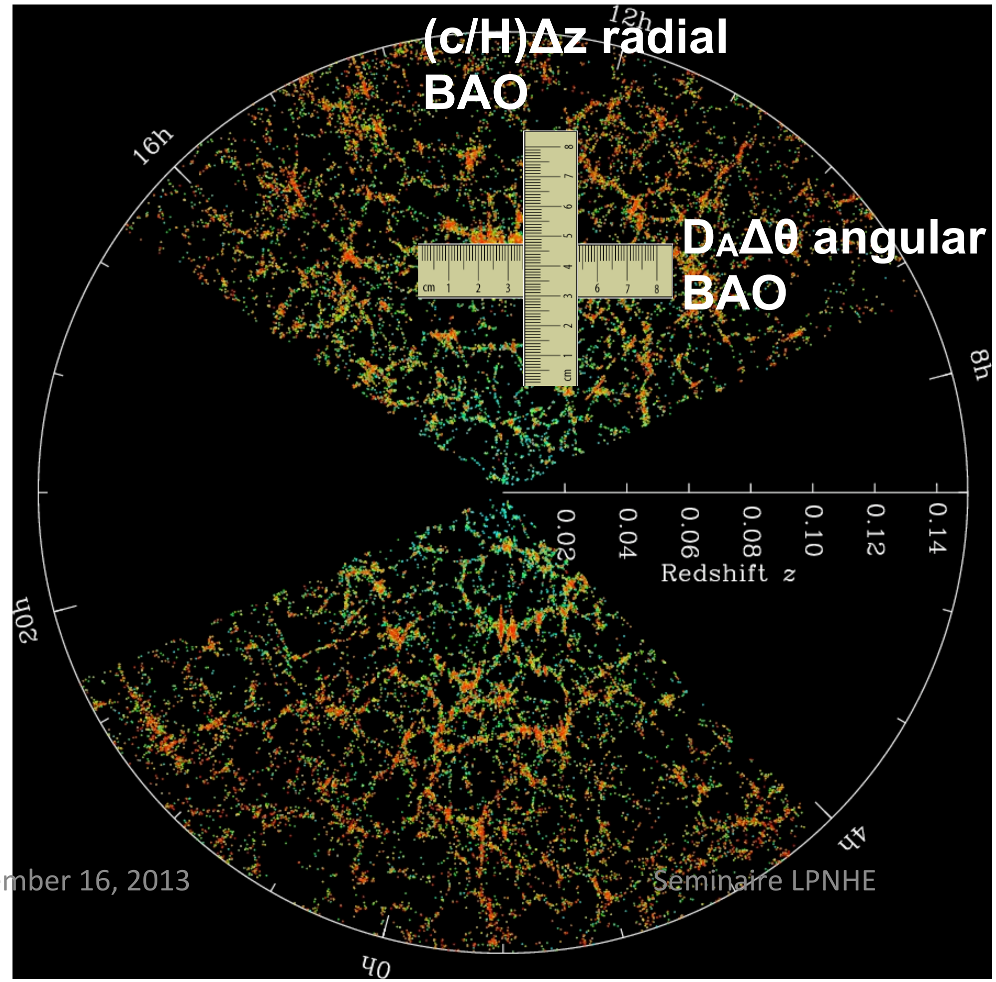


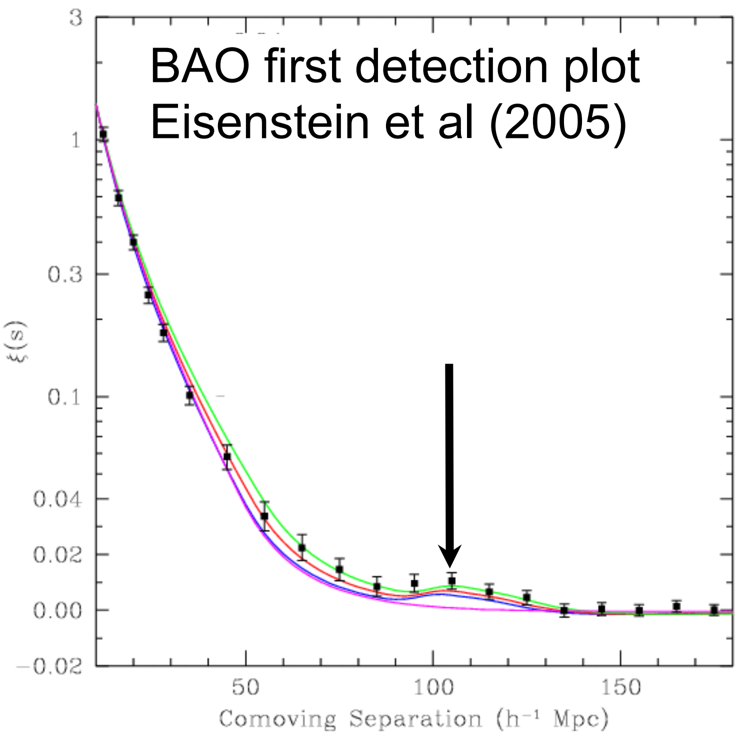
BAO standard ruler from Planck

$\theta_s = 0.596724 \pm 0.00038$ deg

BAO standard ruler from BOSS & DESI

How BAO Works

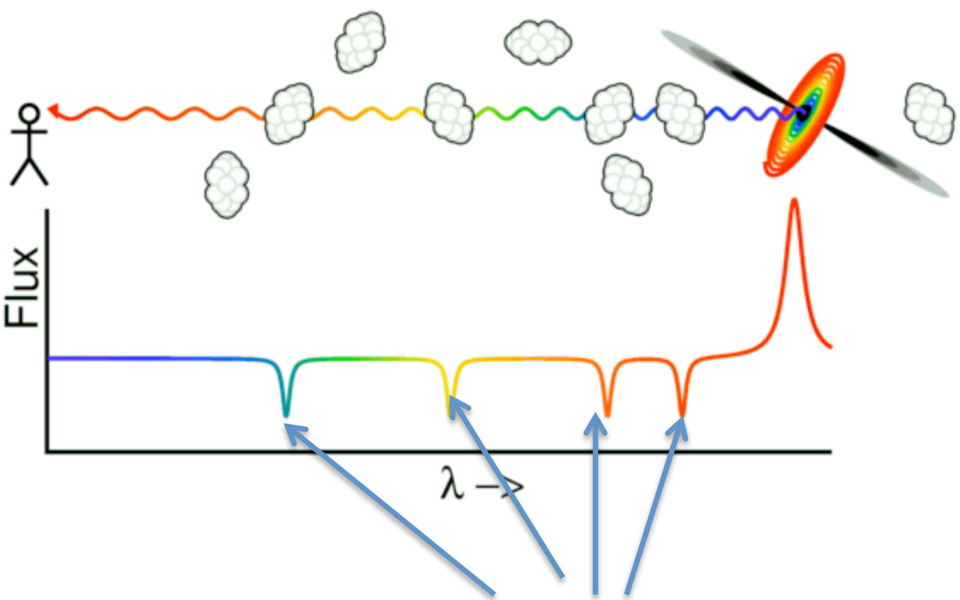




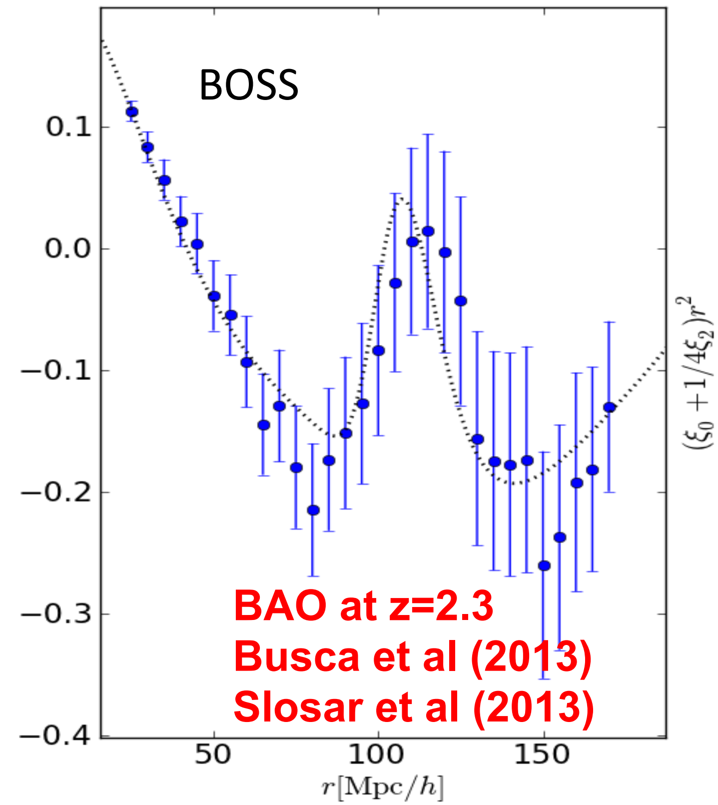
Best BAO so Far: BOSS

Lyman-alpha forest: First dark energy results z>2

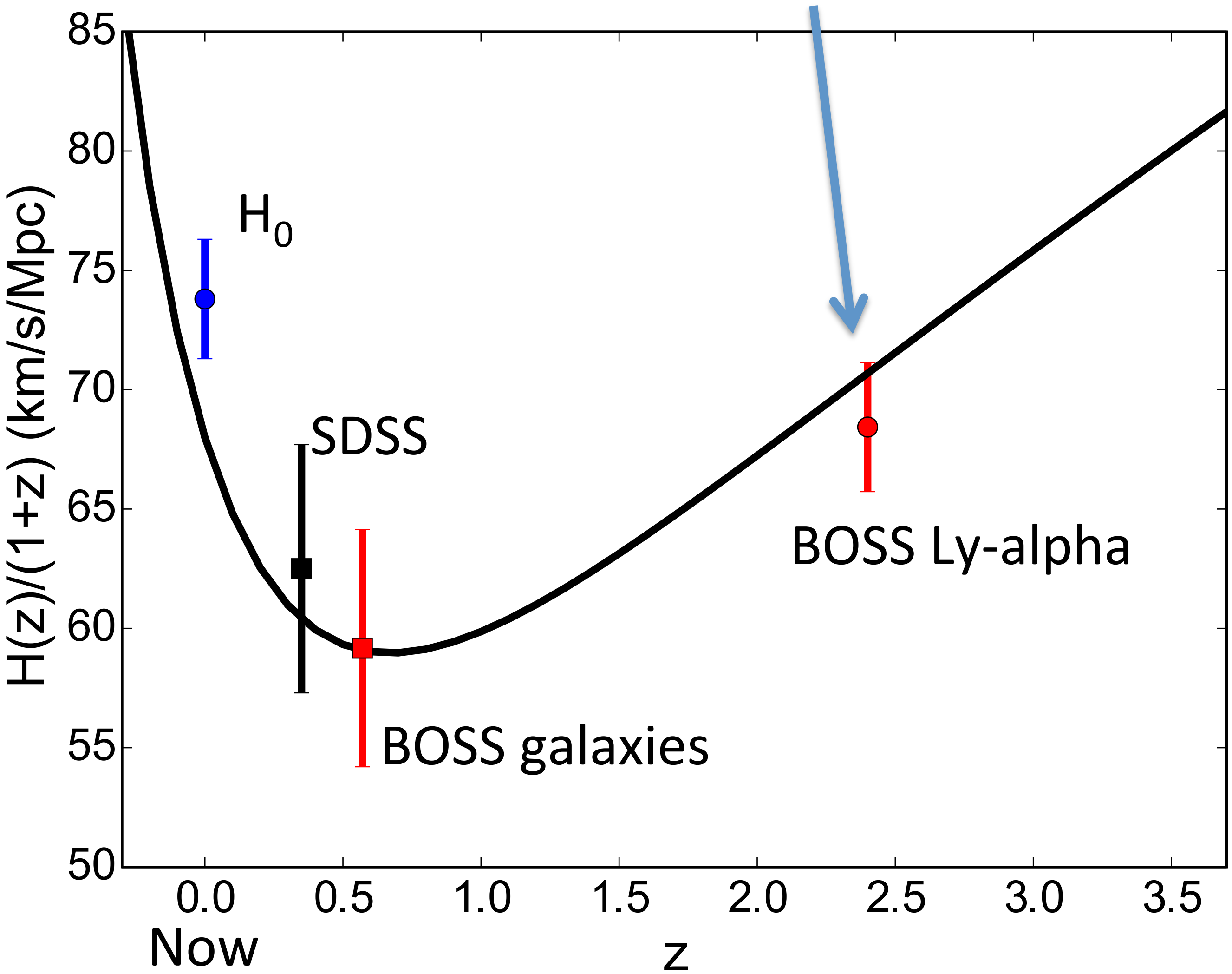
Forest of absorption lines maps location of neutral hydrogen along line-of-sight from quasar.



Light absorbed when stretched to 121.6 nm.

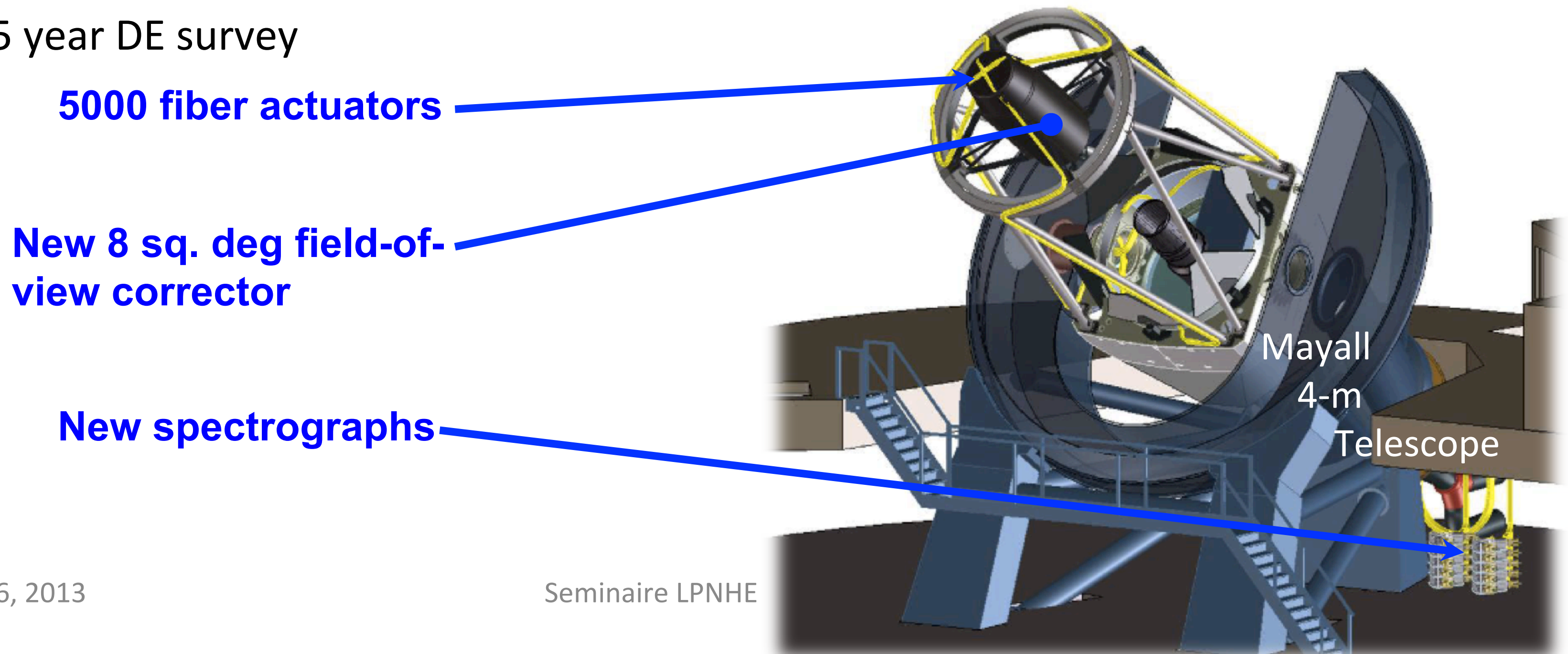


BOSS Lyman-alpha Sees Deceleration!

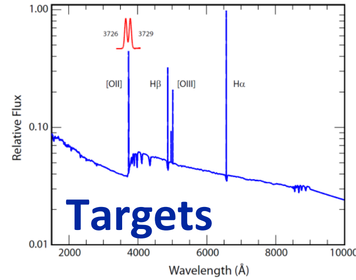


From BOSS to DESI

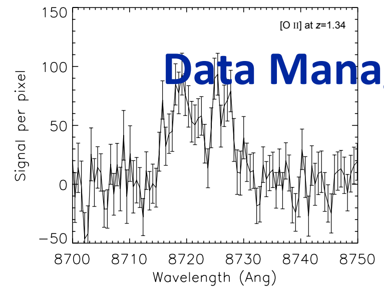
- Scale up BOSS to a massively parallel fiber-fed spectrometer
- Broad range of target classes: LRG's, ELG's, QSO's
- Broad redshift range: $0.5 < z < 1.6$, $2.2 < z < 3.5$ {region between 0.7 – 1.6 new}
- Sky area: 14,000 square degrees
- Number of redshifts: 24 million
- Medium resolution spectroscopy, R ~ 4000
- Spectroscopy from blue to NIR: 360 nm < z < 980 nm
- Automated fiber system, N_{fiber} ~ 5000
- Up to 5 year DE survey



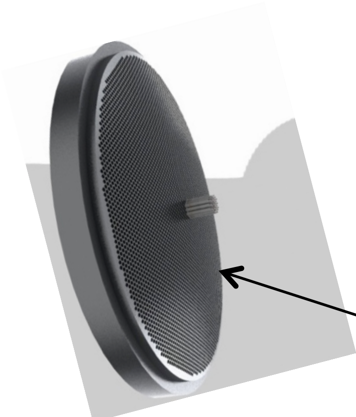
DESI Hardware & Software Elements



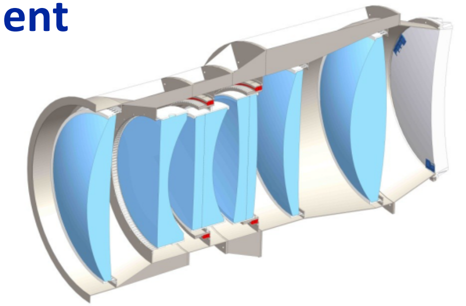
Targets



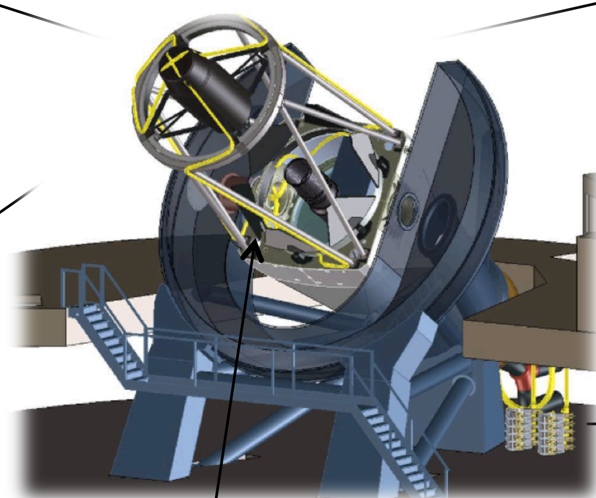
Data Management

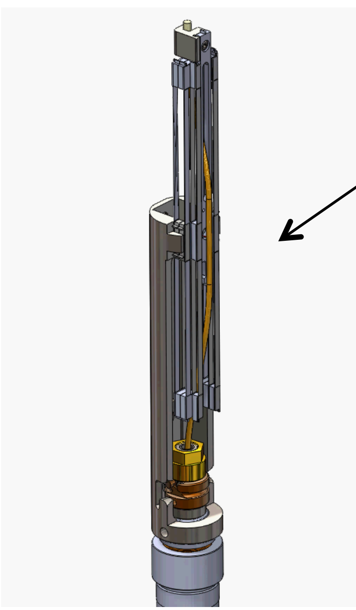


Focal Plate

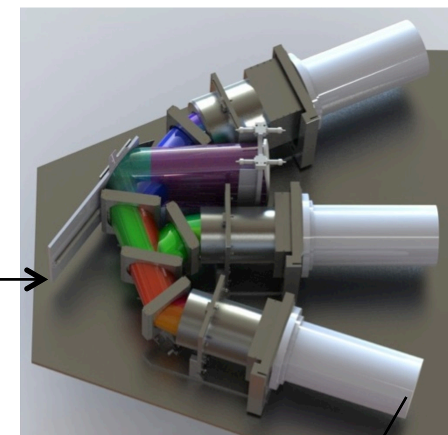


Prime Focus Corrector

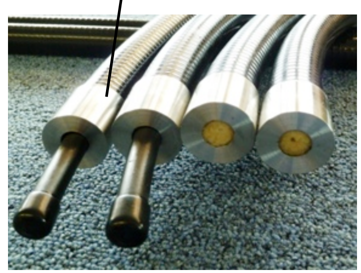




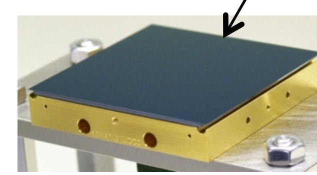
Fiber Positioner



Spectrometer

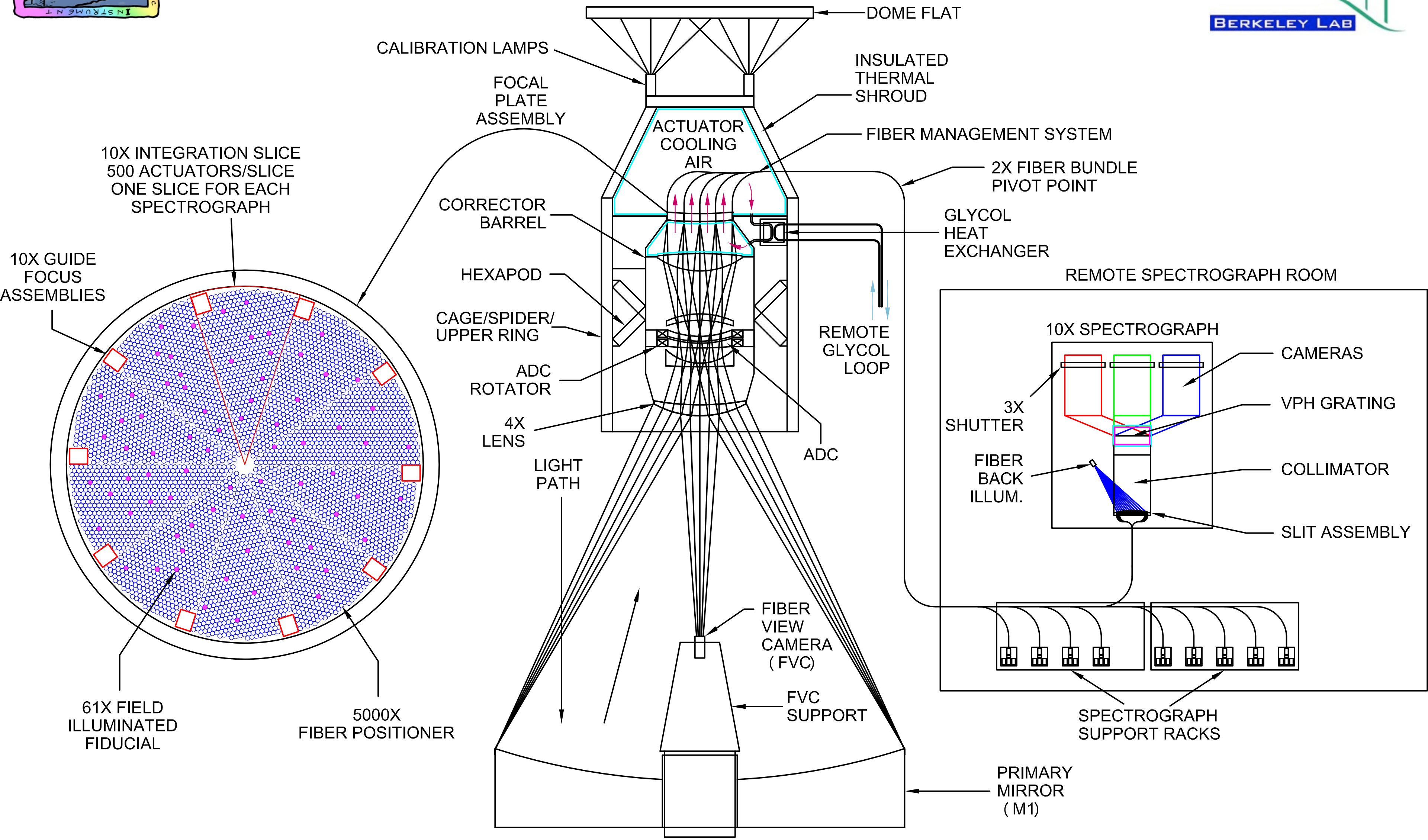


Fiber System

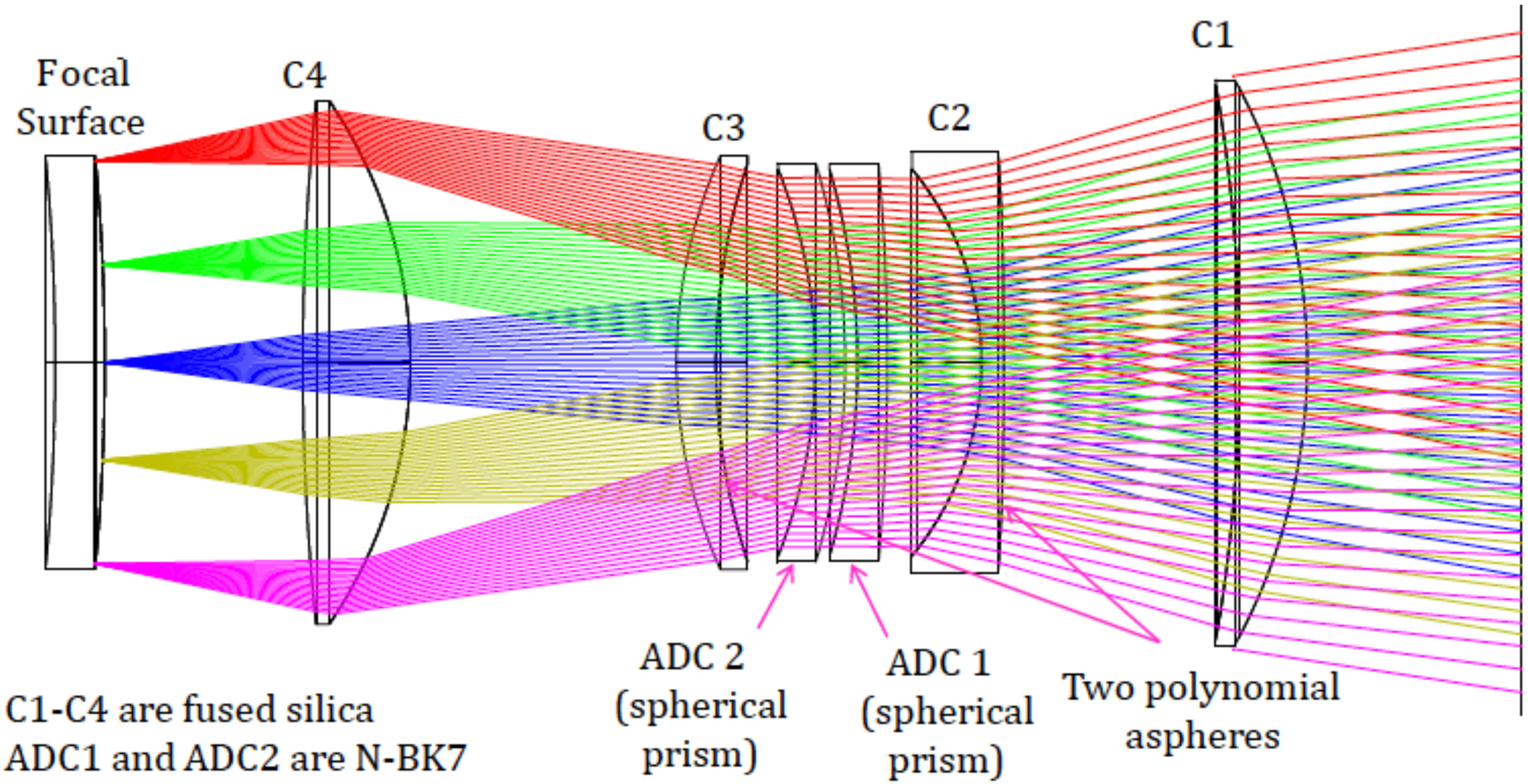


CCD's

Block Diagram

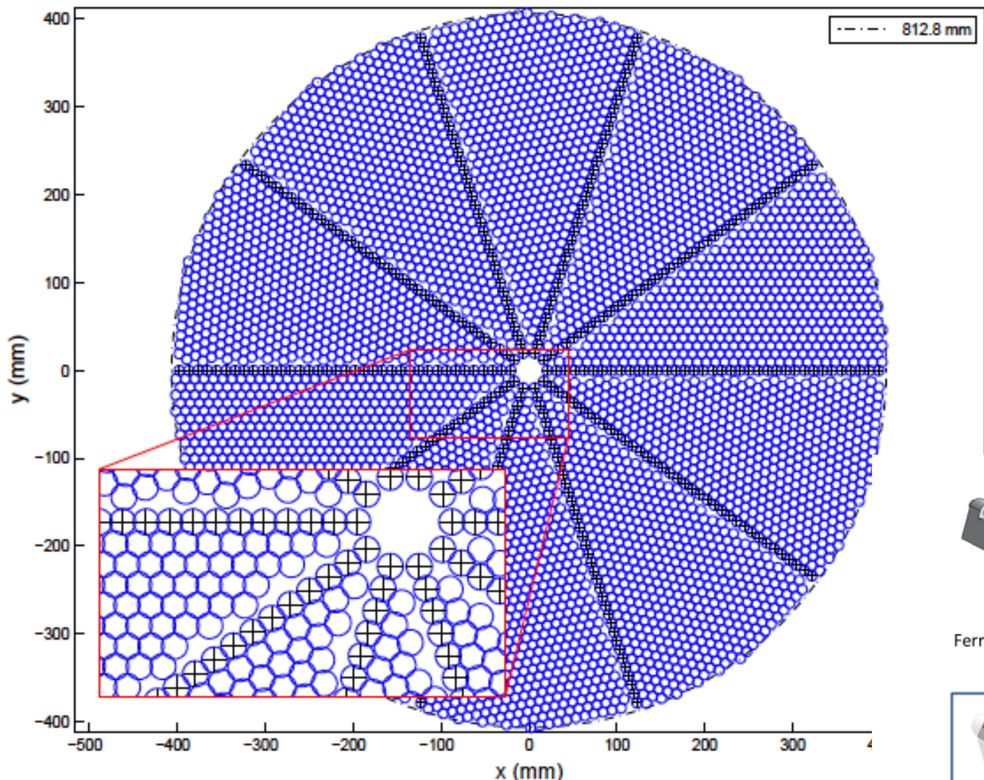


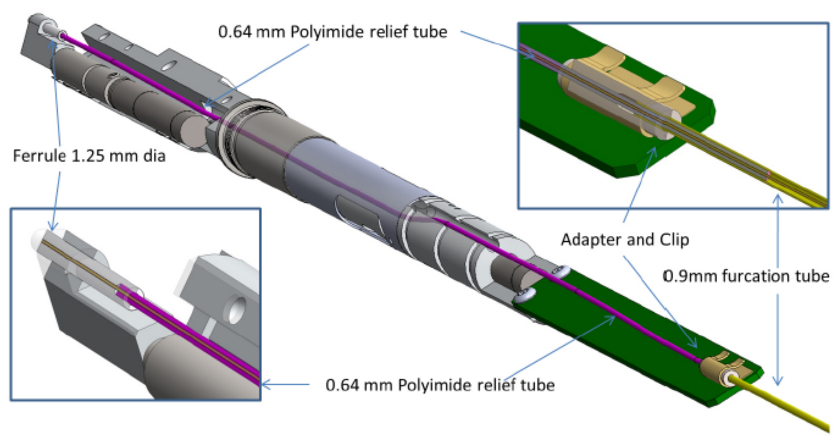
Corrector



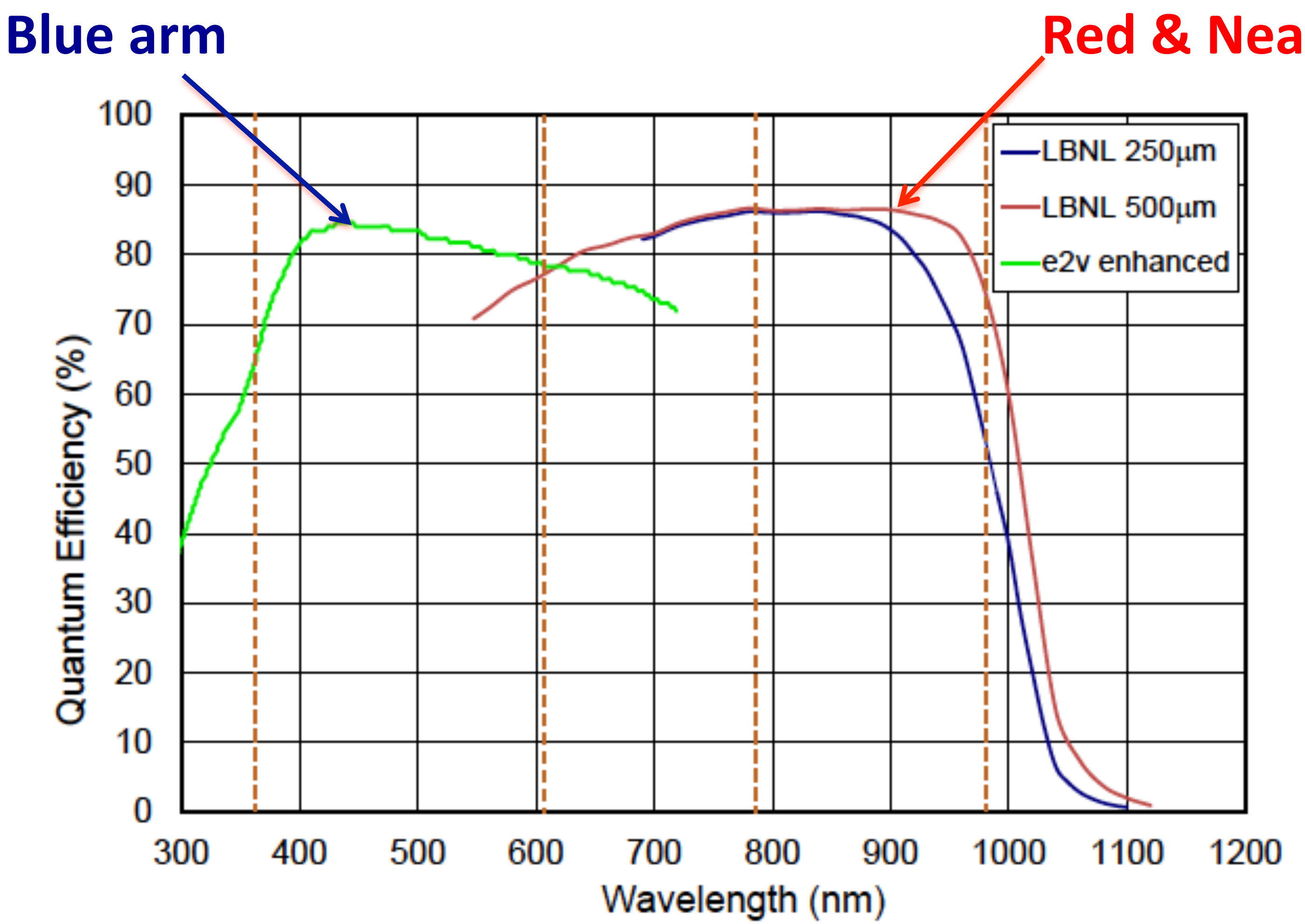
C1-C4 are fused silica
ADC1 and ADC2 are N-BK7

Fiber Positioners in Focal Plane





CCDs

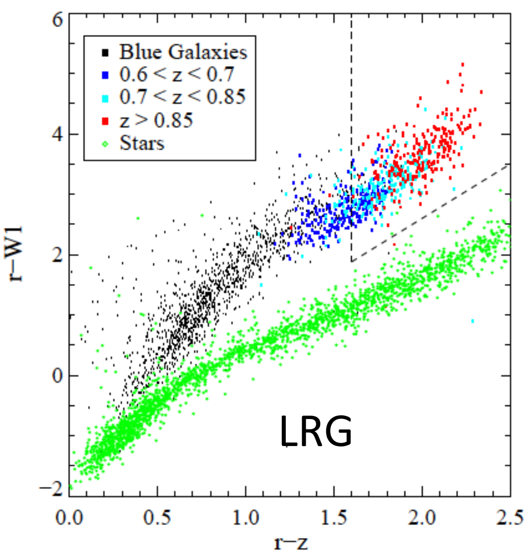


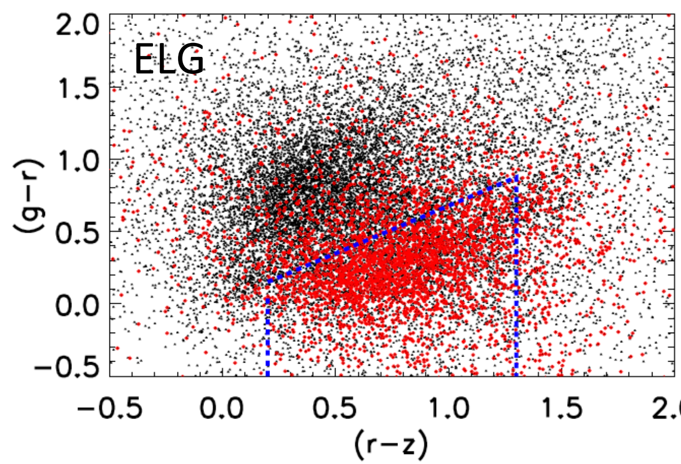
Blue arm
Red & Near IR arms
LBNL 250µm
LBNL 500µm
e2v enhanced
Quantum Efficiency (%)
Wavelength (nm)
0
10
20
30
40
50
60
70
80
90
100
300
400
500
600
700
800
900
1000
1100
1200

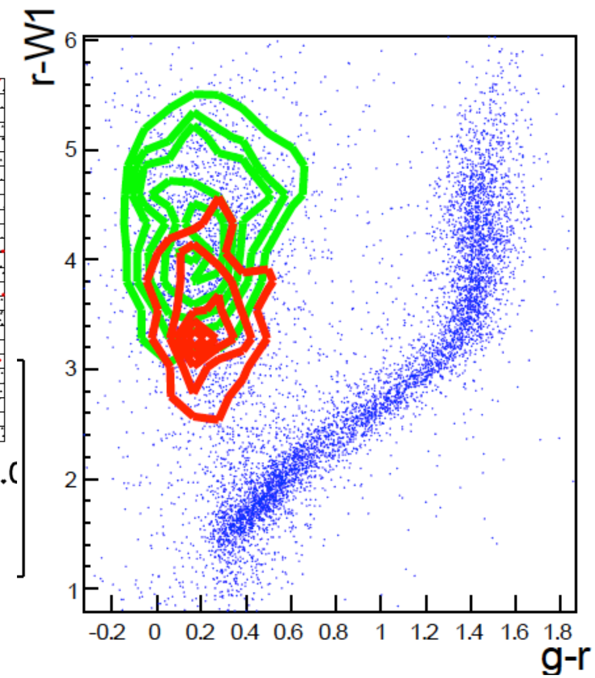
Galaxy Targets

Galaxy type	Redshift range	Bands used	Targets per deg^2	Exposures per deg^2	Good z's per deg^2	Net sample
LRG	0.4–1.0	r,z,$W1$	350	700	300	4.2 M
ELG	0.7–1.6	g,r,z	2300	2300	1400	19.6 M
QSO (tracers)	0.9–2.2	g,r,z,$W1$,$W2$	175	175	100	1.4 M
QSO (Ly-α)	> 2.2	g,r,z,$W1$,$W2$	75	200	40	0.6 M
Total			2900	3375	1840	25.8 M

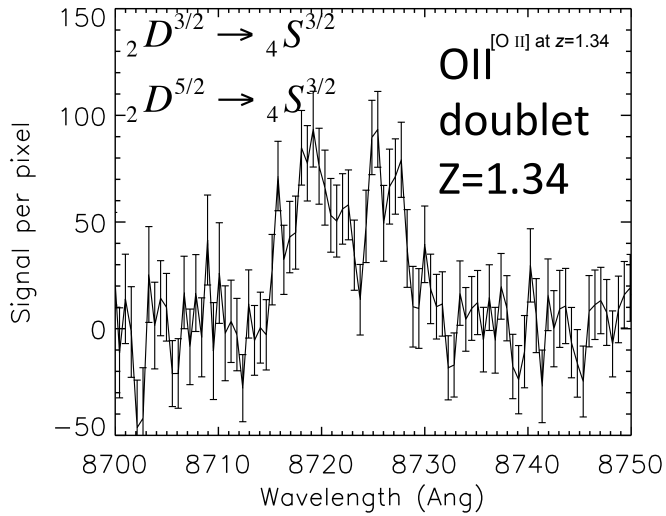
Select photometrically, measure spectroscopically.

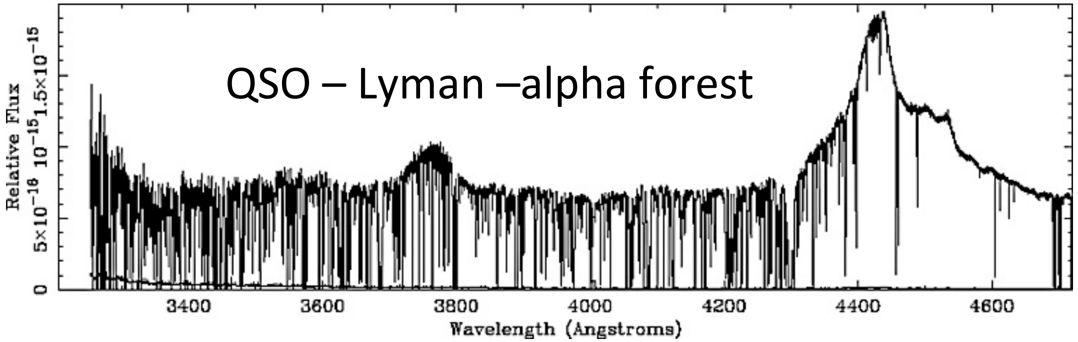


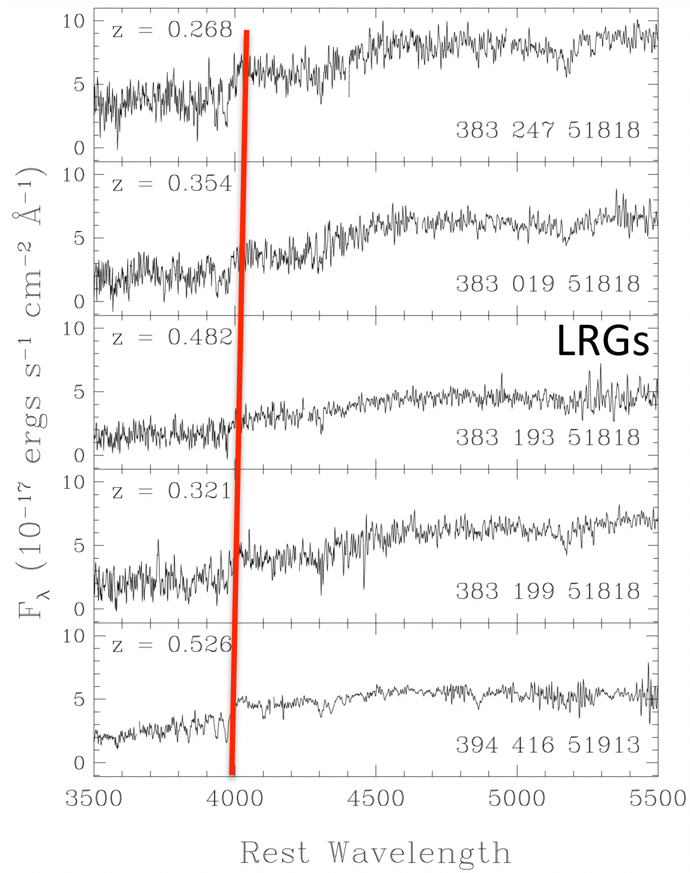




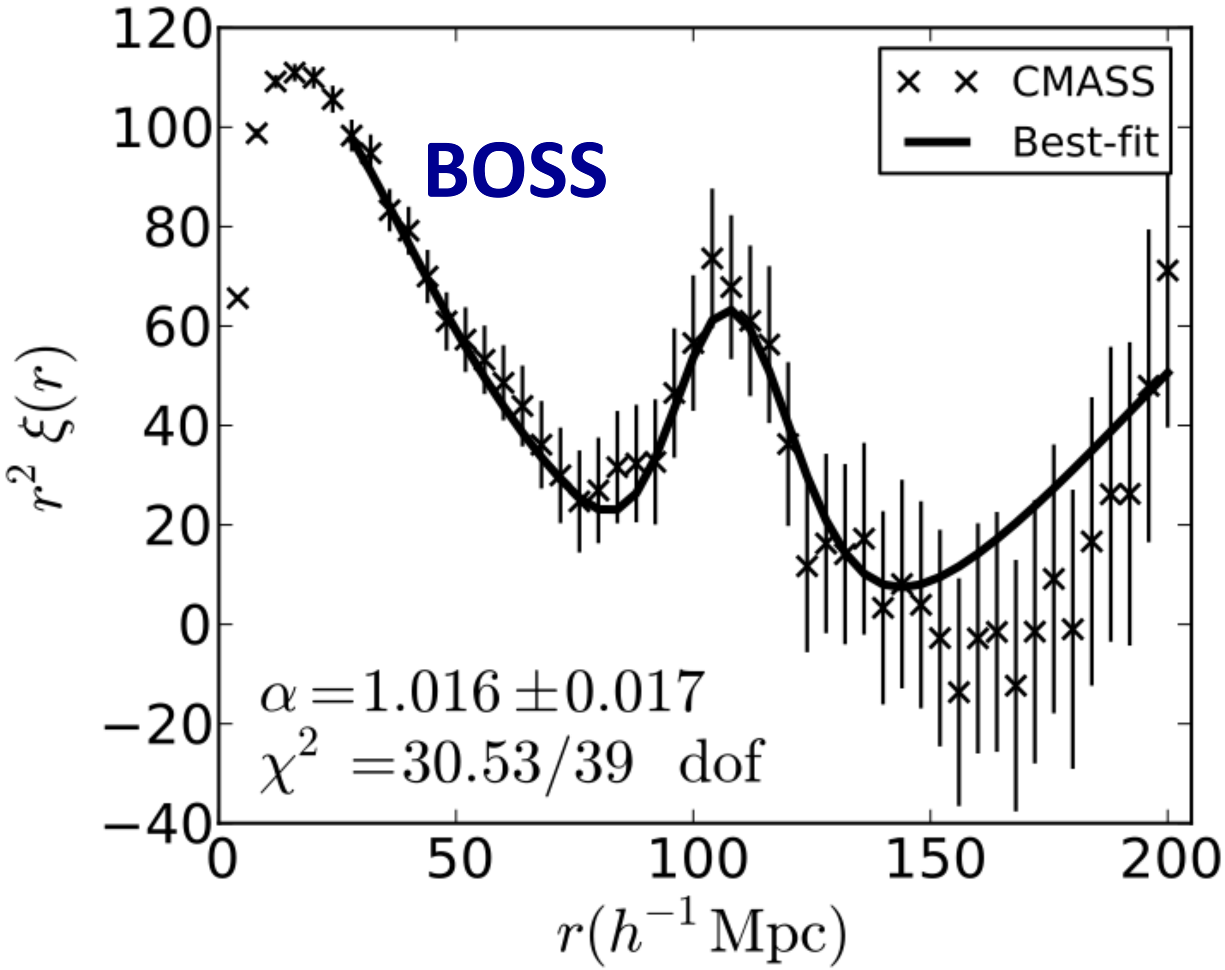
Spectroscopy



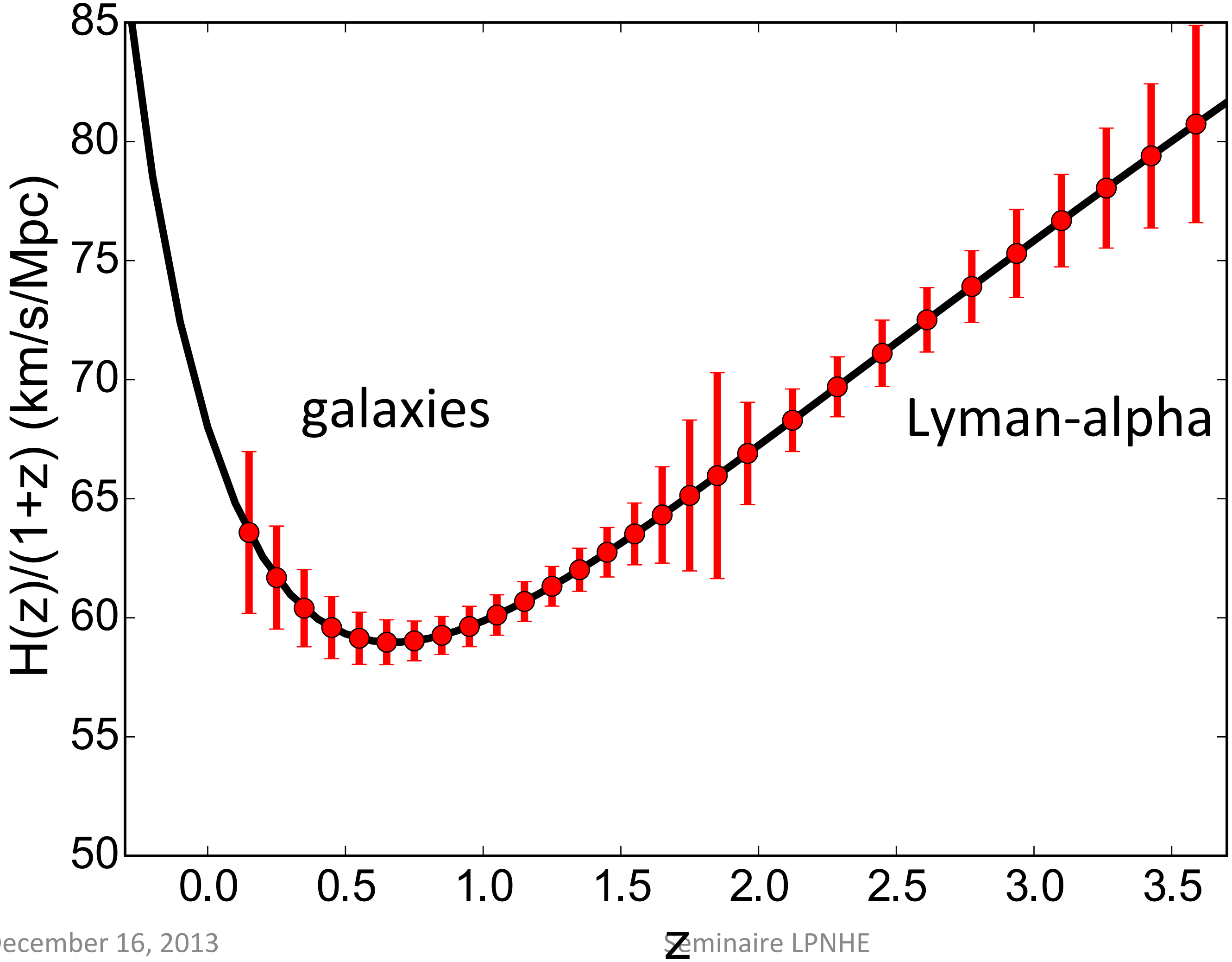




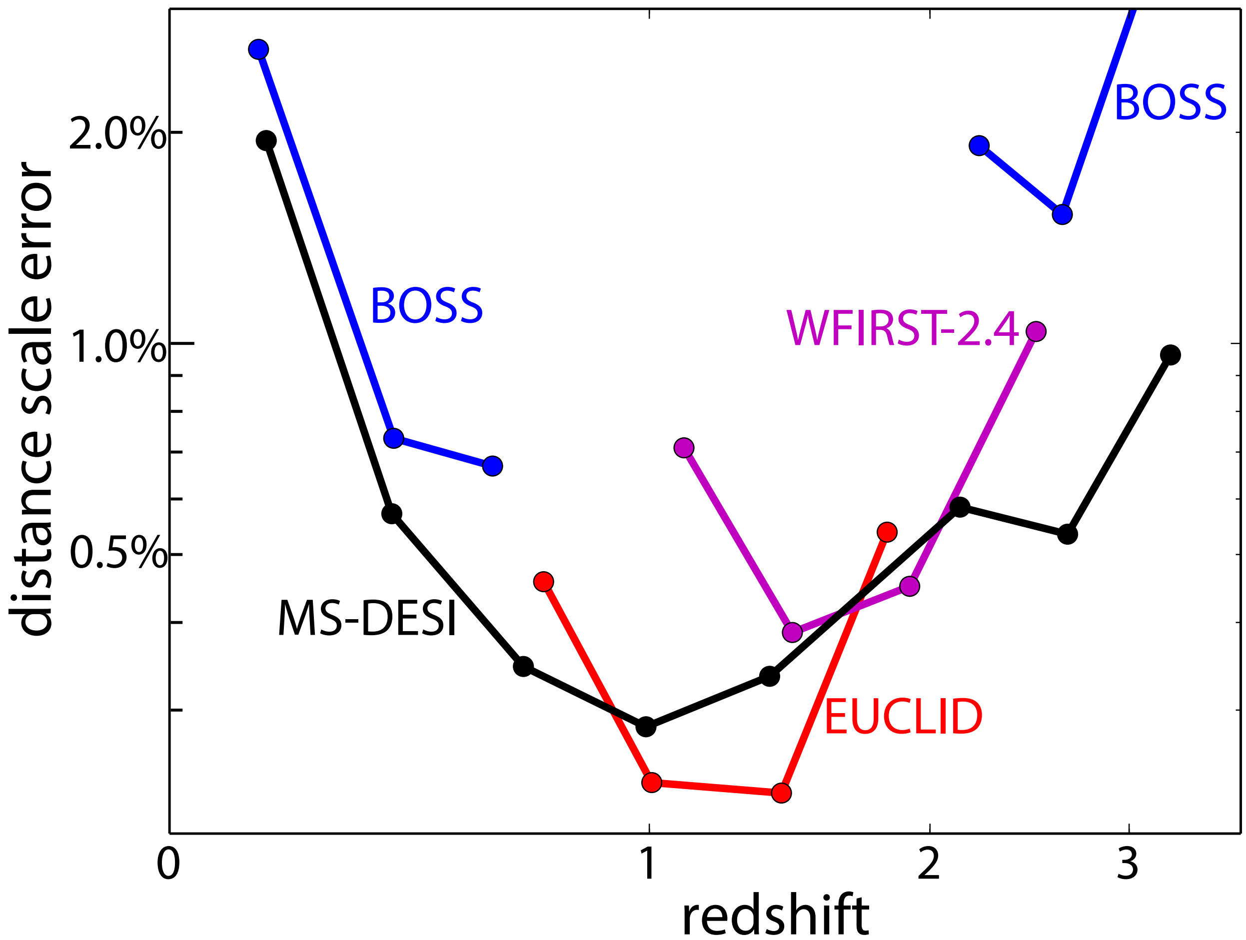
Measure Two-Point Correlation as Function of *z*



Anticipated Quality of DESI Expansion Measurements



DESI Achieves Space-Based Precision

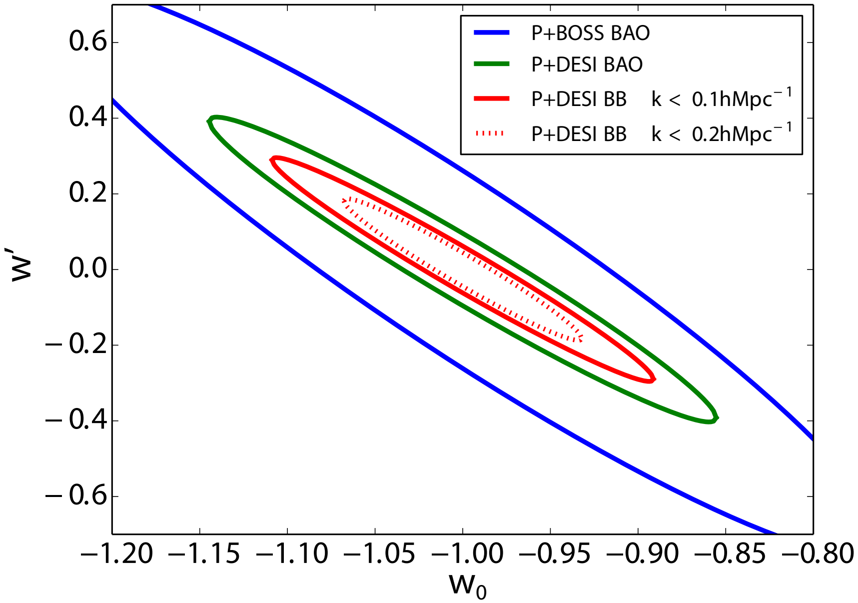


Characterizing Dark Energy Precision

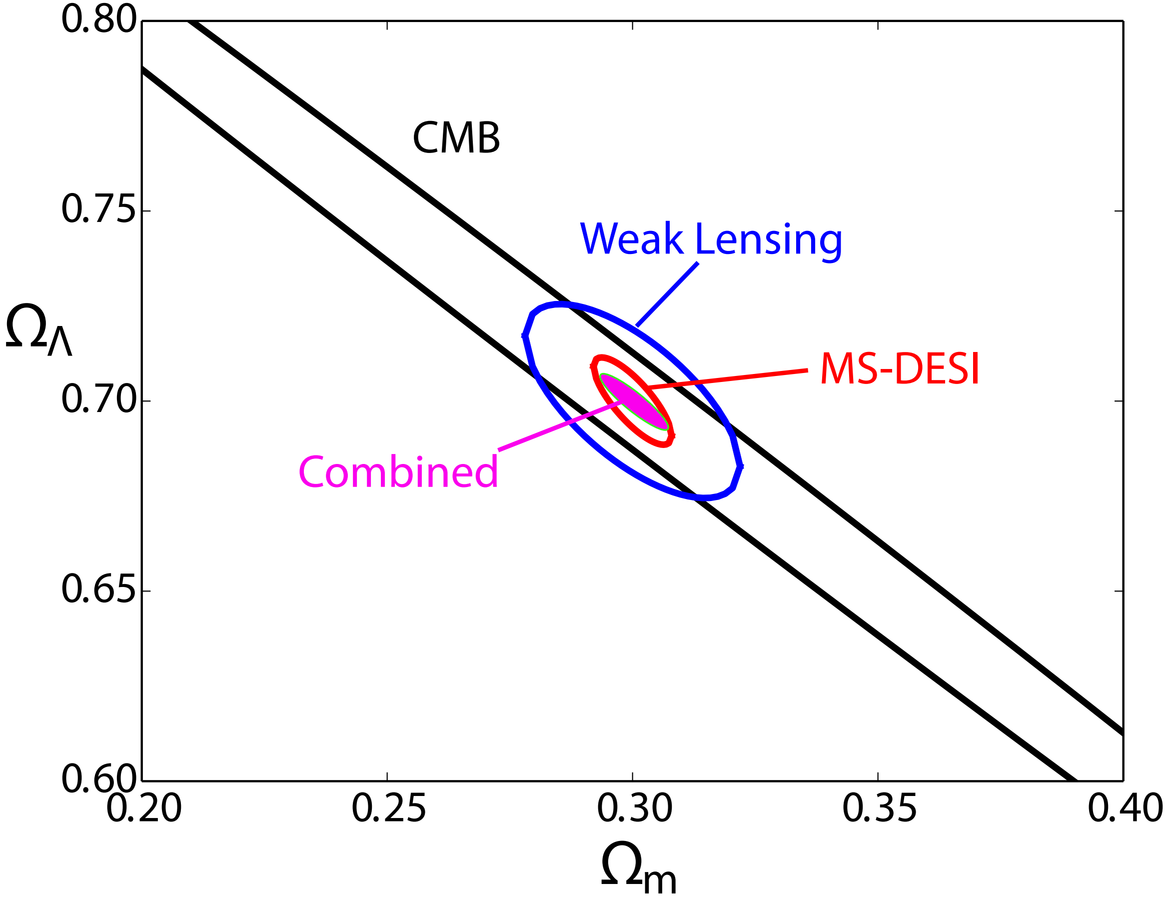
$$w(a) = w_0 + (1-a)w_a$$

Dark Energy Task Force Figure of Merit:

$$\propto 1/\text{Area of } w_0 - w_a \text{ error ellipse}$$



Combining DESI and LSST



Correlation Function and Power Spectrum

- The Wiener (1930)-Khinchin (1934) Theorem – naive version due to Einstein (1914):
  - "The Fourier transform of the correlation function is the power spectrum"

$$\langle \rho(k)\rho^*(k')\rangle = \left\langle \int dx e^{ikx} dx' e^{-ik'x'} \rho(x)\rho(x')\right\rangle = \int dx e^{ikx} dx' e^{-ik'x'} \xi(x-x')$$

$$= \int dx e^{i(kx-k'x)} dx' e^{-i(k'x'-k'x)} \xi(x-x') = 2\pi\delta(k-k')\overline{\xi}(k')$$

DESI: Not just BAO

Power spectrum is Fourier transform of two-point correlation function.

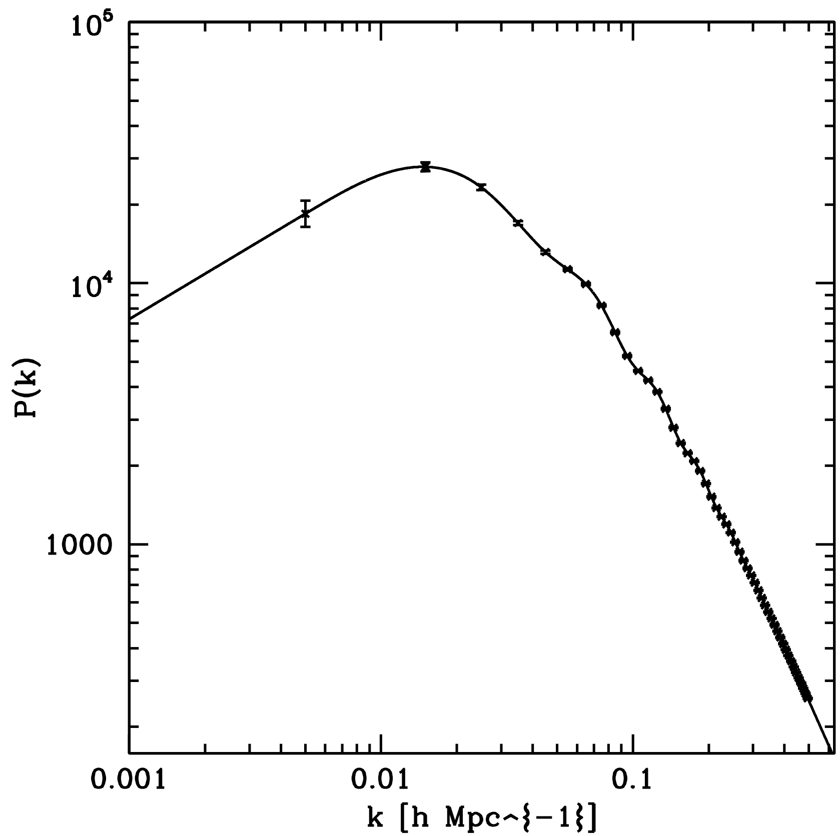
Power spectrum tests:
- General Relativity
- Inflation
- Number of neutrinos
- Sum of the neutrino masses

$$n_s : \pm 0.0022$$

$$\alpha_s : \pm 0.0024$$

$$\Sigma m_\nu : \pm 0.024\,\mathrm{eV}$$

$$\Sigma \mathrm{N}_\nu : \pm 0.056$$

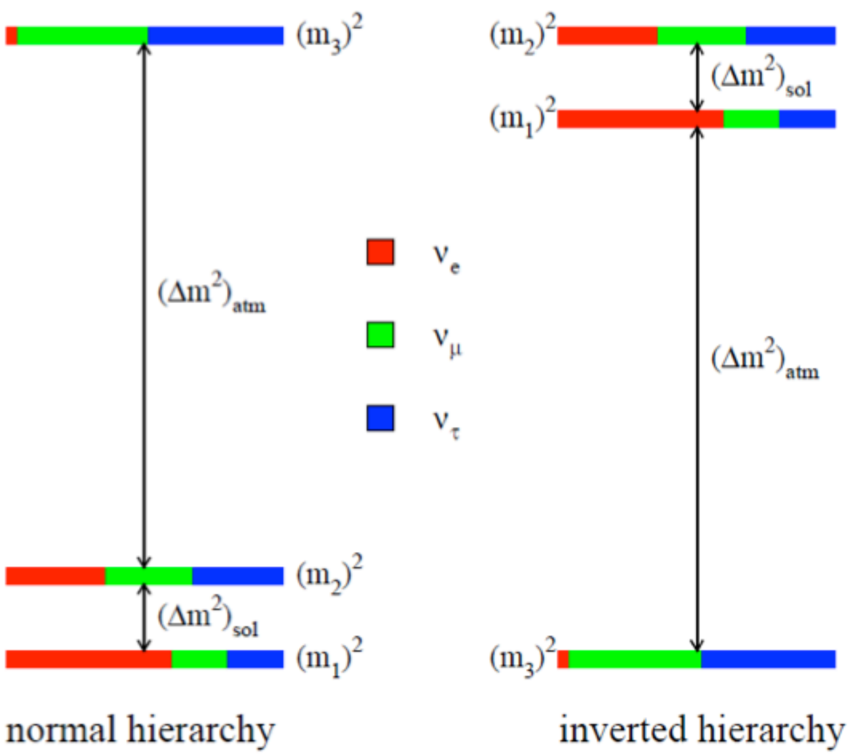


Measuring the sum of neutrino masses

$$\Delta m_{32}^2 = 2.32\times 10^{-3}\,\mathrm{eV}^2$$

$$\Delta m_{21}^2 = 7.50\times 10^{-5}\,\mathrm{eV}^2$$

Data	$\sigma_{\Sigma m_\nu}$ [eV]	$\sigma_{N_{\nu,\mathrm{eff}}}$
Planck	0.350	0.18
Planck+DESI BAO	0.090	0.18
Gal ($k_{\max} = 0.1$)	0.024	0.13
Gal ($k_{\max} = 0.2$)	0.017	0.084
Ly-α forest	0.039	0.11
Ly-α forest + Gal ($k_{\max} = 0.2$)	0.017	0.063



Redshift Space Distortion

- Can't measure distance directly.
- Mismeasure if there is "peculiar velocity"

Assume $\vec{\mathrm{v}} = Hr\hat{n}$ along line of sight

so peculiar velocity $\Delta\vec{v}$ leads to shift

$\Delta r\,\hat{n} = \Delta\vec{\mathrm{v}}\cdot\hat{n}\hat{n}\,/\,H(a)$

- Gravity will amplify all density perturbations.

$$\delta\rho(t) = D(t)\,\delta\rho(t=0) \quad \text{[now]}$$

Galaxies vs Matter

- Assume fractional fluctuation in galaxy density is proportional to fractional fluctuation in matter:

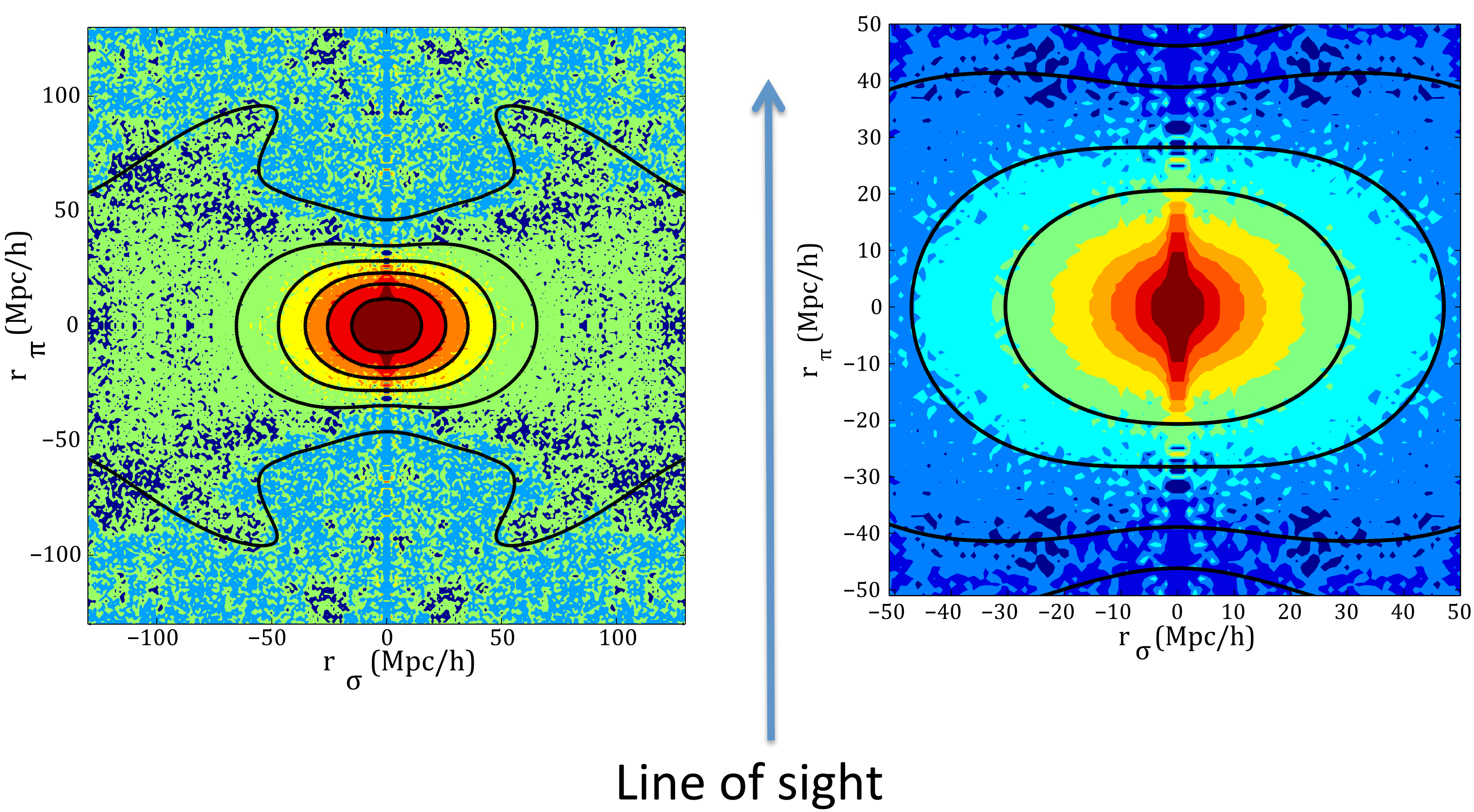
$$\delta_{galaxy} \equiv \frac{\delta\rho_{galaxy}}{\bar{\rho}_{galaxy}} = b\frac{\delta\rho_{matter}}{\bar{\rho}_{matter}} = b\delta_{matter}$$

Because we observe in redshift space, there is a distortion of the power spectrum:

$$P(\vec{k})_{galaxy,RSD} = (b^2 + (\hat{k}\cdot\hat{n})^2 f)^2 P(k)_{matter,realspace}$$

$$f = \frac{d\ln D}{d\ln a}$$

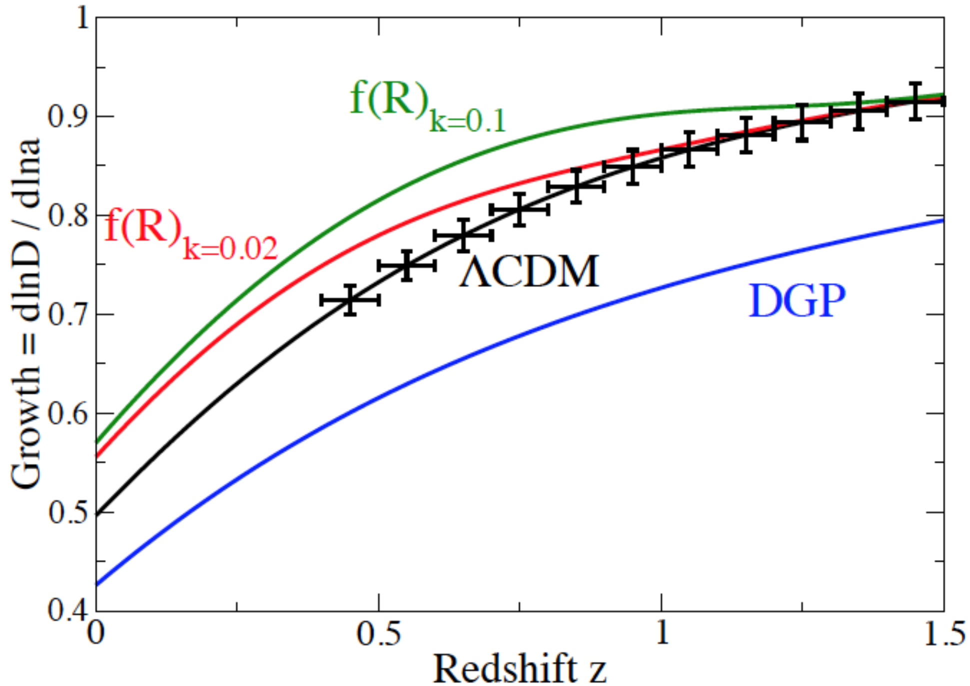
Redshift Space Distortion at BOSS



Testing General Relativity

- The growth function D(a) is determined by the matter density and General Relativity.

In practice, we measure $f\sigma_{8,}$ where σ_8 sets the scale for P(k).
There will be 2% measurements of $f\sigma_8$ at many values of z.



Inflation

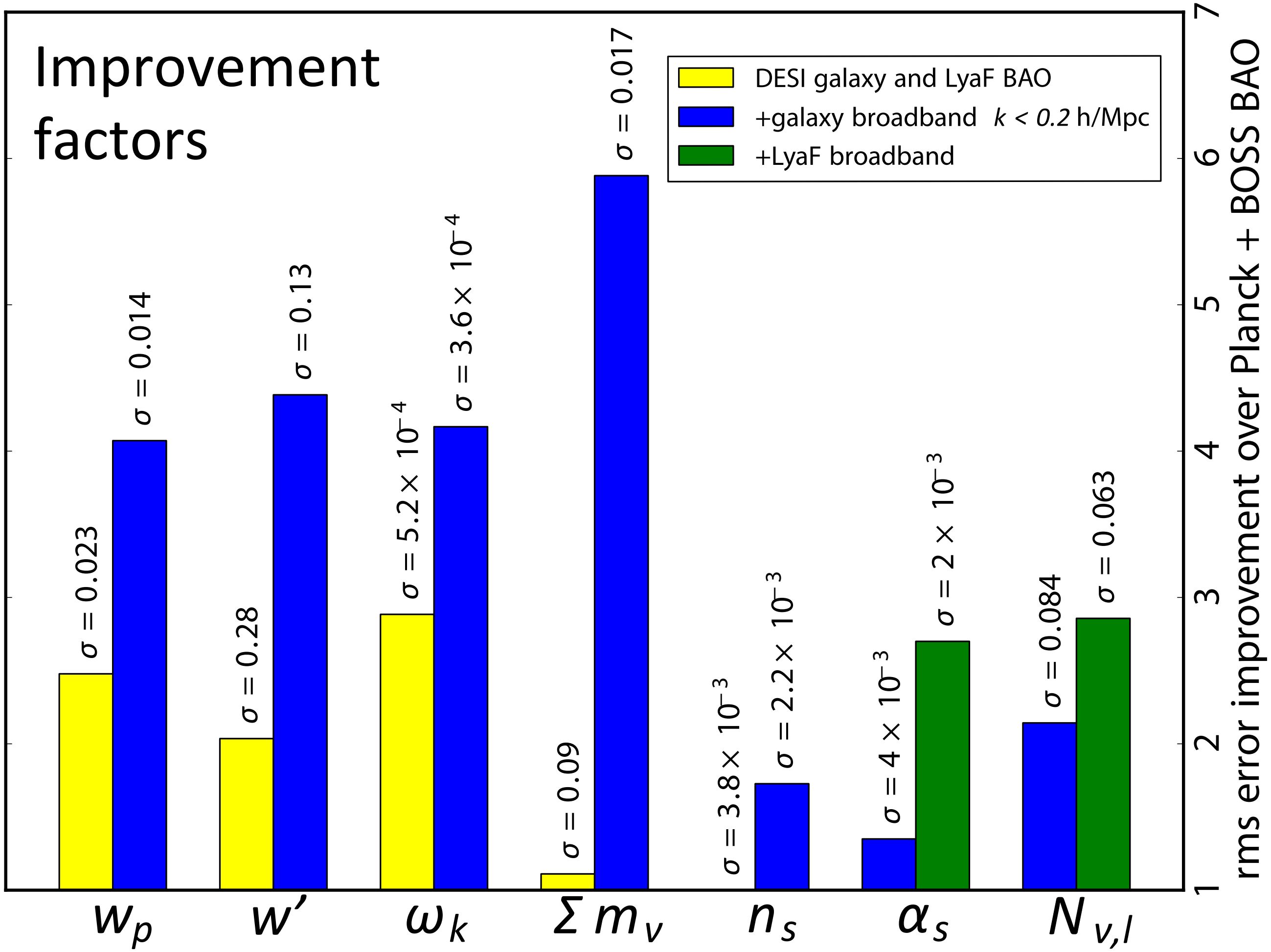
- Look at power spectrum
- Look for three-point correlations (CMB)
- Look a “scale dependence” of bias

$$P(k) = P(k_0)(k/k_0)^{n_S(k_0)+\frac{1}{2}\alpha_S \ln(k/k_0)}$$

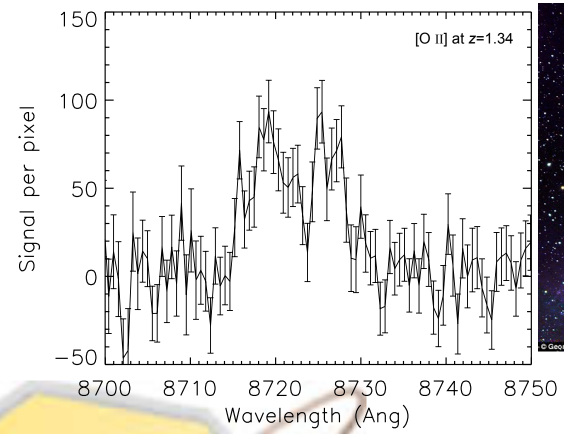
Planck:
n_S=0.9614 ±0.0063
a_S=-0.015±0.017

Data	σ_{n_s}	σ_{α_s}
Gal ($k_{max} = 0.1$ h^{-1}Mpc)	0.0024 (1.6)	0.0051 (1.1)
Gal ($k_{max} = 0.2$ h^{-1}Mpc)	0.0022 (1.7)	0.0040 (1.3)
Ly-α forest	0.0029 (1.3)	0.0027 (2.0)
Ly-α forest + Gal ($k_{max} = 0.2$)	0.0019 (2.0)	0.0020 (2.7)

DESI Improves Many Measurements



Price Tag


[O II] at z=1.34
Signal per pixel
150
100
50
0
−50
8700
8710
8720
8730
8740
8750
Wavelength (Ang)


€2.00

Summary

- DESI: best dark energy information @ 2020
- Modest experiment using existing telescope
- Based on successful BOSS experiment
- Not just dark energy, but GR, inflation, neutrinos